Dipl. Ing. Benoît Bletterie

On the potential of voltage control to increase the hosting capacity of distribution networks

DOCTORAL THESIS

to achieve the university degree of

Doktor der technischen Wissenschaften

submitted to

Graz University of Technology

Supervisor

Ao.Univ.-Prof. Dipl.-Ing. Dr.techn. Herwig Renner
Institute of Electrical Power Systems

Reviewer

Prof. Emmanuel De Jaeger
École Polytechnique de Louvain

Graz, January 2019

AFFIDAVIT

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present doctoral thesis.

28.01.2019

Date

Signature

Acknowledgements

The funding of the research and demonstration projects that hosted part of the research activities presented in this thesis is acknowledged in the corresponding publications (see chapter 6).

I wish to thank Prof. Herwig Renner for his guidance during my PhD and especially during the writing. I appreciated his kind advice and experienced feedback on my work. I hope to be able to further exchange with the Institute of Electrical Power Systems at TU Graz in the future. I also thank Prof. De Jaeger for providing me a very constructive review within a short time.

I would like to acknowledge the support of the Austrian Institute of Technology, which provided me with a unique research environment in which I could work on many interesting and challenging research projects during all these years.

I would also like to thank my former colleagues and friends from the Austrian Institute of Technology. During the many years of joint research, I appreciated the fruitful discussions and the very nice atmosphere in our team.

Similarly, I would like to thank colleagues from other institutions - network operators or manufacturers - who worked with me in several research and demonstration projects. I am thankful for the data they provided and for the valuable inputs from their practical experience.

Finally, I would like to thank my wife Ulli for her continuous support and for providing me the motivation to start and complete this work.

Abstract

Enabled by technological developments and political decisions, the European electricity generation landscape has significantly changed in the last twenty years, and will need to further change to reach the environmental objectives set at national or European level. Since a significant share of this renewable generation is embedded in distribution networks and even low voltage networks (for photovoltaic generation), distribution system operators started facing problems in regions with a high local generation penetration. One of the first constraint limiting the amount of generation which can be integrated to the network (the hosting capacity), is the voltage rise caused by the infeed from the local generation. Once the planning voltage limits are reached, the networks must be reinforced to allow more generation to be connected.

In order to avoid, limit or postpone network reinforcement, efforts have been devoted to smarten networks (research field *smart grids*), and several voltage control concepts have been proposed in the last 10 years.

The deployment of these voltage control concepts has been however very low, mainly due the lack of clear findings on the expected benefits and side effects of these concepts, to the lack of clear recommendations on how to identify networks in which such concepts can actually be used, and to the lack of clear recommendations on how to parameterize these controls.

This doctoral thesis presents the work of several investigations performed to address these gaps, and in particular to evaluate the actual potential of voltage control to increase the hosting capacity of distribution networks. It consists of an introductory part, followed by eight papers.

Starting from the concept of hosting capacity applied to voltage control in distribution networks, the behaviour of feeders is investigated through different types of simulations. The hosting capacity constraint (voltage or current) is determined for "generic" feeders and for a large set of real low voltage feeders. Generic conclusions are derived thanks to the concept of *critical length*, which is calculated for different typical low voltage feeders (e.g. about 500 m for a generic overhead feeder (70 mm^2 AL) and more than 700 m for a generic cable feeder (150 mm^2 AL)). The expected hosting capacity increase which can be reached by implementing Volt/var control strongly depends on the network properties (mainly the R/X ratio), and is low for large R/X ratios. Even if low voltage network are known to have large R/X ratios, the hosting capacity increase expected for the generic feeders previously mentioned reaches about 23 % (cable feeder 150 mm^2 AL) and 52 % (overhead feeder 70 mm^2 AL). Another promising solution is the use of voltage regulated distribution transformers. Installing such assets leads to significantly higher increase of hosting capacity (up to 180 %).

Identifying the hosting capacity constraint allows estimating the expected deployment potential of voltage control solutions such as Volt/var control or voltage regulated distribution transformers. Moreover, a detailed comparison between the most popular voltage control concepts is performed with a parametric study, in order to investigate the impact of the controller settings on the general performance. In addition, active power curtailment is also considered and evaluated with dedicated analyses. Its deployment potential as an "emergency

solution" is discussed. The analyses tend to show a similar performance for the two most popular types of control (*cosφ(P)* and *Q(U)*) for an "average" parameterization of the *Q(U)* control. However, given the significant differences in terms of side effects (i.e. amount of consumed reactive energy and network losses), the *Q(U)* control is recommended.

On the basis of a comprehensive statistical analysis of a large feeder data set, supervised machine learning techniques (classification trees) are used to classify low voltage feeders. This classification is done on the basis of variables which are available without complex network simulations. With the proposed classifier, a set of feeders benefiting from voltage control is identified with a satisfying level of accuracy. By adjusting the misclassification costs, the risk of implementing voltage control in feeders, which could be prone to the current-constraint, is avoided. The actual loss of potential which results from this conservative classification approach is limited: about 18 % of the voltage-constrained feeders which could actually benefit from voltage control are dismissed.

Besides these analyses on the actual potential of voltage control to increase the hosting capacity of distribution networks, dedicated investigations on two insufficiently answered technical issues are performed: the stability of Volt/var control and the performance of Volt/var control under unbalanced conditions. On the basis of detailed dynamic simulations, a stability criterion is established. The analyses show that, even for networks with a high share of distributed generation with Volt/var control, stability problems are not expected. Even considering worst-case conditions, stability issues (poorly damped oscillations) are not observed. For example, a delay in the control loop of about 0.8 s would still allow reaching a response time of 5 s with a damping of 10 %. Special attention should however be given to plant controllers using a remote sensing of the voltage due to the communication delays.

The performance under unbalanced conditions of different Volt/var control implementation options for three-phase generators is investigated, and recommendations for unbalance mitigation are formulated (individual control of each phase or use of the maximal phase-to-neutral phase).

Finally, further technical and non-technical barriers hindering the deployment of these smart grids solutions are also discussed.

The work presented in this thesis suggests that local voltage control can allow increasing the hosting capacity of distribution networks, and possibly defer or limit network reinforcement. The actual potential and the benefits of local voltage control strongly depend on the type of network. It can, however, accurately be estimated thanks to the concepts and analysis methods proposed. The investigations further show that side effects such as an increase of network losses or reactive energy consumption as well as problematic behaviour (unstable operation or increase of unbalance) are not expected if sound parameterization is used.

Kurzfassung

Durch die technologische Fortschritte sowie politisch Entscheidungen hat sich in den letzten 20 Jahren die Stromerzeugungslandschaft in Europa maßgeblich verändert. Weitere Veränderungen sind zu erwarten und notwendig, um die Klimaschutzziele, welche auf nationaler oder europäischer Ebene gesetzt worden sind, zu erreichen. Dadurch, dass ein signifikanter Anteil dieser erneuerbaren Stromerzeugungskapazität in den Verteilnetzen und im Falle der Photovoltaik sogar in den Niederspannungsnetzen angeschlossen ist, sind Verteilernetzbetreiber, insbesondere in Regionen mit einer hoher Durchdringung an lokaler Erzeugung, mit neuen Herausforderungen konfrontiert. Die erste Begrenzung der in das Netz integrierbaren Menge an Erzeugung (Aufnahmefähigkeit), ist meistens durch die Spannungsanhebung gegeben, welche von der lokalen Einspeisung verursacht wird. Ist die Planungsgrenze erreicht, muss das Netz verstärkt werden, um eine zusätzliche Erzeugung an das Netz anschließen zu können.

Um Netzverstärkung zu vermeiden, zu begrenzen, oder zu verzögern, wurden in den letzten 10 Jahren "smarte" Lösungen und insbesondere Spannungsregelungskonzepte entwickelt.

Allerdings wurden diese Lösungen bisher nur selten in die Realität umgesetzt. Grund dafür sind vor allem die fehlenden klaren Erkenntnisse in Bezug auf deren Wirksamkeit und Nutzen, die Nebeneffekte sowie die fehlenden Empfehlungen welche Konzepte in welchen Netzen und mit welcher Parametrierung geeignet sind.

Diese Dissertation stellt die Ergebnisse mehreren Untersuchungen dar, um die oben dargestellten Einschränkungen anzusprechen. Der Fokus wird dabei auf das tatsächliche Potential der Spannungsregelung zur Erhöhung der Aufnahmefähigkeit in Verteilernetzen gelegt. Die Arbeit beinhaltet einen einleitenden Teil, gefolgt von 8 Publikationen.

Ausgehend vom Konzept der Netzaufnahmefähigkeit, mit einer für die Spannungsregelung in Verteilernetzen angepassten Formulierung, wurde das Verhalten von Netzsträngen anhand verschiedener Arten von Simulationen untersucht. Der begrenzende Faktor der Aufnahmefähigkeit (Spannung oder Strom) wurde für generische Niederspannungsstränge sowie für eine große Anzahl an realen Niederspannungssträngen ermittelt. Allgemeine Schlussfolgerungen konnten anhand des Konzepts der *kritischen Stranglänge* abgeleitet werden. Die kritische Stranglänge beträgt z.B. ca. 500 m für einen generischen Freileitungsstrang (70 mm^2 AL) und mehr als 700 m für einen generischen Kabelstrang (150 mm^2 AL). Die durch den Einsatz einer Spannungsregelung zu erwartende Erhöhung der Netzaufnahmefähigkeit, hängt hauptsächlich vom R/X Verhältnis ab, und ist je geringer desto großer das R/X Verhältnis ist. Die Netzaufnahmefähigkeit kann beispielhaft durch den Einsatz einer blindleistungsbasierten Spannungsregelung um 23 % (150 mm^2 AL Kabel) bzw. 52 % (70 mm^2 AL Freileitung) erhöht werden. Eine weitere Maßnahme stellt der Einsatz von regelbaren Ortsnetztransformatoren dar, mit welchen die Aufnahmefähigkeit um bis zu 180 % erhöht werden kann.

Durch diese Analyse kann das erwartete Potential der Spannungsregelungskonzepte wie z.B. blindleistungsbasierte Spannungsregelung oder regelbare Ortsnetztransformatoren abgeschätzt werden. Außerdem erfolgte anhand einer parametrischen Studie ein detaillierter Vergleich der meist etablierten Spannungsregelungskonzepte. Ziel war es die Auswirkung der Parametrierung dieser Spannungsregelungskonzepte auf deren Funktionsweise und Wirksamkeit, zu untersuchen. Die Bewertung erfolgte nicht nur anhand der Wirksamkeit sondern auch anhand der Nebeneffekte wie z.B. den erhöhten Blindarbeitsbezug sowie die erhöhten Netzverluste. Des Weiteren wurde die Wirkleistungsbeschränkung der Einspeisung untersucht und das entsprechende nutzbare Potential als "Notmaßnahme" bewertet. Die Untersuchungen zeigen, dass die am häufigsten eingesetzten Konzepte ($cos\varphi(P)$ und $Q(U)$) mit einer "mittleren" Parametrierung der $Q(U)$ Regelung eine ähnliche Wirksamkeit erreichen. Allerdings unterscheiden sich diese zwei Regelungsarten durch die Nebenwirkungen (d.h. bezogene Blindarbeit oder Netzverluste) wodurch die $Q(U)$ Regelung zu bevorzugen ist.

Im Rahmen einer umfangreichen statistischen Analyse mit einem großen Datensatz von realen Niederspannungssträngen, wurden mehrere Ansätze des maschinellen Lernens erfolgreich eingesetzt. Anhand von Netzparametern, welche üblicherweise Verteilernetzbetreibern zur Verfügung stehen, konnte eine Gruppe von Niederspannungssträngen mit zufriedenstellender Genauigkeit identifiziert werden, welche von einer Spannungsregelung profitiert. Durch die Verwendung von unsymmetrischen Fehlklassifizierungskosten kann das Risiko bei der Umsetzung einer Spannungsregelung in Netzsträngen, für die aber die Aufnahmefähigkeit durch den maximalen Strom begrenzt ist, vermieden werden. Der tatsächliche Potentialverlust, der auf Grund der konservativen Klassifizierung im Kauf genommen werden muss, ist gering. Ungefähr 18 % der spannungsbegrenzten Stränge, die von einer Spannungsregelung profitieren könnten, scheiden aus.

Zusätzlich zu diesen Untersuchungen des tatsächlichen Potentials der Spannungsregelung zur Erhöhung der Netzaufnahmefähigkeit, wurden zwei Fragestellung, welche bisher unzureichend behandelt wurden (Stabilität und Wirksamkeit der Spannungsregelung bei Unsymmetrie), durch weitere Analysen untersucht.

Auf Basis detaillierter dynamischer Simulationen konnte ein klares Stabilitätskriterium abgeleitet werden. Die Untersuchungen zeigen, dass auch für Netze mit einer hohen Durchdringung an dezentraler Erzeugung mit Spannungsregelungsfunktion, keine Stabilitätsprobleme zu erwarten sind. Auch für ein Wost-Case Szenario treten keine Stabilitätsprobleme auf (z.B. schwach gedämpfte Oszillationen). Eine Verzögerung in der Regelschleife von 0.8 s würde beispielsweise, auch mit einer Antwortzeit von 5 s, zu einem stabilen Verhalten führen (Dämpfung größer als 10 %). Bei Erzeugungsanlagen mit größeren Entfernungen zwischen Anlagenregler und Messstelle kann die maximale Verzögerung einschränkend wirken.

Des Weiteren wurde die Wirksamkeit verschiedener Umsetzungsmöglichkeiten der blindleistungsbasierten Spannungsregelung unter unsymmetrischen Bedingungen untersucht, und eine Empfehlung für ein optimales Verhalten formuliert (Regelung der einzelnen Phasen oder Verwendung der höchsten Leiter-Neutral Spannung). Weitere technische und nicht-technische Barrieren für eine Anwendung der untersuchten Spannungsregelungskonzepte wurden ebenso diskutiert.

Die hier vorgestellte Arbeit zeigt, dass die untersuchten, lokalen Spannungsregelungskonzepte tatsächlich die Aufnahmefähigkeit von Verteilernetzen erhöhen können, und dadurch die bisher notwendige Netzverstärkung verzögern oder einschränken können. Der tatsächliche Nutzen hängt stark von der Art der Netze ab, kann aber anhand der eingeführten Konzepte und Methoden quantifiziert werden. Die hier zusammengefassten Untersuchungen zeigen, dass sich die Nebeneffekte wie z.B. erhöhter Blindarbeitsbezug und steigende Netzverluste in Grenzen halten. Problematisches Verhalten (wie z.B. Instabilität oder Verstärkung der Unsymmetrie) ist bei geeigneter Parametrierung, auch unter Worst-Case Bedingungen, nicht zu erwarten.

Table of contents

List of abbreviations and symbols

ANOVA	Analysis of variance
CAPEX	Capital expenditures
cdf	Cumulative distribution function
CENELEC	European Committee for Electrotechnical Standardization
CIGRE	International Council on Large Electric Systems
$cos\varphi$	Power factor
DER	Distributed energy resources
DG	Distributed generation
DSO	Distribution system operator
GIS	Geographical information system
HC	Hosting capacity
HIL	Hardware-in-the-loop
HV	High voltage
I	Current
ICT	Information and communication technologies
IEEE	Institute of Electrical and Electronics Engineers
LV	Low voltage
MV	Medium voltage
OLTC	On-Load tap changer
OPEX	Operational expenditures
OPF	Optimal power flow
P	Active power
PCA	Principal component analysis
pdf	Probability density function
PV	Photovoltaic[1]
Q	Reactive power
RES	Renewable energy resources
TSO	Transmission system operator
U	Voltage
VRDT	Voltage regulated distribution transformer
VVI	Volt/var index

[1] In this document, solar power only considers solar photovoltaic power, excluding solar thermal power.

Overview of the compiled publications

The selected papers listed below form the main part of this doctoral thesis. These papers are provided in chapter 6, together with a brief description of the personal contribution of the applicant. Further papers, which do not fully address the research questions, but which are related to the main topic of this thesis, are listed in chapter 7.

[1] B. Bletterie, J. Le Baut, S. Kadam, R. Bolgaryn, and A. Abart, “Hosting capacity of LV networks with extended voltage band,” in Proc. 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), Vienna, 2015.

[2] B. Bletterie et al., “Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks” Prog. Photovolt. Res. Appl., vol. 20, no. 6, pp. 747–759, Sep. 2012.

[3] B. Bletterie, S. Kadam, A. Abart, and R. Priewasser, “Statistical analysis of the deployment potential of Smart Grids solutions to enhance the hosting capacity of LV networks,” in Proc. 14. Symposium Energieinnovation, Graz, 2016.

[4] B. Bletterie, S. Kadam, and H. Renner, “On the classification of low voltage feeders for network planning and hosting capacity studies,” Energies, vol. 11, no. 3, p. 651, Mar. 2018.

[5] B. Bletterie, S. Kadam, R. Bolgaryn, and A. Zegers, “Voltage control with PV inverters in low voltage networks – In depth analysis of different concepts and parameterization criteria,” IEEE Trans. Power Syst., pp. 1–1, 2016.

[6] F. Andren, B. Bletterie, S. Kadam, P. Kotsampopoulos, and C. Bucher, “On the stability of local voltage control in distribution networks with a high penetration of inverter-based generation,” IEEE Trans. Ind. Electron., pp. 1–1, 2014.

[7] B. Bletterie, S. Kadam, A. Zegers, and Z. Miletic, “On the effectiveness of voltage control with PV inverters in unbalanced low voltage networks,” in Proc. Electricity Distribution (CIRED 2015), 23rd International Conference and Exhibition on, Lyon, 2015.

[8] B. Bletterie, S. Kadam, R. Pitz, and A. Abart, “Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters,” in Proc. PowerTech 2013 IEEE Grenoble, 2013, pp. 1–6.

1 Introduction

1.1 Paradigm shift in the electrical power system – structural changes and technological developments in the last twenty years

1.1.1 Wind and solar power reshaping the generation landscape in Europe

In the last 20 years, the European electric power system has experienced major changes. Triggered by environmental targets (e.g. 20-20-20 objectives set in the 2020 climate & energy package) and political decisions such as the nuclear phase out together with the “Energiewende” (energy transition) in Germany, the share of renewable energy in the generation capacity has been strongly increasing in the last 10-15 years. Wind and solar power have been the sources with the highest growth rates. The total installed wind power capacity in the European Union increased from about 13 GW in 2000 to more than 171 GW at the end of 2017, with the top three countries (Germany, Spain, United Kingdom) summing more than 99 GW [9]. For solar photovoltaic, the figures are similar, with an increase of the installed capacity from nearly 0 GW in 2000 to more than 118 GW at the end of 2017, with the top three countries (Germany, Italy, United Kingdom) summing about 75 GW [9]. In Austria, the installed wind power capacity reached about 2.9 GW at the end of 2017 [9] (of which 90 % are concentrated in two eastern provinces), and the installed solar photovoltaic power capacity reached 1.4 GW. For comparison, the installed wind and solar capacity reached in Germany about 56 GW and 42 GW respectively, at the end of 2017.

Given the European and national objectives and commitments, this trend to decarbonisation of the electricity generation is expected and required to be strengthened in the next decade. At European level, the latest agreed objective is to reach 27 % of electricity from renewable generation by 2030 [10]. In Germany, the current objective is to reach 40-45 % of renewable generation until 2025, 55 % - 60 % until 2035 and 80 % until 2050 [11]. In Austria, the latest energy policy paper sets a target of 100 % of renewable electricity generation until 2030.

1.1.2 A new situation in terms of geographic distribution and generation patterns

The share of the electricity consumption covered by wind power can still be considered as moderate at European level (about 12 % in 2017 [12]), but there is a strong inhomogeneity among European countries. The top five countries Denmark, Portugal, Ireland, Germany and Spain covered between 19 % and 44 % of their electricity consumption from wind power [12]. This inhomogeneity can be further observed at the level of regions within countries. For example, more than two third of the installed wind power in Germany (50.7 GW at the end of 2017 [13]) is concentrated in 5 of the 16 provinces (mainly in the northern part of the country). In Austria, the concentration is even stronger with 90 % of the installed power (2.8 GW) in the two eastern provinces [14].

Regarding solar photovoltaic power, the picture is similar with for example more than 40 % of the installed photovoltaic (PV) power in Germany located in the southern part of the country (Bavaria and Baden-Württemberg) [15].

Besides this inhomogeneous geographical distribution of wind and solar power, the seasonal and daily fluctuations make it challenging to integrate large amounts of this type of generation into the power system. Wind and solar power exhibit rather low capacity factors (for wind power between 17 % in Germany and 30 % in the UK with an average of 23 % for the EU28 [16]) and large temporal variations (maximal absolute wind generation gradient up to 30 % of the installed capacity within 15 minutes in Austria [16]). While the time variability is significantly smoothened with growing level of aggregation (the maximal wind generation gradient at European level is about 6 % of the installed capacity within one hour against e.g. 48 % in Austria [16]), (local or) regional constraints remain and affect the system security.

1.1.3 Resulting challenges for the power system

The inhomogeneous distribution of wind and solar power across regions, together with their time-variability result in significant challenges for European power systems. Given the large growth rates observed for wind and solar power in the last two decades, and the time needed to upgrade the transmission and the distribution infrastructure, system operators have been facing increasing challenges:

- at distribution level, the locally high levels of distributed generation (mostly solar generation) cause local problems
- at transmission level, the geographical mismatch between (wind and solar) generation and large load centres cause high power flows and congestions on transmission lines.

At distribution level, the constraint that generally appears first is the voltage rise (when the voltage rise due to the reverse power flows exceeds the planning limits) – see chapter 2.1.1. The most common cause of these reverse power flows at distribution level is the solar power infeed during weak load periods. The amount of wind generation at medium voltage level is low since most of the generation is connected to the subtransmission or to the transmission network.

The challenges at transmission level appeared by nature later than the ones at distribution level, but have been increasing steadily in the last years. In Germany, increasing congestion management measures have been necessary to maintain a secure system operation in the last years. One of the main reasons for this are the strong north-south power flows caused for example by

- wind power surplus in the north, together with
- power deficit in the south due to the shutdown of several (nuclear) power stations, together with
- delayed network extension projects.

The redispatch volumes necessary to maintain a secure operation of the German transmission system (including measures at national level and cross-border measures) increased from about 0.3 TWh in 2010 to more than 15 TWh in 2015, and more than 18 TWh in 2017 [17], [18]. For 2017, the total costs to maintain a secure operation reached a maximum with about 1.4 milliard €, including redispatch, counter-trading, curtailment of renewable infeed and standby capacity [18]. In Austria, the costs for congestion management have been multiplied by more than three between 2016 and 2017, reaching about 100 millions € in 2017 [19].

A very specific property of solar generation in Europe is its highly decentralized nature: according to [20], more than 70 % of the installed PV capacity was embedded in low voltage networks (more than 25 GW at that time (2014)). This means that the impact of this large amount of generation is visible both at distribution and transmission level. In fact, the split perspective *distribution level* / *transmission level* (see above) is no longer suitable and these two levels cannot be considered independently anymore. Individual wind and solar parks connected to distribution of sub-transmission systems, which have, alone, a modest size compared to large classical hydro, thermal or nuclear power stations, are now relevant for the system operation.

For this reason, the technical requirements to be fulfilled by wind and solar generation have been significantly revised and extended in the last decade. *System level* topics such as power frequency control, reactive power provision, behaviour under fault etc. have appeared in connection standards for generation down to the low voltage (see chapter 2.1.1). Since about 10 years, generators connected to the distribution network are required to support, to some extent, the system operation.

Besides the strong growth of renewable generation mentioned previously, new applications allowing a further decarbonization of the energy will also further shape the electrical power system, and in general the whole energy supply. Most of these new applications are named under the umbrella term Power-to-X (PtX or P2X). X stands for heat, gas (methane, hydrogen), liquid, chemicals and transport/mobility. P2X can play a key role in enabling a decarbonization of many different sectors (e.g. transport, heat, chemistry, etc.), and can offer at the same time new flexibility sources for the electrical power system in terms of storage. This flexibility obtained by coupling different sectors could allow using electricity surplus, which currently cause additional costs in the power system (congestion management). In parallel, a large-scale decarbonization requires a massive development of the renewable generation, and of the transmission and distribution infrastructure. For example [21] estimates that in order to reach CO_2-neutrality for the sectors of electricity, transport and chemistry in Germany, an additional power need between 100 and 330 GW would be necessary. The developments in this field will therefore drastically affect the electrical power system, and in general the whole energy supply.

1.1.4 Research activities to facilitate the renewable integration – smart grids

These challenges rising from the integration of large amounts of renewable generation into the power system have been the subject of considerable research and development activities in the last decades. The topics of many of these research efforts can be grouped into the umbrella term of *smart grids*. One of the early European initiative in this field is the European Technology Platform (ETP) SmartGrids (now the European Technology & Innovation Platform (ETIP) *Smart Networks for Energy Transition* (SNET) [22]), which was initiated in 2005 by the European commission, with the objective to bundle the research and development activities to speed-up the decarbonization of the electric power system.

Instead of giving a (another new) definition of smart grids, the vision and objectives mentioned in this early initiative [23] are reminded here, and a personal analysis is provided.

<u>Vision [23]:</u>

- *Flexible: fulfilling customers' needs whilst **responding to the changes and challenges** ahead;*
- *Accessible: **granting connection access** to all network users, particularly for renewable power sources and high efficiency local generation with zero or low carbon emissions;*
- *Reliable: assuring and improving security and **quality of supply**, consistent with the demands of the digital age with resilience to hazards and uncertainties;*
- *Economic: providing **best value through innovation**, efficient energy management and 'level playing field' competition and regulation.*

<u>Objectives [23]:</u>

- *Creating a **toolbox of proven technical solutions** that can be deployed rapidly and cost-effectively, enabling existing grids to accept power injections from all energy resources;*
- ***Harmonizing regulatory and commercial frameworks** in Europe to facilitate cross-border trading of both power and grid services, ensuring that they will accommodate a wide range of operating situations;*
- *Establishing **shared technical standards** and protocols that will ensure open access, enabling the deployment of equipment from any chosen manufacturer;*
- ***Developing information, computing and telecommunication systems** that enable businesses to utilize innovative service arrangements to improve their efficiency and enhance their services to customers;*
- *Ensuring the successful interfacing of new and old designs of grid equipment to **ensure interoperability** of automation and control arrangements.*

These vision and objectives were formulated more than 10 years ago. Looking at the trends in the last two years, one would probably put a stronger focus on new technologies such as residential storage, utility-scale storage, energy management systems at home or energy communities level, and emerging enabling technologies like blockchain. However, most of the basic elements listed above remain relevant.

In [24], a review of the state of play of smart grid innovation efforts in Europe is provided. The smart grids applications are grouped into the following domains:

- **Smart network management** (SNN) with e.g. new capabilities for reactive power control, controllable distribution substations, smart inverters…
- **Demand side management** (DSM) with e.g. demand response and energy management within energy communities)
- **Integration of distributed generation** (DG) **and storage** with e.g. network planning and analysis tool for assessment of network capacity for DG connections, active grid support (power-frequency control, voltage control) through smart inverters to facilitate DG connection.
- **E-Mobility** with e.g. Integration of electrical vehicles (EV) for provision of ancillary services
- **Integration of large-scale renewable energy resources** (RES) with e.g. forecasting tools for RES production or Integration of DSM for provision of ancillary services by distribution systems to support transmission system operation.

In the context of this thesis, smart grids mainly refer to technical solutions allowing, from technical and economical point of view, a better integration of distributed energy resources into distribution systems and limiting or postponing network reinforcement.

This can be achieved through letting/requiring from generators to contribute to the system operation rather than just being connected and injecting power into the system (*fit and forget* approach [25]), or by using other technologies (e.g. use of smart meters, information and communication technologies (ICT), or specific assets such as voltage regulated distribution transformers (VRDT)).

A detailed review of the state of the art is provided in chapter 2.1.

1.2 Research motivation

Nowadays, most of the human activities rely in one form or the other on electricity (public transport, water supply and treatment, communications, industries, services, leisure…). Ensuring a secure power supply has therefore been given a very high priority at European and country level. At the same time, power systems have been evolving since the first electrification steps into a very complex system, involving technical, economical and regulatory aspects. The changes in the electricity generation landscape mentioned in chapter 1.1.2 led to major challenges for the power system as a whole, involving all the sectors (generation, transmission, distribution and retail). With a clear objective of decarbonizing the electricity supply, system operators have been facing different challenges in the last decades: not only local problems at distribution level but also system-wide challenges as explained in chapter 1.1.3.

The main motivation of this thesis is to support the cost-effective integration of larger amounts of renewable generation into distribution networks with smart grids concepts. Despites the substantial amount of efforts on research, development and demonstration, undertaken in the last decade (see state of the art in chapter 2.1), the deployment of smart grids solutions to improve the integration of renewable generation into distribution networks has been rather limited. This tends to show that crucial questions such as “what is the real potential of smart grids solutions as an alternative to network reinforcement?” or “which type of voltage control should be preferred and how should the controller settings be chosen?” have not been answered properly. The main objective of this thesis is to provide clear answers to these questions (a detailed formulation of the research question(s) is provided in chapter 2.2.1), and to try to formulate general recommendations supported by comprehensive analyses rather than on individual case studies.

2 Voltage control in distribution networks – State of the Art and scope of the work

Before presenting the own contribution (chapters 3 and 6), chapter 2.1 and chapter 2.2 present the state of the art and the scope of the work respectively.

As indicated in chapter 1.2, the focus of this work is on the challenges associated to the integration of large amounts of renewable generation into distribution networks. The state of the art is therefore limited to distribution level. A short generic overview on the challenges of integrating renewable generation into the power system including transmission or system-level issues is nevertheless provided in the following.

The technical interactions between distributed generation and the power system have been classified in [25] into the following topics:

- steady state operation
- protection coordination
- dynamic behaviour
- provision of ancillary services

While many studies can be found on the steady-state operation of power systems with a high share of renewable energy resources (e.g. over-voltage problems (see chapters 2.1.1 and 2.1.5 for a comprehensive review), thermal line rating to better use the existing infrastructure [26], [27]), less studies have been performed on the second item: protection coordination (a review is provided in [28]).

One of the popular research topic related to the dynamic behaviour of distributed energy resources at distribution and transmission level is the behaviour under fault or fault-ride-through (FRT or low voltage ride through LVRT), i.e. the ability of generators to stay connected during and after the fault, and to inject reactive current to support the voltage. While connection standards have been requiring this capability for generators connected to the high voltage (HV) and then medium voltage (MV) networks (see chapter 2.1.2), similar requirements are now to be applied to small generators connected to the low voltage (LV) network [29], [30]. Another popular topic is the limitation of ramp rate for large PV generators [31]–[34] which can, especially in small power systems, negatively affect the power quality or even the system stability.

The provision of ancillary services by distributed generators has been investigated in [35], with a focus on reactive power supply. With the steadily increase of the share of renewable generation, system-level issues have been gaining importance in the last years.

Due to the decreasing share of conventional generation, and in particular in periods with high wind and/or PV generation, the lack of inertia has been identified as a possible problem. The need for additional fast frequency controlling actions (e.g. enhanced frequency response EFR [36]) or synthetic (or virtual) inertia, have been identified and drawn to the attention of stakeholders in the last years [37]–[40]. Meanwhile, a considerable amount of research has been devoted to the characterization of the behaviour of non-synchronous generators under frequency disturbances [41] and to the design of control schemes to support frequency stability [42]–[46].

2.1 State of the Art on voltage control in distribution networks

2.1.1 Impact of high penetration levels of distributed generation on network planning

The effects of distributed generation on distribution networks that are most reported in the literature, are reverse power flows and voltage rise [47]–[51], even if other effects such as power quality deterioration (e.g. flicker, harmonic distortion, unbalance), increase of fault level, protection and even stability are also mentioned [47].

With large penetration levels of distributed generation, power flows can start to reverse, with the power flowing for example from the LV networks to the secondary substation or even to the primary substation. This reversal of the power flow is, as such, not a problem for distribution networks, but depending on the severity, it can lead to over-load or over-voltage situations. Most of the studies on this topic identify the issue of voltage rise as the most problematic for the integration of distributed generation. The reason for this is that distributed renewable generation (e.g. PV, wind, small hydro and biomass) is mostly available in rural areas with a low load density, where distribution networks have usually rather long feeders designed to supply small loads.

The voltage rise caused by the power infeed from a generator connected to a distribution feeder can be estimated (approximation usually used in distribution networks [47]) with equation (1):

$$\Delta U \approx \frac{R \times P + X \times Q}{U_N^2} \tag{1}$$

with

ΔU	Relative voltage rise caused by the active / reactive power infeed
P	Active power infeed of the generator
Q	Reactive power infeed of the generator
R	Equivalent network resistance at the point of connection
X	Equivalent network reactance at the point of connection
U_N	Nominal voltage

More details on the regulatory requirements in terms of admissible voltages are provided in the following.

Without presenting the details of control concepts (see chapter 2.1.5), equation (1) shows that one way to counteract the voltage rise is to consume reactive power: when Q and P are of opposite signs, the voltage rise can be partly compensated. This generic way of controlling the voltage with reactive power is generally called Volt/var control.

System planning is defined in [52] as an essential task "*to assure that the growing demand for electricity can be satisfied by distribution system additions which are both technically adequate and reasonably economical".* From today's perspective, this definition should be extended to consider also in addition to the growing electricity demand, the growing distributed generation.

The task of distribution network planners has become more and more complex due to the high level of uncertainty, in terms of load and generation evolution. Another aspect making the planning work more complex, is the necessity to consider and compare different alternatives such as network reinforcement or the implementation of smart grids solutions.

Distribution network planning is subject to very diverse technical and regulatory requirements on e.g. the admissible loading of assets, power quality levels, exposure to noise or electromagnetic fields, etc. Given the importance of the voltage rise (see chapter 2.1.1), the requirements specified in different standards are briefly explained in the following. The voltage magnitude is one of the power quality characteristic covered by power quality standards, and in particular by the standard EN 50160 *Voltage characteristics of electricity supplied by public electricity networks* [53]. According to this standard, the voltage should stay between +10 % and -10 % of the nominal voltage (the exact requirement is that, on a weekly basis, 95 % of the 10 minutes average values of the voltage should be between +10 % and -10 % of the nominal voltage, and 100 % of the values should be between +10 % and -15 %[1]).

Based on these global requirements, individual requirements need to be specified for network users (loads and generators). This allocation of the available voltage band among network users is partly specified in technical guidelines in Austria [54] and Germany [55], [56]. According to these guidelines, the stationary voltage rise caused by the active power infeed of distributed generators in LV and MV networks shall not exceed 3 % and 2 % respectively (see Figure 1). As visible on the figure, a challenging situation occur with feeders dominated by generation and others by loads. In such cases, it is not possible to modify the voltage set point at the primary substation to get some freedom and optimally use the available voltage band. Some more details on how to detect such situations and how to optimally use the voltage band are given in chapter 3.2.1.

[1] These requirements are for low voltage networks. For medium voltage networks, the requirements are slightly different.

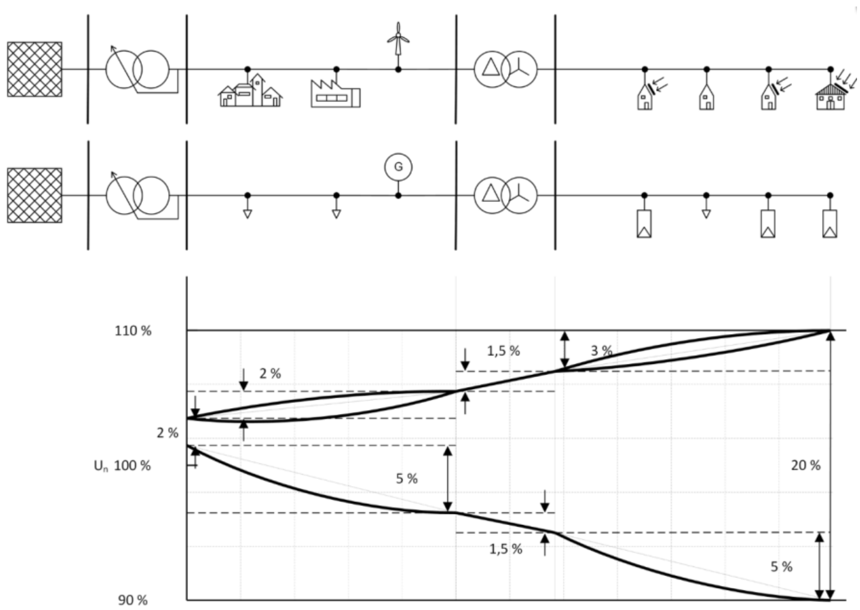


Figure 1: Illustration of the voltage band allocation [57]

With the appearance of voltage problems caused by large power infeeds from (renewable) generation into distribution networks, research and standardization have been intensified, as visible on Figure 2 (evolution of the number of published papers with the key words "inverter" and "reactive power", starting in 2000).

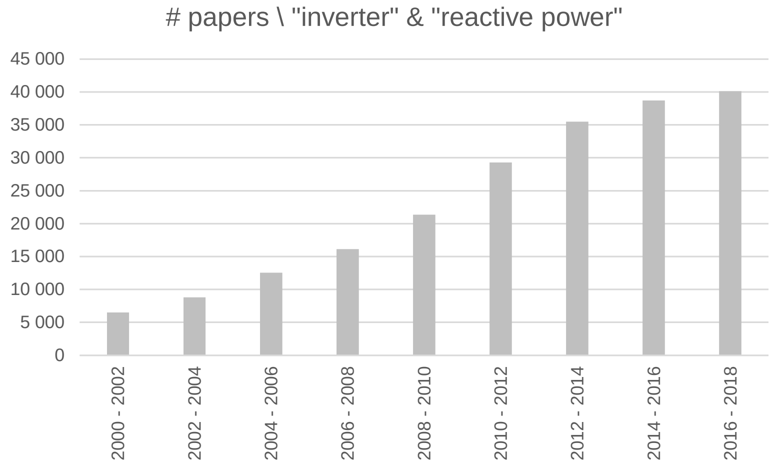


Figure 2: Number of papers published (data from [58])

Several promising voltage control concepts have emerged out of these research activities (see chapter 2.1.5). Standards and connection guidelines have therefore been modified accordingly to allow distribution system operators (DSOs) to make use of them [59], and they have then been updated several years later [60].

2.1.2 Overview of requirements on Volt/var control in selected European countries

Regarding voltage control with reactive power (Volt/var control), the first versions of the guidelines usually specified a list of possible controls which can be used by DSOs.

In Germany, the MV guideline [56] published in 2008 required that generators should be able to operate at a power factor of 0.95 in different control modes:

- a fixed power factor $\cos\varphi$
- a variable power factor depending on active power $\cos\varphi(P)$
- a fixed reactive power Q in Mvar
- a reactive power/voltage characteristic $Q(U)$.

Regarding LV-connected generators, similar requirements as for MV generators appeared a few years later (2011 in Germany), with however a differentiation according to the generator size (i.e. power smaller or greater than 3.68 or 13.8 kVA) [55].

Similar requirements are specified in the Austrian guideline which covers both MV and LV voltage levels [61]. The first version of the Austrian guideline including such requirements [62] has indeed been aligned in 2013 with the requirements of the German LV guideline [63], and has been recently updated again [64]. Currently, both German LV and MV guidelines are under revision.

Besides Germany and Austria, reactive power requirements appeared also rather early in Belgium and Italy.

In Belgium, generators above 1 MVA must be able (since 2012) to operate at $\tan\varphi$=-0.10 (reactive power consumption) and 0.33 (reactive power injection).

In Italy, the latest connection standard for LV consumers [65] requires from inverter-based generators smaller than 11.08 kW to be able to operate in a triangular area in the PQ-plane (down to $\cos\varphi$=0.90) in $\cos\varphi(P)$ mode, and from generators larger than 11.08 kW to be able to operate according in a rectangular area (up to a maximal reactive power of 0.48 p.u. (independently from the injected active power)) in $Q(U)$ mode. More details on these types of control are provided in chapter 2.1.5.1.

In France, the largest DSO *Enedis* published in 2016 a note describing how to implement local voltage control for generators connected to the MV network. This control is not compulsory but can be chosen by the connection applicant to e.g. save network reinforcement costs needed to reinforce the network. The control consists in a $Q(U)$ control with a maximal reactive power of 0.40 p.u. (injection) or 0.35 p.u. (consumption).

Having recognized the need to harmonize requirements throughout Europe, some standardization work has been launched at CENELEC level in 2007, leading to the standard EN 50438 [66] for small generators (<16 A) and two technical specifications: EN 50549-1 and -2 [67], [68] for LV and MV connected generators respectively.

The standard EN 50438 requires from inverter-based generators to be able to operate down to a power factor of 0.90 in the three modes *Q(U)*, *cos*φ fix or *cos*φ*(P)*. The technical specifications EN 50549-1 and -2 require a similar operation area (down to a power factor of 0.90), with however a possibility to over-fulfil with a rectangular area. This technical specifications required more control modes than the previously mentioned standards:

- *Q fix*
- *Q(U)*
- *Q(P)*
- *cos*φ *fix*
- *cos*φ*(U)*
- *cos*φ*(P)*

These European standard or technical specifications are however only rarely referred to in national regulations and therefore only relevant in a few countries.

Finally, the network code "Requirements for Generators" shall be mentioned. In 2009, the European Commission identified the need for coordinating the framework conditions of the energy market in the EU and the development of European "Network Codes" (NCs) was launched to establish a harmonized set of rules for the electricity sector in Europe.

After a long drafting and consultation process the network code "Requirements for Generators" (RfG) was published in April 2016 [69]. This grid code defines four categories of generators based on the power and voltage at the point of connection, with different requirements for each category. In terms of reactive power provision, requirements are applicable to almost all categories (B, C and D), i.e. for generators above 1 MW in the synchronous area Continental Europe. This grid code will play a major role in harmonizing system-relevant issues such as frequency control or response to large disturbances (fault-ride-through). In terms of reactive power provision, the grid code mainly specifies U-Q operation areas for generators and leaves further details to national regulations (non-exhaustive requirements).

Alongside with these new requirements for generators connected to the distribution network, additional standards specifying how to test equipment supposed to fulfil these requirements, have been published and used by testing institutes [70].

In the next chapter, the requirements are briefly analysed and the most relevant gaps are identified.

2.1.3 Comparison of the connection requirements related to voltage control in selected European countries

About 10 years after the introduction of the first requirements related to voltage control in connection standards or guidelines, the requirements are still inhomogeneous. In the following, the items which are addressed differently are briefly discussed.

- **Threshold for the requirement to contribute to voltage control**

The thresholds used for requiring from generators the capability to control the voltage which are set in terms of voltage level (e.g. in France [71]), in terms of power (e.g. Belgium [72]), or both (e.g. Germany [55], [56], Austria [64]) differ significantly. While the voltage control or reactive power control capability is not required from LV-connected generators in France and Belgium, it has been required in Germany and Austria for about 5 years (which does not necessarily means that it has actually been used).

- **Design requirements (PQ-operation area, reactive power capability)**

The connection requirements differ significantly in terms of design requirement (or PQ-operation area), i.e. on the amount of reactive power which the generator must be able to inject or consume.

Some standards require from generators to be able to operate in a triangular area on the PQ plane down to power factors of 0.95, others down to 0.90 (sometimes depending on the voltage level or generator power). In some standards, the requirement is relieved when the injected active power is low (e.g. below 20 % of the nominal power in Germany [55], Austria [64] and Italy for generators < 11.08 kW and below 10 % e.g. in Italy for generators > 11.08 kW [65]).

Some standards mention the possibility to over-fulfil these requirements by being able to operate in a rectangular area (i.e. the possibility to consume or inject reactive power independently from the active power output): in Italy [65] or according to the technical specifications EN 50549-1 and -2 [67], [68].

- **Type of control**

The most required types of control are *Q fix*, *cosφ fix*, and *Q(U)*, but some connection guidelines require additional types of control such as *Q(P)* and *cosφ(U)*. Only very few standards provide a clear recommendation for a particular type of control.

- **Steady-state control settings**

From all the connection guidelines and standards, only a few ones mention specific settings for all the types of control required (e.g. deadband, droop, thresholds – see chapter 3.2.1 and in particular Figure 8 for more details on the steady-state control settings): [65] in Italy and [71] in France. For all the others (Germany, Austria, Belgium, European standards / specifications), no information about the settings is given (such as default settings or how to select the settings).

- **Response time**

While there is a general consensus that reactive power-based voltage control should not react "too fast", the requirements on the dynamic response of the voltage control were missing in the first versions of the connection guidelines, and are still generally vague:

  - Germany: response time of 10 s [55] or first order characteristic with an adjustable time constant between 5 s and 60 s in the latest draft [30]
  - Austria: first order characteristic with a time constant adjustable between 3 s and 60 s [64] (the same requirements are mentioned in the technical specification EN 50549-1 and -2 [67], [68])
  - France: voltage measurement with a moving average of 10 s, sampled every second, and a response time of 30 s [71]
  - Italy: maximal settling time of 10 s [65].

- **Maximal power for single-phase generators**

This requirement is not directly related to the topic of voltage control but has an indirect impact (see next point and chapter 2.1.5.2). The maximal power of single phase generators is for example 3.68 kVA in Austria [64], 4.6 kVA in Germany [55], 5 kVA in Belgium [72] and 6 kVA in Italy [65] or France [73] (the max. power of single-phase consumers is 12 kVA in France)[1]. In the last years these thresholds have been decreased in a few countries (from 4.6 kVA to 3.68 kVA in Austria and 18 kVA to 6 kVA in France) to limit the unbalance in LV networks.

- **Control under unbalanced conditions for three-phase generators**

Most of the standards do not address this topic at all, although significant differences in terms of behaviour have been identified several years ago [74].

Only a few documents and the technical specification EN 50549-1 [67] address this issue:

- Germany (only in the current draft for the revised German LV connection guideline [30]): for the *Q(U)* control, the maximum of the three phase-to-neutral voltages should be used.
- Austria: if the phases are not controlled individually, the controller should use the maximum of the three phase-to-neutral voltages (using the average value of the three voltages is however allowed) [64].
- EN 50438 [66]: "*the input signal of the voltage controller can be the positive sequence voltage, the average of the phase-to-neutral voltages or a an independent control of the three phases*"

[1] The requirements can be in fact more complex, with a maximal constructive unsymmetry or an actual unsymmetry between phases.

- EN 50549-1 [67]: "*in the absence of consensus, one of the following three methods should be used:*
    - *the positive sequence component of the fundamental*
    - *the average voltage of a three phase system*
    - *phase independently the voltage of every phase to determine the reactive power for every phase*".
- **Requirements on the control error**
    - Italy and France: +/- 5 % of the connected power [65], [71]
    - Germany: the applicable testing procedure only covers the *cosφ(P)* control and specifies a maximum error of +/- 0.01 on *cosφ*.

This brief comparison of the requirements shows a rather inhomogeneous picture. This situation can result in the following difficulties:

- for generator manufacturers, having to design equipment able to fulfil the full variety of requirements, leading to additional development costs
- for network planners:
    - having to rely on devices which might behave differently
    - having to adjust the settings without clear recommendations.

For the topics of dynamic behaviour, behaviour under unbalanced conditions and in particular the type and parameterization of control, a consensus is apparently missing.

2.1.4 Hosting capacity of distribution networks

As mentioned in chapter 2.1.1, the reversal of the power flow can lead to over-load or over-voltage situations.

The impact of distributed generation on distribution networks can be quantified by the so-called hosting capacity. This concept, which has been introduced in [50], *identifies the acceptable degree of DER penetration under given circumstances*.

In the last years, the rapid deployment of renewable generation in distribution networks has raised the interest on the concept of hosting capacity and many publications on this subject can be found. In particular, a number of them are using a probabilistic approach to evaluate the hosting capacity to deal with unknown factor such as the (future) location and size of generators and/or loads.

The authors in [75] developed a streamlined analysis to determine the amount of photovoltaic generation that can be integrated into a distribution feeder. This streamlined analysis provides, for each considered feeder, a maximum hosting capacity (total PV penetration for which a constraint is experienced) and a minimum hosting capacity (total PV penetration for which a constraint is likely experienced). This method has been used on several feeders, showing a great diversity among them. In [76], a probabilistic distribution of the voltage is used to determine the hosting capacity of sample networks in terms of acceptable number of PV generators and loads. In [77], Monte Carlo simulations are used to calculate a congestion risk. Defining an acceptable risk allows calculating a corresponding maximal amount of generation: the hosting capacity. In [20], the potential of Volt/var control has been analyzed by determining the gain in hosting capacity achievable for different networks. For this, a probabilistic assessment varying the location of the PV generation has been used.

2.1.5 Voltage control and further smart grids concepts for hosting capacity enhancement

2.1.5.1 Review of basic voltage control concepts and further smart grids concepts

As mentioned in chapter 2.1.1, voltage rise is one of the most common limitation of the hosting capacity, and extensive research material on voltage control concepts has been published in the last years.

From a general perspective, there are several possibilities to counteract the voltage rise caused by the infeed from renewable generation into distribution networks, and therefore to extend the network hosting capacity. These possibilities can be classified based on the architecture of the control concepts (e.g. local / centralized / distributed) or based on the assets they rely on. In the following, another smart grid concept aiming at avoiding congestions (overload) is briefly presented for completeness in point b) although it is by nature not related to voltage control.

a. Network reinforcement

Network reinforcement and network extension have been one of the main tasks of network planners for decades. They can be considered to be the business as usual scenario, even if the complexity of the task should not be underestimated. Indeed, for feeders for which the hosting capacity is exhausted (voltage or current constraint), several alternatives such as reinforcing part of the feeder or splitting the feeder (see [78] for some theoretical considerations) must be evaluated. While network planning covers many different aspects, trying to identify the optimal network reinforcement or extension on the sole basis of voltage and loading requirements (ignoring other considerations related to e.g. asset management) is already a challenging task. For example, [79] proposes the use of a heuristic optimization to determine the optimal network extension. All the possible measures (e.g. new secondary substation, feeder reinforcement, use of Voltage Regulated Distribution Transformers…) are considered and monetized in order to find the lowest total costs.

The concepts presented to increase the hosting capacity (points c) to f)) are all devoted to voltage control – the focus of this thesis. Before presenting these, another concept, which is used to increase the hosting capacity of feeders experiencing the current constraint, is presented in point b).

b. Dynamic line rating

The concept of dynamic line rating consists in using dynamic values for the maximal currents of transmission or distribution lines according to the external conditions (e.g. ambient temperature, wind speed, solar irradiance). It therefore addresses the other limitation of networks (current limit) and has been used successfully by transmission system operators for some years [99]. The theoretical formulation has mainly been elaborated by CIGRÉ [100], [101] and IEEE [102].

[103] quantifies the transmission capacity increase in networks with high wind power share through the use of dynamic line rating (against static line rating). The authors state that this increase can reach up to 70 % for some locations. The authors of [104] analyse the actual benefits of dynamic line rating when considering inaccuracies in generation and rating forecast on the basis of statistical calculations for a case-study.

In [27], a concept for minimizing the redispatch costs have been proposed and analyzed into details. In this study, the dynamic rating is incorporated into the optimization by simulating the conductor temperature.

In [86], active power curtailment and dynamic line rating are considered and compared for wind power integration. The authors come to the conclusion that dynamic line rating leads to a significantly higher hosting capacity increase than curtailment (both concepts can be combined).

c. Local reactive power-based voltage control (local Volt/var control)

Most of the literature on local voltage control focuses on Volt/var control (local reactive power-based voltage control without communication and coordination). In [80] a high level comparison between the most popular types of voltage control (*cosφ fix*, *cosφ(P)*, *Q(U)*) is provided. This comparison considers the effectiveness, the impact on the reactive power balance, impact on the network losses and the implementation complexity.

In [81], several local Volt/var control methods for over-voltage prevention are investigated and a new concept is proposed – a *cosφ(P,U)* control – to combine the advantages of both types of control *cosφ(P)* and *Q(U)*.

Authors in [82] proposed to introduce a location component into the parameters of the *Q(U)* control in order to ensure a more homogenous contribution of generators along LV feeders. This is done by parameterizing the dead band of the *Q(U)* control based on the network impedance at the point of connection. The authors evaluate the total amount of reactive power needed to maintain the voltage below the planning limit while maximizing the amount of generation.

In [83], another location adaptive *Q(U)* droop control using a fuzzy inference system to input the location into the control is proposed. The authors come to the conclusion that this concept overcomes the drawback of the standard *Q(U)* droop method of a very inhomogeneous contribution of generators along feeders without requiring communication infrastructure.

In [84] and [85], the authors presented successful field tests results of local and coordinated voltage control concepts for MV and LV networks. These field tests demonstrated the feasibility of the proposed concepts and allowed to validate the expected benefits of the control concepts in terms of voltage band utilization.

d. Local active power control (curtailment)

As considered in [86], active power curtailment can be, from the generator point of view, a viable alternative to network reinforcement as long as the income losses are lower than the network reinforcement costs over the generator lifetime. Since active power curtailment has a direct implication on the generator production and therefore on its revenues, concepts ensuring an equitable or “fair” distribution of the curtailed power has received a particular attention. In [87], a concept based on a centralized control (“consensus control”) is proposed. In [88], an offline coordination is proposed to ensure a homogeneous distribution of the curtailment among generators connected along a feeder. For this purpose, the voltage sensitivity factors (determined from a power flow computation) are used to adjust the droop factors of each generator. This concept is in fact very similar to the concept used for reactive power control mentioned previously [82].

e. Local control of the on-load tap changer (at the primary or secondary substation – if available))

Another way to control the voltage is to use transformers with On-Load Tap Changers (OLTC). While such assets have been used for decades in primary substations (e.g. 110 kV/30 kV), recent technological progresses have made possible to use a similar principle with different technologies (e.g. vacuum switching) for distribution transformers (so-called Voltage Regulating Distribution Transformers – VRDT [89]).

Such transformers allow decoupling the low voltage network from the medium voltage network and therefore to better use the available voltage band. The use of a VRDT allows theoretically to double or triple the voltage rise that is allowed for generators connected to the LV network (3 % in Germany and Austria – see chapter 2).

Several studies have compared the effectiveness and competitiveness of controlling the voltage with such devices (VRDT) or with Volt/var control, compared to network reinforcement [20], [90]–[92], coming usually to the conclusion that it depends on the specific network conditions.

f. Coordinated voltage control (with OLTC and/or reactive and optionally active power control)

The disadvantages of purely local voltage control concepts such as *Q(U)* (e.g. risk of over-voltage risk while generators at the beginning of the feeder do not contribute at their maximum) can be avoided by coordinated control. The coordinated voltage control concepts proposed in the literature are often based on a central controller together with local *Q(U)* controllers. The central controller calculates (optimal) voltage set-points for the local controllers (supervision), and the generators operate according to the centrally adjusted local control rule [93].

In [94] and [95], a step model of increasing complexity is introduced to control the voltage of low voltage networks. The proposed coordinated control senses the voltage of strategic nodes through smart meters and sends settings to a VRDT and to PV generators.

In [96], a high-level overview on different implementations of such controls is provided, classifying them based on the observer (e.g. smart meters, dedicated sensors) and the actuators (e.g. generators, VRDT for secondary substations, OLTC at primary substations).

Further concepts based on supervisory control have also been proposed in other studies. The task of the supervision can be to ensure a proper sharing the control burden between generators ([82], [88]), to minimize the reactive power flows [84] or to avoid voltage violations considering uncertainties. A number of papers have also addressed the question of coordination between OLTC and devices controlling reactive power in order to e.g. reduce the frequency of operation of the OLTC [97], or to combine different types of control (e.g. “line drop compensation” [98]).

2.1.5.2 Performance of local voltage control under unbalanced conditions

Unbalanced generation infeed from e.g. small single-phase solar generators worsens the problem of voltage rise [105]. Indeed, the voltage rise caused by a power injection on one phase is up to 6 times greater than for a symmetrical infeed [106]. This means that the hosting capacity is decreased by a factor 6 compare to a fully symmetrical power infeed.

In order to limit this effect, the maximal power of single-phase generators (or the maximal power imbalance between phases) is usually limited by connection guidelines to about 5 kVA (see chapter 2.1.3). However, unbalance cannot be fully avoided and, in some particular cases, significant unbalance levels can occur.

In [106] and [107], the impact of unsymmetrical power infeed in terms of neutral point shifting is analysed. The analyses performed in [106] or [108] show that in addition to the voltage rise caused by the unsymmetrical infeed in the corresponding phase, a voltage drop occurs in one of the remaining two phases due to the neutral point shifting. In fact, even more complex situations can occur with voltages exceeding the limit at nodes without any power injection [109].

Besides the voltage rise problem explained before, further effects of unbalanced power flows in LV networks caused by unsymmetrical power infeed are mentioned in the literature:

additional losses in cable/lines and transformers [110], [111], the loss of performance and the over-heating of induction motors [112].

Although a large share of the installed PV capacity is connected to low voltage networks (see chapter 1.1.3), the actual impact of these installations on the network is still not very well known. This issue has been recognized and somehow addressed in standards only recently. As mentioned in chapter 2.1.3, standards still do not really specify how (three phase) generators should behave under unbalanced conditions. For example, [108] reports about an increase of the voltage unbalance factor (ratio between negative and positive sequence voltage) due to the reactive power consumption aiming at lowering the voltage.

One of the critical point with the voltage unbalance caused by unsymmetrical power infeed is that distribution system operators usually do not have much information about the low voltage network. Indeed, there is usually no detailed information about loads and generation, and especially about their distribution over the three phases [113]. Without detailed information on the LV networks, conservative assumptions are necessary (e.g. conservative assumption on the distribution of single-phase generators) and they might severely limit the available hosting capacity of LV feeders. For this reason, investigations on how to balance the grid have been performed (the own contribution to this topic is summarized in chapter 3.4.2, and the corresponding research papers are provided in chapter 6). In [114], the authors investigate the possibility to change the connection phase of single-phase generators to mitigate unbalance and primarily reduce the network losses due to the increased current through the neutral conductor. In [115], the benefits of “phase-switching” have been investigated with a case study, with the main objective to reduce the voltage unbalance factor.

In the recent years, several concepts to actively reduce the unbalance through unsymmetrical control of inverters have been proposed. The authors in [116] try for example to mitigate the voltage unbalance by injecting unsymmetrical currents with a set point determined on the basis of a comparison between the phase voltages and the positive sequence voltage. This way, the voltage unbalance is reduced, and the neutral current and the line losses decrease. In [117] and [118] an unsymmetrical control is proposed to mitigate voltage unbalance with electric vehicle chargers.

2.1.5.3 Stability issues for local voltage control

From the different types of local voltage control presented in chapter 2.1.5.1, the *Q(U)* control has a feedback loop which can, in theory, cause instabilities[1]. Most of the literature related to *Q(U)* deals with steady-state operation and do not address the actual stability of networks with a significant amount of generation operating with such a local control mode. Only few studies have investigated the stability of *Q(U)* control, and they tend to conclude that stability problems are not expected [74], [119]. In [74], the stability of the *Q(U)* control has only be investigated

[1] Only the outer control loop is considered. The inner (current) control loop has a significantly higher bandwidth and is therefore not taken into account here.

through testing of three photovoltaic inverters. The authors report that the tests have not revealed any sign of instability and recommend without real justification the use of a time response of 5 s. In [119], the authors managed to shows on the basis of simulations that oscillations can occur when operating several inverters in *Q(U)* control mode. Moreover, they showed that the steepness of the *Q(U)* curve has an impact on the stability. However, the previous studies have not systematically analysed the problem and did not formulate clear recommendations.

The own contribution to this topic is summarized in chapter 3.4.1 and the corresponding research papers are provided in chapter 6.

2.1.6 Analysis of the deployment potential of voltage control in distribution networks

Despite the large number of research papers published on smart grids solutions aiming at increasing the hosting capacity of distribution networks, the actual potential of these solutions has not been analysed in a systematic way. Most of the research is devoted to specific control concepts which are then investigated trough simulation or field tests. However, the findings of these investigations are usually based on case studies, and they are therefore difficult to generalize.

In this context, identifying “representative” networks which can be used for generic studies have received increasing attention in the last years. The purpose of these representative networks is for example to be able to estimate the benefits of smart grids solutions, to compare different parametrizations, to compare different types of solutions, or to identify types of networks in which specific solutions best perform.

An overview of the previous works in this field is provided in Table 1 [4]. Despite the different wording that all these studies use, they generally follow a similar objective, namely to identify a set of “typical” or “representative” feeders in order to conduct “generic” network analyses. Most of these studies rely on clustering (and in particular on the k-means algorithm) to identify the representative feeders. Moreover, these studies vary significantly in terms of number of clusters (from 3 to 35), using different criteria to select the “right” number of clusters. Finally, almost all these studies have not validated the clustering results due to the selected approach and available data. Validation is in fact very important because even very good clustering results might be of poor added value for a specific question if the variables used to characterize the feeders are not relevant enough for the considered question. The own contribution to this topic is summarized in chapter 3.3 and the corresponding research papers are provided in chapter 6.

Table 1: Main characteristics of existing studies on distribution feeder / network classification [4]

Study	Scope	Target	Data set	Statistical method [1]	# of param.	# of clusters
[120] (US)	MV feeders	"representative feeders"	1 350	k-means	11	10
[121] (US)	MV feeders	"prototypal feeders"	575	hierarchical	35	24
[122] (NL)	LV feeders	"most common types of feeders"	88 000	fuzzy k-medians	94→8 [2]	8
[123][124] (DE)	LV networks	"reference networks"	86/358	"qualitative and statistical analysis"	3	7/5
[125] (DE)	LV and MV networks	"network area classes"	LV: 177 MV [3]: 20	k-means	4	11 [4]
[126] (DE)	LV feeders	"benchmark feeders"	n/a	k-means	6	18
[127] (US)	MV feeders	"representative feeders	3 000	k-means	12 [5]	22
[128] (DE)	LV networks	"reference networks"	203	k-medoids	4	20
[129] (US)	MV feeders	"representative feeders"	1295	k-medoids / random forest	16	12
[130] (AU)	LV and MV feeders	"representative feeders"	LV: 8 858 MV: 204	hierarchical	LV: 7 MV: 6	LV: 8 MV: 9
[131] (DE)	LV networks	"cluster reference grids"	>20 000	k-means	5 [5]	10
[132] (IR)	MV feeders	"representative feeders"	195	self organized maps	7 [5]	9

[1] further methods are additionally used in some cases (e.g. principal component analysis in [127], [129] for visualization purpose).

[2] a large number of clusters has been selected (94). Feeder properties have been only provided for the 8 largest clusters (representing only about one third of the whole population of feeders).

[3] HV networks have also been considered (out of scope here).

[4] the clusters are further grouped within five load density areas.

[5] after parameter reduction (based on e.g. correlation analysis).

2.2 Scope of the research work

2.2.1 Research questions and contribution of this thesis

While voltage control, and in particular Volt/var control, has been successfully implemented in several pilot projects (see chapter 2.1.5), it is still not used in a systematic way by distribution system operators. The main research question addressed in this thesis can be formulated as following:

⇨ *What is the actual potential of Volt/var control to increase the hosting capacity of distribution networks, and which recommendations could foster a stronger deployment, where appropriate, as an alternative to network reinforcement?*

This main research question encompasses in fact further sub-questions (SQ), also to be answered by this thesis:

- SQ1: *How can the hosting capacity formulation be used to analyze systematically distribution networks?*
- SQ2: *To which extent can the benefits of voltage control be fully used to increase the hosting capacity of distribution networks? What are the possible side effects? Is Volt/Watt control a suitable complementary measure to Volt/var control?*
- SQ3: *Can the behaviour of real distribution networks be predicted with the data usually available? Can the actual deployment potential of voltage control be estimated? Is it possible to identify a reduced set of "typical networks"?*
- SQ4: *What are the most promising Volt/var control concepts? How should they be parametrized to ensure highest effectiveness while limiting the side effects? How to avoid stability problems in networks with several devices controlling the voltage?*
- SQ5: *How does Volt/var control perform under unbalanced conditions? Which control strategies should be recommended? What are the limitations and what are the alternatives to actively reduce unbalance?*

In chapters 2.2.1.1 to 2.2.1.5, the relevance of these questions and the knowledge gap are presented.

2.2.1.1 SQ1: *How can the hosting capacity formulation be used to analyze systematically distribution networks?*

While the concept of hosting capacity has been introduced more than 10 years ago and used in several studies to quantify the benefits of specific smart grids solutions (see chapters 2.1.4 and 2.1.5), one of its major added value – to serve a metrics to classify networks or compare smart grids solutions – has been little used.

2.2.1.2 SQ2: *To which extent can the benefits of voltage control be fully used to increase the hosting capacity of distribution networks? What are the possible side effects? Is Volt/Watt control a suitable complementary measure to Volt/var control?*

Numerous studies based on simulations and field tests have investigated the benefits of voltage control (and in particular Volt/var control) in terms of hosting capacity enhancement. However, the limits of voltage control have not been clearly investigated (e.g. under which conditions voltage control is no longer a meaningful alternative to network reinforcement). Side effects such as additional reactive power flows and additional network losses have been considered in a number of studies but most of the results are specific to case studies (see chapter 2.1.5).

While it is always difficult to formulate sound generic conclusions, such conclusions on the basic potential of smart grids solutions are needed by stakeholders such as distribution system operators or equipment manufacturers to better evaluate the cost-benefit balance of smart grids solutions.

2.2.1.3 SQ3: *Can the behaviour of real distribution networks be predicted with the data usually available? Can the actual deployment potential of voltage control be estimated? Is it possible to identify a reduced set of "typical networks"?*

As previously mentioned, the knowledge about distribution networks, and in particular low voltage networks, is usually limited due to the absence or the very limited amount of measurements, and due to the large number of networks. At the same time, low voltage networks host a significant share of distributed generation (see chapter 1.1.3). For these reasons, being able to predict the behaviour of distribution networks would allow distribution system operators to decide on whether or not, and where, to deploy voltage control solutions. On the one side, the use of "typical" networks can allow benchmarking different solutions on a common basis, but at the same time, it might be difficult to relate "typical" networks to the real networks of a given DSO. Instead, a simplified prediction based on the specific network data set of DSOs might bring a better benefit. While these topics have been partly addressed in several research works (see chapter 2.1.6), a comparison between the different approaches previously mentioned and clear recommendations are missing.

2.2.1.4 SQ4: *What are the most promising Volt/var control concepts? How should they be parametrized to ensure highest effectiveness while limiting the side effects? How to avoid stability problems in networks with several devices controlling the voltage?*

A large number of papers have been published on voltage control and Volt/var control in particular. Some of these concepts could provide interesting advantages but have poor implementation chances due to their complexity. Even in the group of local control concepts, some require specific tuning to each network (see chapter 2.1.5.1). Since networks evolve, sometimes very fast (for example the number of distributed generators), such concepts would require considerable amounts of resources to be implemented and maintained. Even when focusing on the simplest concepts, which could be implemented with limited efforts, clear recommendations on which control and which settings to use are missing. This might have been one of the major reasons why even simple control concepts have mostly only been used in pilot projects.

Another reason can be the lack of clear results on the issue of stability. As mentioned in chapter 2.1.5.3, only a few studies have analyzed this topic, and clear conclusions or recommendations on how to adjust the time behaviour of generators to ensure a stable operation even with high share of generation, are missing.

2.2.1.5 SQ5: *How does Volt/var control perform under unbalanced conditions? Which control strategies should be recommended? What are the limitations and what are the alternatives to actively reduce unbalance?*

As mentioned in chapter 2.1.3, the threshold for single-phase generators has been decreased over the years in some countries to limit the unbalance. However, low voltage networks remain unbalanced. In some networks, the level of unbalance might be very high and some actions must be taken to reduce it. On the one hand, distribution system operators could change the connection phase of some generators, and on the other hand existing three-phase generators could actively contribute to reduce the unbalance (or at least not worsen it). Both topics have been addressed in several research works in the last years, but clear recommendations are still missing as explicitly mentioned in some standards (see chapter 2.1.3).

The compilation of these sub-questions form the main research question of this work. The objective of this thesis is to evaluate and discuss the potential of Volt/var control to increase the hosting capacity of distribution networks, and to provide recommendations on how to implement and where to deploy such a control in distribution networks. In addition to Volt/var control, the extension of the voltage band with voltage regulated distribution transformers has also been considered since these “new” assets received an increasing attention in the last years.

2.2.2 Concept of the compilation of this doctoral thesis

This thesis addresses, as previously mentioned, the expected potential of voltage control in distribution networks, by addressing the questions (sub-questions presented in chapter 2.2.1) which have not been answered or only partly answered in previous works. Figure 3 shows a visual illustration of the structure of this thesis, linking the chapters and the compiled papers with the research questions.

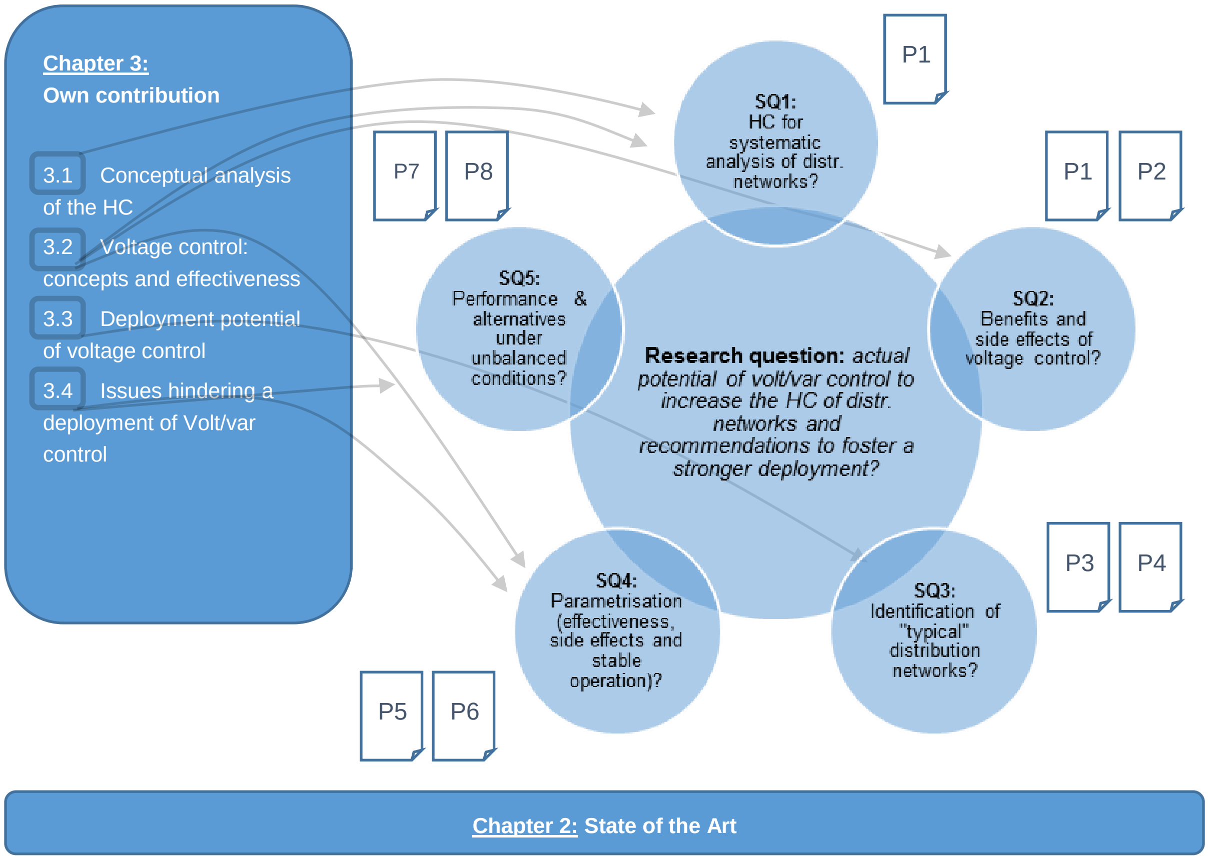


Figure 3: Concept of the compilation of this thesis: research questions, chapters and compiled papers

Having introduced the topic and the research motivation in chapter 1, presented the relevant state of the art and the scope of the work in chapter 2, the remainder of this thesis is organized as following. In chapter 3, the research work conducted for this thesis is summarized. The main conclusions of this work are presented in chapter 4. The papers forming part of this thesis are provided in chapter 6, and further publications authored or co-authored by the applicant are listed in chapter 7. All the cited references are listed in chapter 5.

3 Summary of the conducted research work on voltage control in distribution networks

This chapter summarizes the conducted research work, on the basis of, but not limited to, the papers provided in chapter 6 (see Figure 3 for an overview of the contributions). The most important contributions of this thesis are summarized in chapter 4.2.

3.1 Conceptual analysis of the hosting capacity of distribution networks

As mentioned in chapters 1.1.3 and 2, the hosting capacity of (rural) distribution networks is in most cases limited by the voltage rise caused by the infeed of renewable generation. One of the most important planning principles impacting the amount of generation which can be hosted by a particular network is the voltage band allocation, which consists in distributing the total available voltage range (±10 % according to [53]) among network assets and network users at medium and low voltage level: see Figure 4 (and also Figure 1).

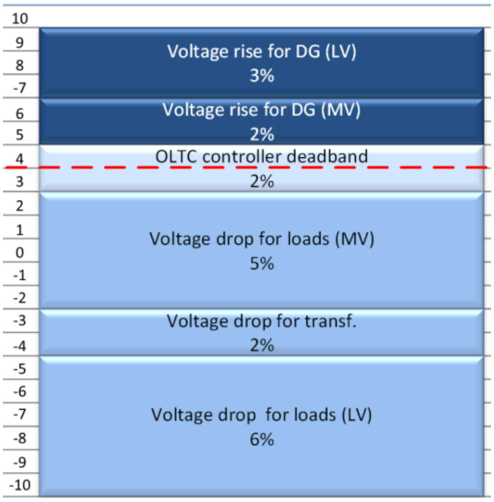


Figure 4: Voltage band allocation [106]

As visible from this figure, the voltage band is shared between loads and generators for both voltage levels, and the maximal voltage rise caused by distributed generators is 3 % for LV-connected generators and 2 % for MV-connected generators in Austria [54] and Germany [55], [56].

When trying to determine the hosting capacity of distribution networks, the voltage rise caused by the generation (or the maximal voltage occurring during a simulation) can be used as criterion, as for example in [77] and [75]. Further indicators such as the voltage spreading (difference between the maximal and minimal voltage) can also be used [133].

In *Publication 1* [2] (see chapter 6), an indicator introduced in [84], [134] has been used for the purpose of hosting capacity determination: the *local voltage control need* (LVCN). This indicator quantifies the need for locally controlling the voltage at some nodes of the network as shown in equations (2) to (7) [2].

$$u_{max}(t) = max\{u_k(t), k = 1..n\} \tag{2}$$

$$u_{min}(t) = min\{u_k(t), k = 1..n\} \tag{3}$$

$$U_{max} = max\{u_{max}(t), t = 1..m\} \tag{4}$$

$$U_{min} = min\{u_{min}(t), t = 1..m\} \tag{5}$$

$$LVCN(t) = \left(u_{max}(t) - u_{min}(t)\right) - (U_{maxlim} - U_{minlim}) \tag{6}$$

$$LVCN_{max} = max\{LVCN(t), t = 1..m\} \tag{7}$$

with

t	time
k	node index
n	number of nodes in the network
m	number of time stamps in the simulation
$u_{max}(t)$	locus of the maximal network voltage
$u_{min}(t)$	locus of the minimal network voltage
U_{max}	maximal network voltage values over the simulation time frame
U_{min}	minimal network voltage values over the simulation time frame
U_{maxlim}	maximal allowed voltage according to the planning rules
U_{minlim}	minimal allowed voltage according to the planning rules. $U_{max-lim} - U_{min-lim}$ is the available voltage band for the considered voltage level(s)
$LVCN$	Local voltage control need

The local voltage control need LVCN, defined as the difference between the maximum and the minimum voltage and the available voltage band, provides information whether the voltage at all the nodes of the network could be maintained within the limits by adjusting the voltage set-point with the OLTC to a suitable value (i.e. without local control). On the example provided in Figure 5, there is no need to control the voltage locally since it is possible for each time stamp to shift both curves up and down to bring them into the limits.

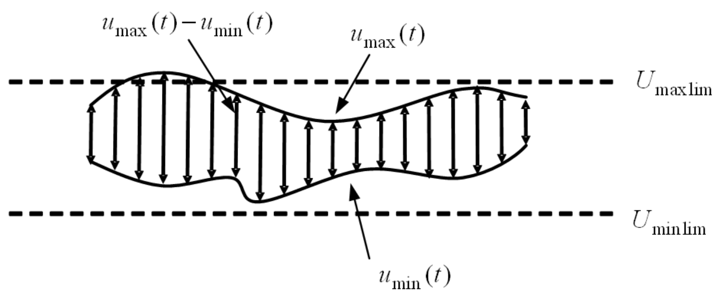


Figure 5: Definition of the local voltage control need [2]

In *Publication 3* [3] (see chapter 6), the concept of hosting capacity has been used to perform a statistical analysis of LV feeders. In this work, the hosting capacity analysis has been restricted to the two most relevant limitations in distribution networks: the maximal admissible voltage rise and the maximal admissible loading [3]. The hosting capacity of a distribution network (or feeder) is reached when the maximal allowed voltage rise is reached at one node (Feeder A on Figure 6) or when the maximal current is reached for one line or transformer (Feeder B on Figure 6).

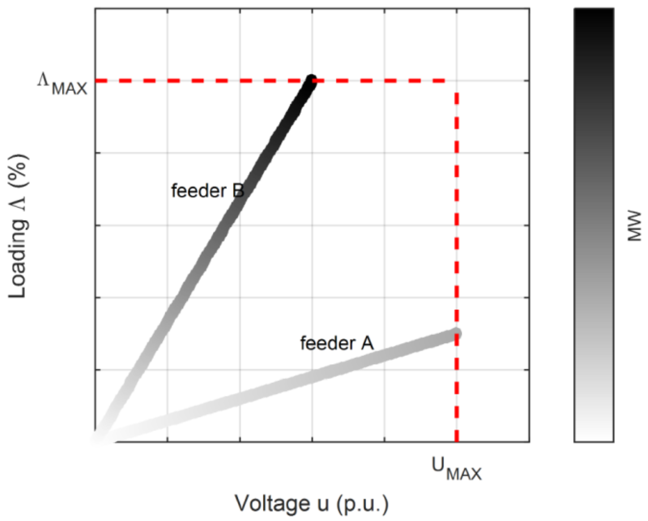


Figure 6: Hosting capacity visualization on the U-I plane [135]

The hosting capacity can be determine by deterministic studies once scenarios for the deployment of distributed generation are defined, as for example in [50]. However, since it is difficult to predict the location and size of generators which will be connected to the grid in the future, a probabilistic evaluation of the hosting capacity has been introduced in the last years [75], [77], [136]. In [135], the hosting capacity determination considering voltage and current constraints as previously mentioned has been implemented on a probabilistic basis. For this purpose, a special algorithm has been developed: “Monte Carlo based feeder screening” [135].

This algorithm uses Monte Carlo simulations to generate random distributions of generation along feeders. For each scenario (distribution of the generation along the feeder), the hosting capacity and the corresponding constraint are determined with a search algorithm [135]. The results have been presented in the form of a cumulative density function (CDF) of the hosting capacity for each feeder, which is coloured according to the constraint limiting the hosting capacity – see Figure 7 (blue for voltage-contraint and red for current-constraint). This colouring of the feeders according to the hosting capacity constraint has been also used in the work done on the feeder classification (see chapter 3.3).

The CDF-curves consist in fact of points, which correspond to the randomly generated scenarios for the location of the generation along the feeders. This figure shows for example that feeders 01,03,04,07 always experience the voltage constraint before the current constraint whereas the others are mostly loading-constrained (some specific scenarios lead to the other constraint but these are mostly outliers). One would expect the purely voltage-constrained feeders to be rural feeders but a detailed analysis of the feeders confirms that the situation is more complex. For example, feeders 01 and 08 have almost the same length (11.9 km and 10.5 km) but have an opposite behaviour in terms of hosting capacity constraint.

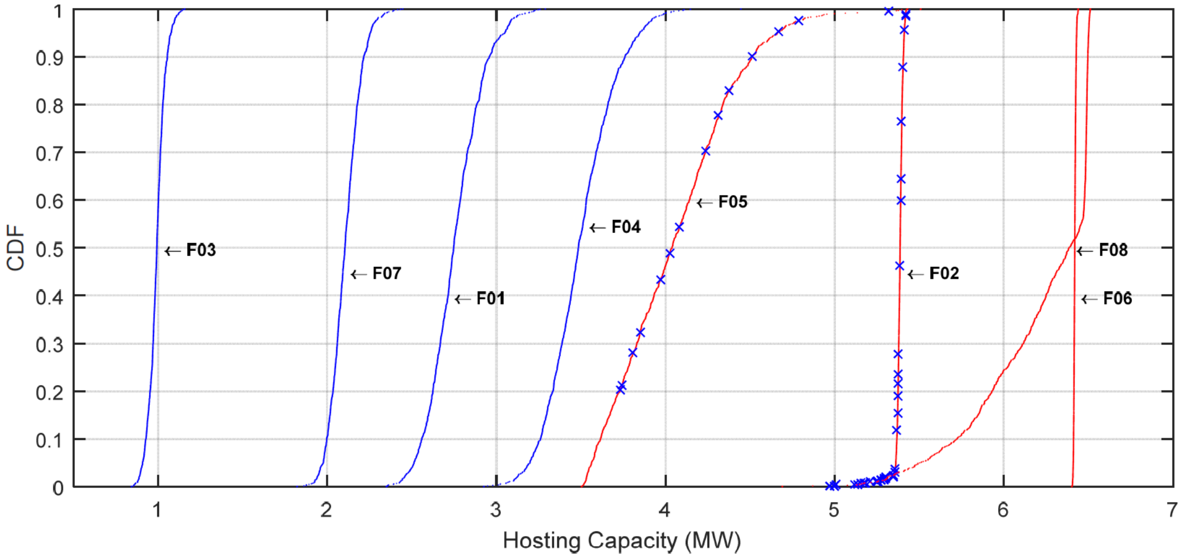


Figure 7: Cumulative density function of the hosting capacity of an exemplary MV network [96], [135] blue = voltage-constraint / red = current-constraint

3.2 Voltage control in distribution networks: comparison of different concepts in terms of effectiveness and side effects

3.2.1 Investigated voltage control concepts

The papers compiled in this thesis consider the voltage control concepts most cited in connection standards (see chapter 2.1.5.1), which have, a priori, the highest deployment potential. These control concepts are purely local and can be implemented directly into the generator control.

The first one consists in controlling the power factor as a function of the injected active power (*cosφ(P)*). As visible on Figure 8 (left) – corresponding to the default settings according to [55], [64], the more active power is injected into the network, the more inductive the power factor. The consumption of reactive power starts only for active power values above 50 % of the maximal power, and the maximal reactive power consumption (*cosφ*=0.9) is met at full power injection.

The second type of control consists in controlling the reactive power as a function of the voltage measured at the point of connection (*Q(U)*). As visible on Figure 8 (right) – drawn with exemplary settings (adapted from [80]) since as mentioned in chapter 2.1.3 connection standards do usually not specify any settings) – no reactive power is injected as long as the voltage stays within a dead-band area (in the example between 0.94 p.u. and 1.05 p.u.). When the voltage leaves this dead-band, reactive power is consumed (in case of over-voltage) or injected (in case of under-voltage).

With both types of control, the voltage rise caused by the active power infeed is partly compensated by the reactive power consumption. In addition, a *P(U)* control can be used (together with the *Q(U)* or even *cosφ(P)* control), as visible on Figure 8 (right). The advantage of this *P(U)* control is that it guarantees that the voltage does not exceed a given threshold since the active power infeed will be reduced directly. An analysis of this control is provided in chapter 3.2.4.

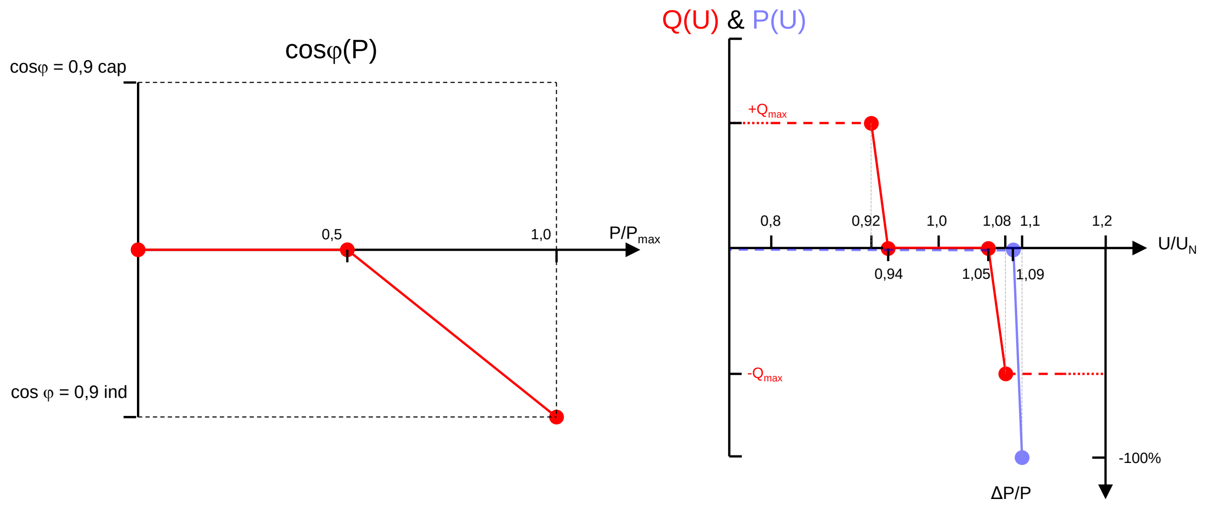


Figure 8: Exemplary characteristics for cosφ(P) (left) and Q&P(U) (right) controls – adapted from [80] right part (Q(U)): dead-band area between 0.94 and 1.05 p.u. / droop area between 0.92 and 0.94 p.u. (under-voltage) and 1.05-1.08 p.u. (over-voltage)

In addition to these two local control concepts using distributed generators to solve the problems caused by themselves (see [48]), further concepts involving OLTCs have been developed:

- Control of OLTC based on remote voltage measurements

With this concept, usable at MV (OLTC at the primary substation) or LV (OLTC at the secondary substation) level, the tap position is set according to the voltage measured at special nodes (*critical nodes* [84] or *pilot nodes*). This optimal tap position is calculated by an algorithm, which can have several objective functions such as the minimization of OLTC operation [84], [137] for example.

- Optimal OLTC and Volt/var control

This concept which is also usable at MV ([84], [134], [137]) or LV ([94], [95]) level, consists in combining the OLTC control and the Volt/var control by distributed generators.

A central voltage controller computes the optimal tap position for the OLTC and the optimal reactive power set points for selected distributed generators (generators with a significant impact on the voltage profile). For this, the controller receives measurement from critical nodes (as in the previous control), which can be smart meters for the LV case [94], [95]. As for the previous control, the set points can be calculated with different objective functions such as the minimization of the amount of reactive power exchanged with the network ([84], [134], [137]).

3.2.2 Used methods and tools to analyse the control concepts

In the frame of this thesis, a broad spectrum of (power network simulation) methods has been used. Almost all these network simulations have been performed with the software PowerFactory [138].

- Steady-state simulations

For most of the analyses presented in this thesis, steady-state simulations have been used to analyse voltage profiles, loading, losses, reactive power import, etc.

In many cases, the load flow simulations have been done using load and generation profiles (e.g. 15 minutes average values for one year, representing 35040 values). When analyzing several scenarios (e.g. several controller settings [5] or generation scenarios [140]), automating simulations is necessary, and, in some cases, parallelization (execution in parallel of independent simulations) is needed to reduce the simulation time [96].

An example of automation framework developed for PowerFactory is presented in [139]. In addition, special tools have been developed to allow a performant simulation of specific types of controls such as *Q(U)* (with *P(U)*) for large time series.

Finally, for all the studies conducted on the issue of voltage control under unbalanced conditions [7], [8], [106], [113], [113], [141], special network and load / generation models have been developed and validated. In these models, the neutral conductor has been modelled explicitly, and in some cases, the grounding has been implemented according to the grounding practises.

Finally, a specific study on the impact of the load modelling on the results of network planning studies has been conducted [142]. In this paper, the impact of the load model (ZIP-model) on the voltage profiles, loading, losses and reactive power balance has been investigated for several MV feeders. The results show that the impact of the load model is limited, except for long feeders and some recommendations are formulated in this paper.

- Probabilistic power flows

In order to properly consider the stochastic nature of load and renewable generation, Monte Carlo simulations have been used. For this, load and generation profiles following distribution functions previously determined from measurements, have been generated. One of the challenge of these Monte Carlo simulations is that, in order to estimate, with a high level of accuracy, high percentiles (e.g. the 99 % percentile of the voltage), a large number of samples is necessary. The higher the percentile and the confidence level, the larger the number of samples [143]. A possible solution to this problem is to use the method of *Hybrid Latin Hypercube Sampling* instead of random sampling to generate the Monte Carlo samples [144]. This method which provides accurate results with smaller sets of samples, has been used for studies involving a very large number of simulations [96], [135], [145].

- Dynamic simulations

For the stability analysis presented in *Publication 6* [6], RMS-simulations have been performed. For this, suitable models of the controllers have been implemented and parameterized (see chapter 3.4.1). In addition to the RMS simulations, the stability analysis has been conducted with the modal analysis engine of PowerFactory [138], as well as with Matlab [146].

- Laboratory tests

In the frame of the projects morePV2grid [80] and MetaPV [147], numerous lab tests have been conducted. For this, the inverter test bench available at the Austrian Institute of Technology (AIT) has been used. A programmable network simulator which allows producing virtually any network condition has been used together with a variable impedance to emulate the network (see Figure 9). Some of results of the laboratory tests are provided in [6], [80], [109], and a more comprehensive overview of testing techniques for network support functionalities of inverters is given in [70].

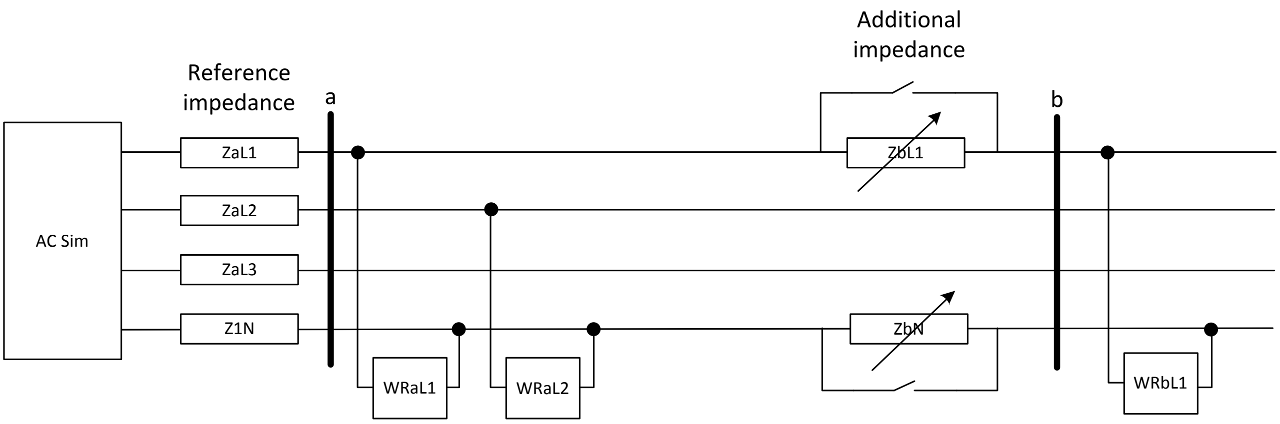


Figure 9: Simplified scheme of the test bench used to test inverters operating in Volt/var mode [80]

- Power Hardware in the Loop PHIL

Power-Hardware-in-the-Loop (PHIL) has developed in the last years to a powerful method to test components or control concepts. Indeed, it combines the benefits of classical simulation and lab testing avoiding limitations related to the availability and the rating of hardware. In [148], a study aiming at investigating possible interactions between OLTC controllers and Volt/var controllers is presented. Indeed, in this study, a real low power inverter (few kVA) has been used and a “scaled” network model has been implemented in the real time simulation. For this, a strong amplification of the measurements has been necessary, which lead to noise and even instabilities of the simulation. Classical filtering techniques could not be used to solve this noise amplification problem since it would considerably reduce the bandwidth of the simulation. To solve this problem, the approach of shifting impedances from software to hardware has been proposed and implemented.

- Field tests

Finally, the concepts developed, modelled, simulated and tested in laboratory conditions have been validated through field tests in the frame of several projects (e.g. MetaPV [147], [149], morePV2grid [80], [85], [109] and DG DemoNet [84], [137], [150]).

Field test validation is usually a challenging task due to the non-controlled conditions. Besides varying load and generation profiles, topology changes occurring in real can make the analysis of the results more difficult. Moreover, the actual penetration levels of distributed generation are usually low (to avoid e.g. voltage violations in case of problems with the tested controls), which makes it difficult to evaluate the benefits of the control under test.

In order to deal with these challenges, a validation plan as well as statistical methods are necessary. In [80], the benefits of the Volt/var control which had been estimated via simulations have been validated by using the ANOVA (analysis of variance) method. On the basis of these field tests, the proper operation of the Volt/var control has been demonstrated and the expected benefit has been validated.

3.2.3 General performance, benefits, and side effects of different control concepts

In this chapter, the main results on the general performance of the different types of controls are presented for different scenarios (chapter 3.2.3.1). In a second chapter, an analysis of the side effects (network losses and reactive power consumption) is provided.

3.2.3.1 General performance and benefits

The general performance of the Volt/var controls considered in this thesis have been analyzed in several papers. The first basic analysis has been performed within the project morePV2grid and presented in [80]. A summary is provided in Table 2. This table presents, in a condensed way, the generic characteristics of the considered types of control in terms of:

- *effectiveness*: ability to compensate the voltage rise caused by the active power infeed
- *impact on the reactive power balance* (e.g. increase of the reactive power consumption) and on the *network losses*
- *complexity* to parameterize correctly and integrate the control in the network planning process.

Table 2: Generic comparison of the considered types of Volt/var control (adapted from [80])

Control	cosφ fix	cosφ(P)	Q(U)	Q&P(U)
Effectiveness	**++ the most effective** All generators contribute by the same amount.	**++ as effective as cosφ fix** All generators contribute by the same amount.	**+ slightly less effective than cosφ(P)** Only generators experiencing a higher voltage contribute.	**+++ the "safest"** Thanks to P(U), the voltage cannot exceed the chosen threshold (which is not the case for the other controls)
	-- unselective In case of under-voltage (heavily loaded feeder), generators further decrease the voltage instead of supporting it.	**- unselective** (similar as but less than cosφ fix)	**+ Support in case of under-voltage**	**+ Support in case of under-voltage**
Impact on the reactive power balance and losses	**-- highest reactive power consumption** **-- highest network losses**	**- some unnecessary reactive power flows** **- increase of network losses**	**- less unnecessary reactive power flows** **- less unnecessary network losses**	**- less unnecessary reactive power flows** **- less unnecessary network losses** **- yield reduction which is difficult to estimate**
Complexity	**++ lowest complexity**	**+ simple to implement**	**- more complex parameterization**	**- more complex parameterization**
		- the generator sizing should be considered (PQ-diagram for e.g. inverters)	**- the generator sizing should be considered** (PQ-diagram for e.g. inverters)	**- the generator sizing should be considered** (PQ-diagram for e.g. inverters) **- more complex contracts** with a "non-firm generation capacity"

Before presenting the detailed results of the comparison between the considered control modes for different parameterization, a discussion on the generic effectiveness of Volt/var control is provided in the following.

As mentioned in chapter 2.1.1, consuming reactive power can help in lowering the voltage at the end of feeders experiencing over-voltage situations. Equation (1) can be rewritten in the following form:

$$\Delta U \approx \frac{R.P}{U_N^2} \cdot \left(1 - \frac{\tan\varphi}{R/X}\right) \tag{8}$$

with

ΔU	Relative voltage rise caused by the active / reactive power infeed
P	Active power infeed of the generator
R	Equivalent network resistance at the point of connection
X	Equivalent network reactance at the point of connection
φ	Phase angle
U_N	Nominal voltage

Equation (8) shows that the voltage rise caused by the active power infeed can be partly compensated by reactive power consumption. For a given $cos\varphi$ (and therefore $\tan\varphi$), the lower the R/X ratio, the higher the effectiveness. LV networks are known to have high R/X ratios, which means that the benefits of Volt/var control can be expected to be low in LV networks.

The achievable compensation of the voltage rise caused by an active power infeed has been evaluated with equation (8) for different typical LV cables and overhead lines (see Table 3).

Table 3: Effectiveness of reactive power consumption to compensate the voltage rise for different LV cables and overhead lines [80]

Cross section (AL mm^2)	Overhead line		Cable	
	R/X	Compensation @$cos\varphi$ = 0.90	R/X	Compensation @$cos\varphi$ = 0.90
50	1.9	26.1 %	7.2	6.8 %
70	1.4	34.4 %	5.3	9.1 %
95	1.1	45.6 %	3.8	12.9 %
120	0.8	57.1 %	3.2	15.2 %
150			2.6	18.6 %
240			1.7	29.2 %

This table shows that even for the very widespread cable type 150 mm^2, the voltage rise can be reduced by almost 20 %, which means that the hosting capacity can be increased by more than 20 %.

In *Publication 1* [1], the basic potential of increasing the hosting capacity of LV feeders through Volt/var control alone, as well as in combination of Voltage Regulating Distribution Transformers (VRDT), has been analyzed for “generic” LV feeders. The main objective was to quantify to what extent LV feeders with extended voltage band (e.g. through the use of VRDT) are more prone to current constraints, with or without the additional use of Volt/var control from generators. Answering this question allows to gain some insights about the deployment potential of purely local smart grids solutions (such as the use of VRDT or Volt/var control), not relying on any additional measurements (observers). Another objective of this work was to quantify the impact on network losses in scenarios with maximal hosting capacity enhancement.

These “generic” feeders consist of cable or overhead line feeders of different cross-sections (from 50 mm^2 to 120 mm^2 for overhead lines and 50 mm^2 to 240 mm^2 for cables) with two different penetration profiles of photovoltaic generation: punctual (upper part of Figure 10), where all the generation is connected at the end of the feeder, and uniform (lower part of Figure 10), where the generation is uniformly distributed along the feeder. Dedicated simulations showed that feeders for which the generation is (roughly) equally distributed among at least 10 nodes along the feeder behave almost like “continuous feeders” (with a perfectly uniform distribution of the power along the feeder) [5]. In this work, an extension of the voltage band to 8.5 % has been considered (compared to the 3 % currently used – see chapter 2). The detailed modelling details and assumptions are given in [1] / chapter 6.

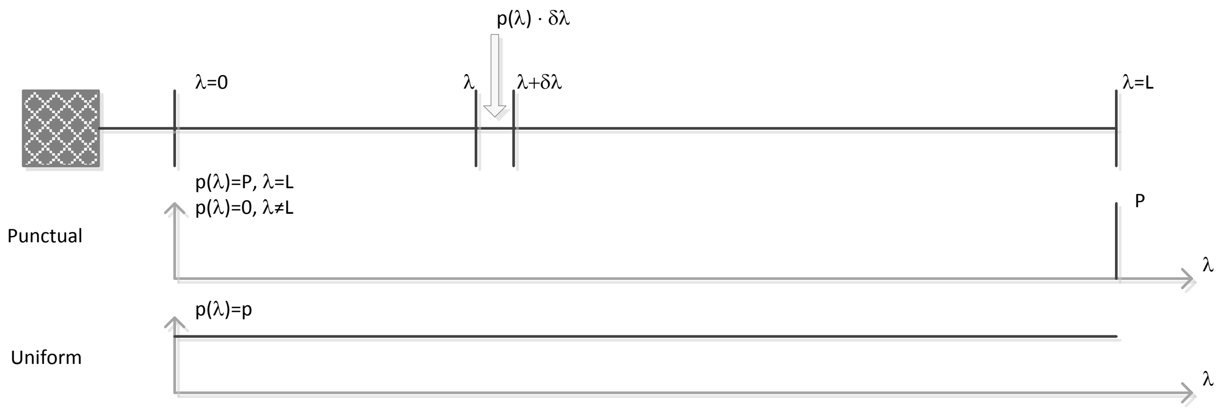


Figure 10: Considered feeders (punctual / continuous uniform distribution) [1]

The simulations performed showed that the hosting capacity could be increased by about 23 %, and confirmed the results previously presented (from equation (8)). In *Publication 1* [1], the concept of “critical length” has been introduced. It is defined as “*the feeder length for which the loading and voltage constraints are simultaneously limiting the hosting capacity*” [1]. This length has been calculated for the different types of cables and overhead lines, and for the two generation distribution scenarios. This critical length is a useful metric: by comparing the length of real or typical feeders with this length, the expected behaviour of the feeder can be predicted. If the feeder is shorter than the critical length, over-loading is occurring before over-voltage and special care must be given when implementing voltage control solutions (e.g. use of VRDT and/or use of Volt/var control).

As observed in Figure 11, standard cable feeders with a cross-section of 150 mm^2 with uniform generation can only benefit from an extension of the voltage band (through the use of a VRDT) if they are longer than 705 m. The combined use of voltage band extension and Volt/var control is only suitable for feeders longer than about 1000 m.

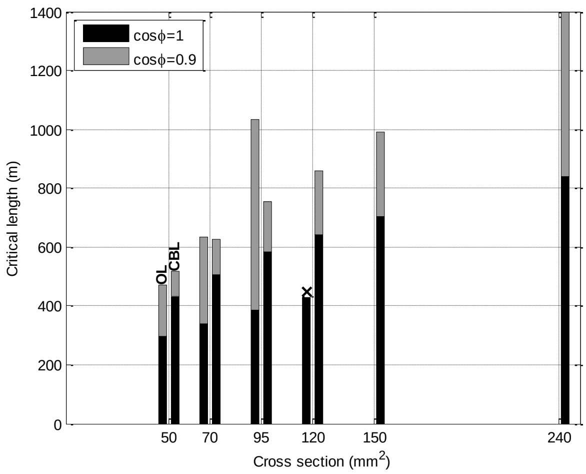


Figure 11: Hosting capacity with two different power factors for a uniform generation (OL: Overhead Line | CBL: CaBLe) [1]

For a 70 mm^2 overhead conductor, only feeders longer than 506 m would actually benefit from the extension of the voltage band. These computations show that the full potential of extending the available voltage band (through the use of VRDTs) can only be used for rather long feeders, which can mainly be found in very rural areas.

In *Publication 5* [5], a more comprehensive analysis has been done, with the objective of comparing different types of Volt/var control and different parameterizations. For this purpose, a similar approach as in *Publication 1* [1] has been followed: two scenarios of distribution of the generation along the feeders (punctual and uniform), and two types of feeders (cable and overhead lines of typical cross-sections (150 mm^2 and 70 mm^2 respectively) have been considered. The feeder length has been arbitrarily chosen since it does not impact the results (with a first order approximation), as long as the feeders are voltage-constrained.

In this study, the control modes listed in Table 4 have been investigated. This table also provides information about the settings used (variable for *Q(U)*). For the reactive power control, typical PQ-capability diagrams have been assumed (see [5] / chapter 6 for all the details).

Table 4: Settings used for the different control modes [5]

Control	
Q(U)	*Q(U)* with “all possible settings”
cosφ(P)	characteristic according to [55], [64]
P&Q(U)	*P(U)* according to Figure 12 with U_{max} = 1.10 p.u.
cosφ(P)&P(U)	as previously
Optimal Power Flow	objective function = maximize the generation infeed subject to equalities (power flow) and inequalities (constraints on the maximal voltage 1.10 p.u. and maximal loading 100 %)

The *Q(U)*-settings (see Figure 12) have been varied between 1.02 p.u. and 1.09 p.u., leading to 28 different settings combinations. To enable an easy comparison between the settings, an index has been introduced: the Volt/var-index (VVI). It is defined as the ratio between the dashed and the dotted areas in Figure 12. This index has been used in most of the analyses and showed a good correlation with the general performance of the control.

In addition to the local Volt/var controls, an optimal power flow (OPF) has been simulated for comparison purposes. The use of a full OPF at LV level is not really realistic given the requirements in terms of control and communication, but it has been considered here for benchmarking purpose.

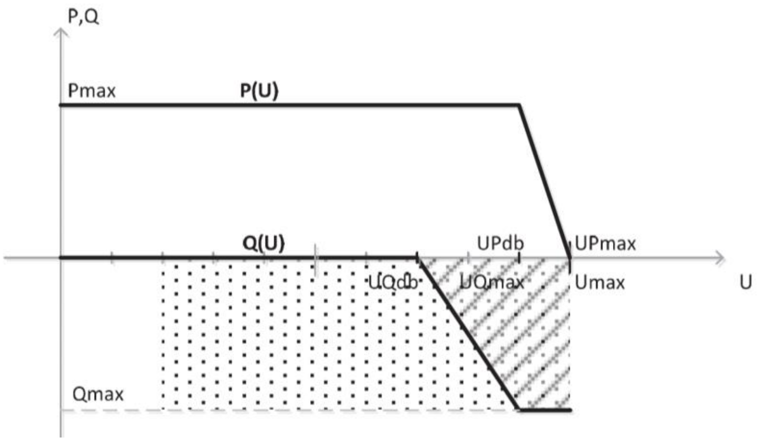


Figure 12: Used Q(U) and P(U) characteristics [5]

In a first step, the voltage and power profiles along the feeder have been determined via simulations for three different controller settings of the *Q(U)* control (operated together with a *P(U)* control). Figure 13 shows the obtained profiles: in all the cases the maximal voltage of 1.10 p.u. is not exceeded thanks to the reactive power consumption and to the active power reduction. As visible on this figure, generators connected close to the end of the feeder have a greater contribution than generators connected close to the beginning of the feeder. For the parameterization VVI = 0.75, more inverters closer to the feeder begin are forced to contribute to the voltage control.

A systematic comparison between different control settings ($cos\varphi(P)$ and *Q(U)*) is shown on Figure 14 for the maximal voltage. As visible on this figure, the maximal voltage exhibits a monotonous characteristic with the VVI, which confirms that this index is suitable to predict the expected performance of the *Q(U)* control. This figure also shows that the difference between the two extreme VVI values (most effective / least effective) is rather small (about 1.3 % of the nominal voltage or 10 % of the voltage rise caused by the PV infeed without control). According to this figure, the effectiveness of the $cos\varphi(P)$ control is comparable to the one of the “average” parameterization (VVI $\approx$ 0.5).

Similar analyses have been performed for the side effects (e.g. network losses, reactive power consumption). They are presented in the next chapter.

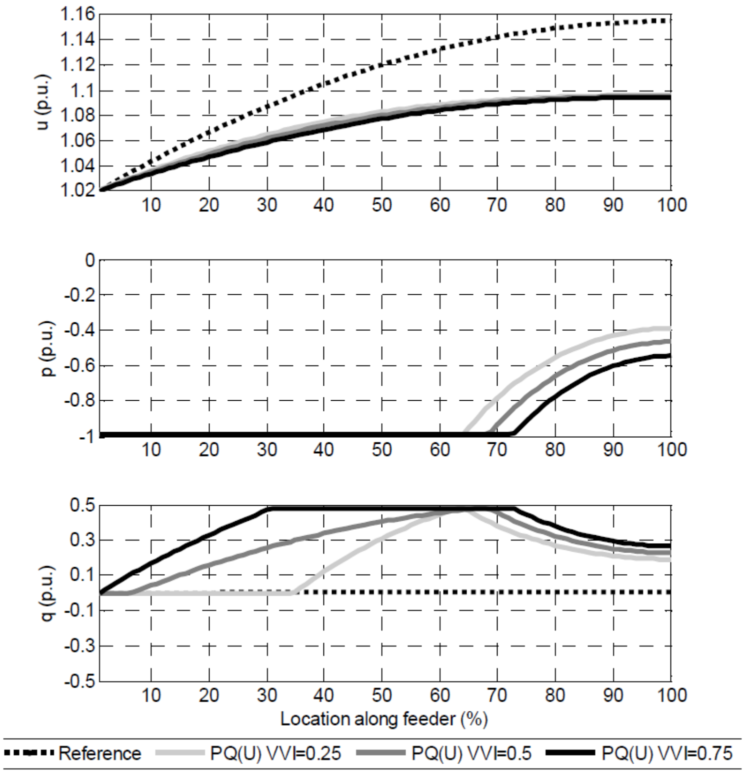


Figure 13: Voltage, active and reactive power profiles along the feeder for three different control parameterizations (overhead-line) [5]

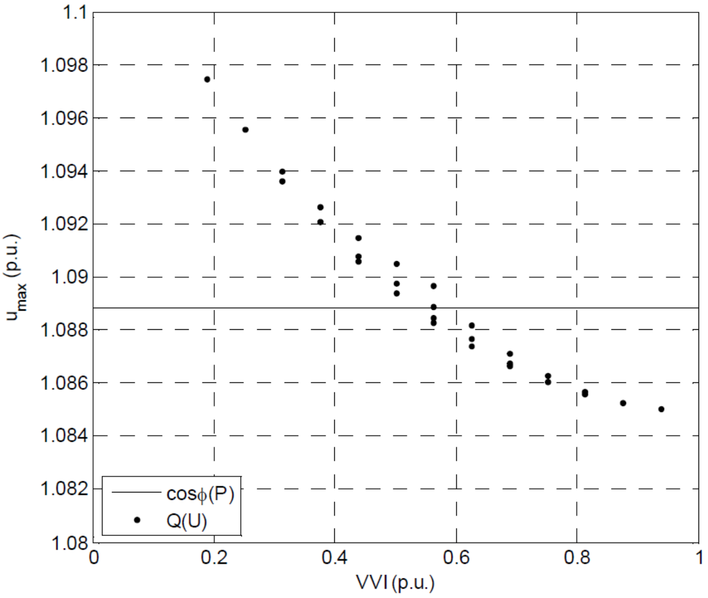


Figure 14: Impact of the controller settings on the effectiveness of the control (reached maximal voltage) – overhead-line [5]

Another approach has been followed in the work presented in *Publication 3* [3]. Instead of using a "generic feeder", a statistical analysis performed on a large set of real feeders from two Austrian DSOs participating to the project IGREENGrid [151] (*Netz Oberösterreich GmbH* and *Salzburg Netz GmbH*) allowed evaluating the deployment potential of smart grids solutions. In total, the analysis has been done on about 11.000 LV networks and 37.000 LV feeders.

For this study, the *cosφ(P)* control has been parametrized according to [55] and the *Q(U)*-control according to results from previous works [80], [85]. The full details of the study are presented in [3] / chapter 6.

Figure 15 shows the increase of hosting capacity which can be reached with cosφ=0.90 (compared to the reference hosting capacity without reactive power control) in the form of a cumulative distribution function (cdf). The expected hosting capacity increase

- exceeds +30 % for about 17 % of the feeders
- is between +20 % and +30 % for about 28 % of the feeders
- is below +20 % for about 31 % of the feeders
- is negative (decrease) for about 14 % of the feeders (feeders which are loading-constrained).

The large number of feeders for which an increase of the hosting capacity of about 23 % can be reached corresponds to the standard cable type 150 mm² which is one of the cable types most used by this DSO (vertical part of the curve). This number confirms the results previously presented on the generic feeders.

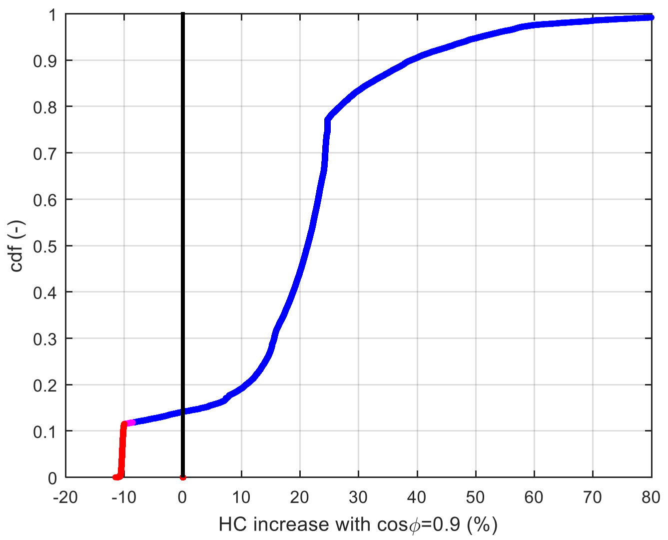


Figure 15: Hosting capacity increase with cosφ=0.90 for one DSO [3]

In in *Publication 3* [3], a systematic comparison between the two most common reactive power controls *cosφ(P)* and *Q(U)* has been performed for the large data set of real feeders, to validate the results obtained on the "generic feeder" (see Figure 14). As visible on Figure 16, the effectiveness of the *Q(U)*-control is lower than the one of the *cosφ(P)* control since not all the generators are fully contributing (only those at the end of the feeder). However, the difference is rather limited (for 95 % of the voltage-constrained feeders, the effectiveness of the *Q(U)* is smaller than the effectiveness of the *cosφ(P)* by only 4 %). This confirms the conclusions of previous work [85]: the difference between both controls in terms of effectiveness is rather small.

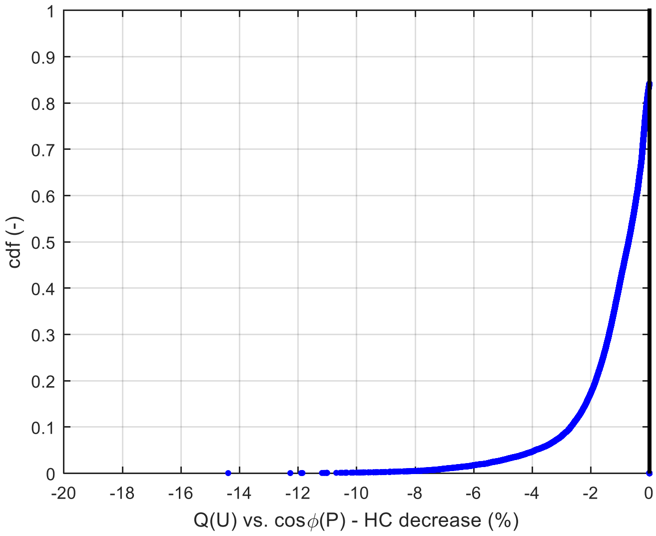


Figure 16: Hosting capacity decrease for Q(U) against cosφ(P) [3]

3.2.3.2 Side effects

The “side effects” considered in this work include mainly the following three items:

- increase of the current
    - With an extended voltage band (through the use VRDT or actually any solution increasing the hosting capacity), the additional generation which can be hosted into a network results in an increase of the current.
    - The use of Volt/var control leads to additional reactive power flows, increasing the apparent current.

  As such, the current increase is not a direct (negative) side effect (an indirect effect is the increase of network losses), but it can limit the deployment potential of voltage control since feeders can experience an over-loading which can usually not be detected given the absence of suitable current monitoring.

- increase of network losses
- increase of reactive power consumption.

Besides the determination of the hosting capacity and of the critical length for different typical LV feeders, *Publication 1* [1] also provides the result of an analysis of the impact of an extension of the voltage band on the network losses, with or without a combination of Volt/var control.

Figure 17 shows the losses (normalized to the annual yield) without and with Volt/var control for the initial and the extended voltage band. The increase of losses due to the Volt/var control is not negligible, but limited (from 1.2 % to 1.6 % for the standard voltage band, representing a relative increase of about 33 %). The impact of the extended voltage band is however significantly higher: fully using the additional hosting capacity provided by an extension of the voltage band from 3.5 % to 8.5 %, leads to an increase of the network losses by a factor of almost four.

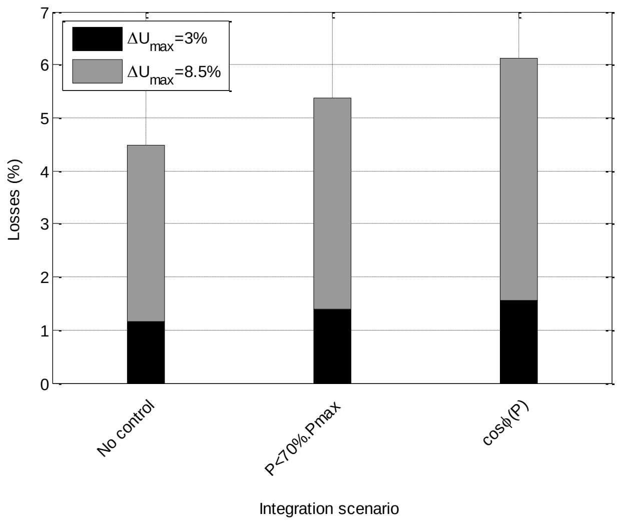


Figure 17: Network losses for the three network integration alternatives with a uniform generation for the current and an extended voltage band – 150 mm² cable [1]

In *Publication 5* [5], the impact of the Volt/var control settings on network losses has been analyzed in detail. Figure 18 shows that, as expected, the network losses increase with increasing VVI (increasing effectiveness – see Figure 14). The most effective *Q(U)* parameterization (highest VVI) leads to a relative increase of losses of about 28 % (compared to without control) while the *cosφ(P)* control leads to an increase of about 10 %. With an "average" parameterization (VVI~0.5 – see chapter 3.2.3.1), the difference of losses between the two types of control is rather small (about 10 %). This increase of losses might appear to be large, but is corresponds to scenarios with a very high penetration of distributed generation, and do not consider the effect of consumers. The absolute level os losses being small (a few percentage points), the absolute increase stays small.

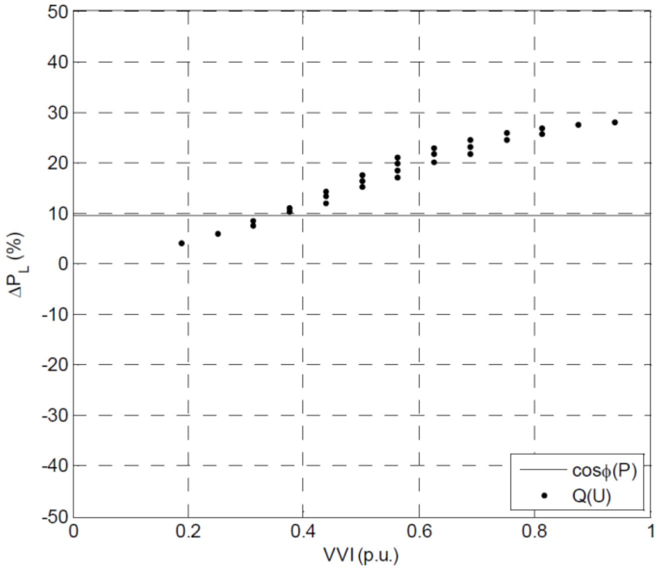


Figure 18: Impact of control settings on network losses (relative increase) – overhead line [5]

Similar analyses have been conducted for another side effect: the additional reactive power consumption. These analyses confirmed that the propose index (VVI) allows to predict the behaviour of the *Q(U)* control (good correlation between the total amount of reactive energy and the VVI). Moreover, the variation range for the reactive power consumption (the integral of it) varies significantly between the most and the least effective parameterization. The most effective *Q(U)* control leads for example to almost 200 % more reactive power consumption than the $cos\varphi(P)$ control. This is due to the fact that for high VVI values, reactive power is consumed even for voltages close to the nominal voltage, which forces all generators (even those close to the feeder begin) to consume reactive power.

3.2.4 Active power curtailment: “emergency solution” or economical alternative to network reinforcement?

This chapter presents the results of some analyses and discussions on the deployment potential of active power curtailment. As mentioned in chapter 2.1.5.1, active power curtailment has been investigated in a number of studies as an alternative to network reinforcement.

For example, the option to curtail (fix curtailment – as considered in [1]) the generator output power (to 70 %) has been introduced in Germany in 2012 and is still required in [11] for generators between 30 kW and 70 kW which do not have the capability to reduce the power remotely. Even if this requirement (or possibility) is not intended to increase the hosting capacity (at distribution level) but to allow network operators to reduce the infeed in case of critical situations in the (sub-transmission or transmission) network, it shows that, under some circumstances, it might be more economical to reduce the infeed than to invest in communication and control devices. This requirement opened the discussions whether it is always economical to have the guarantee to be able to inject 100 % of the installed power for 100 % of the time.

In [140], the possibility to increase the hosting capacity by means of active power curtailment (Volt/Watt control) has been investigated. This Volt/Watt control has in fact even be introduced in some connection guidelines recently [64] – see Figure 19. The proper operation of generators featuring this Volt/Watt control has been validated through simulations and lab tests [80], [85].

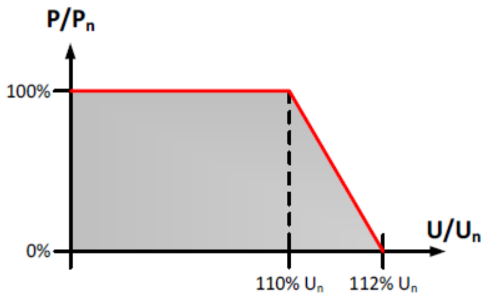


Figure 19: Volt/Watt control as specified in [64]

In principle, a Volt/Watt control should be preferred to a fix curtailment since the generator output power would only be reduced in case of over-voltage, and not as soon as the output power exceeds 70 % of the nominal power. In [140], these two options (fix curtailment and Volt/Watt control) have been analyzed based on several simulations. A generic comparison is however rather complex since it depends on the network situation (e.g. distribution along the feeder, load profiles …).

In practice, the available power is unknown and not easily measurable, meaning that the yield lost due to the control cannot be determined accurately. A worst-case assumption is therefore necessary: that the Volt/Watt control cuts off the maximal power when activated (reduction from maximal power to zero). The energy lost with a fixed curtailment to 70 % can be transformed into an equivalent activation time (see yellow areas on Figure 20). For the power duration curve of an average photovoltaic generator considered in [140] for six European countries, the maximal Volt/Watt activation time is between 50 minutes and 81 hours (66 hours or 0,25 % of the year on Figure 20). When transforming this maximal activation time back into a maximal power, a value of about 90 % is obtained (90 % of the maximal power). This means that assuming a full curtailment of the 66 hours with the highest generation is equivalent to a reduction of the maximal power from 100 % to 90 % - compared to the reduction from 100 % to 70 % for the fix curtailment. This smaller reduction (-10 % compared to -30 %) means a smaller increase of the hosting capacity (+11 % instead of +43 %), and therefore smaller benefits.

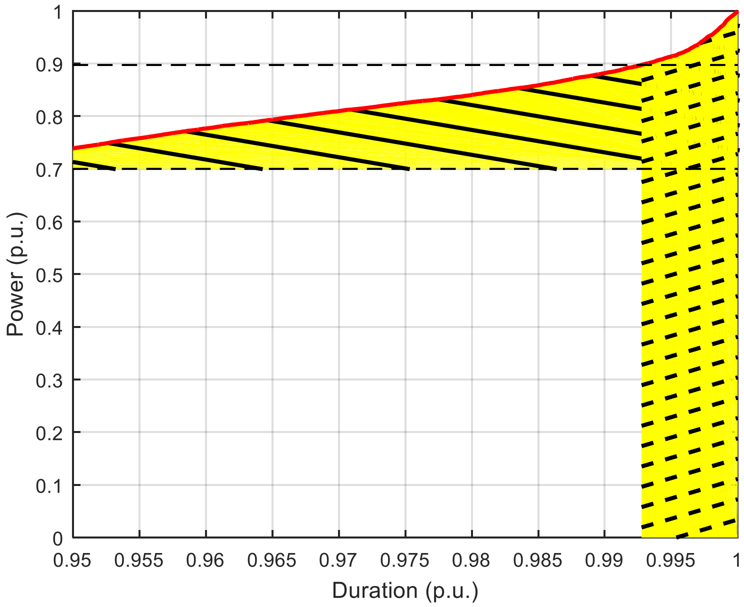


Figure 20: Curtailed energy equivalent [140]

A detailed case-study performed for a real LV network in Austria showed that the amount of curtailed energy with Volt/Watt control is small (1 % of the annual yield in total) compared to the yield lost with a fix curtailment [140]. This means that, as expected the Volt/Watt control would be, in theory, preferable to a fix curtailment. However, as discussed previously, the estimation of the curtailed energy necessarily based on worst-case considerations implies that the potential of Volt/Watt control is actually smaller than the potential of fixed curtailment.

Besides the difficulty to estimate accurately the yield losses which severely limits the deployment potential of Volt/Watt control, the curtailment is unequally distributed among generators (generators located at the end of the feeder are the most (only) curtailed). In the case study presented in [140], the curtailment ranged between 0 % and almost 8 % for an average of 1 % only (percent of the annual yield). This unequal distribution of the curtailment being very hard to predict (since depending on the location and profiles of loads and generators as well as their distribution over the three phases for single-phase generators - see [140]) represents a real barrier to the deployment of this solution even if it can be, in some cases, theoretically interesting.

Nevertheless, active power curtailment is still a topical issue and a few examples of industrialization can be mentioned. For example, the French DSO Enedis developed a connection offer for generators allowing a faster and cheaper connection to the network [152]. With this option, the contract (non-firm contract) specifies a minimum power or a maximum curtailment volume per year.

This chapter on the effectiveness and side effects of the considered voltage control concepts can be concluded with the following main conclusions:

- The hosting capacity of low voltage networks can be increased to an amount which strongly depends on the network properties. Even for high R/X ratios (as usual for LV networks), the expected compensation of the voltage rise is not negligible (about 19 % for 150 mm^2 cable feeders and 34 % for 70 mm^2 overhead lines), leading to an increase of hosting capacity of about 23 % and 52 % respectively.
- A detailed comparison between the two most popular types of Volt/var controls ($cos\varphi(P)$ and *Q(U)*) with generic feeders shows that a similar effectiveness can be reached for an “average” *Q(U)* parameterization. Moreover, the expected effectiveness can be well predicted with the index introduced (Volt/var-index VVI).
- In terms of side effects, the analyses showed that the increase of losses due to the Volt/var control is not negligible but limited (relative increase of +33 % in the considered worst case). In terms of reactive energy consumption, $cos\varphi(P)$ and *Q(U)* have again a similar performance. However, the *Q(U)* control would, in general (loads have not been taken into account to allow an unbiased comparison), lead to lower reactive energy consumption and lower network losses than the $cos\varphi(P)$ control. It should therefore be preferred.
- The combined use of Volt/var and Volt/Watt control (*P(U)*) has the advantage of guaranteeing that the over-voltage limit will not be exceeded. Even if it could, in theory, allow increasing significantly the hosting capacity when accepting a small amount of curtailment, the worst-case assumptions needed to estimate the yield losses cancels out the potential benefits.

3.3 Quantification of the actual deployment potential of voltage control in distribution networks

As explained in chapters 1.2, 2.2.1 and 2.1.6, only few studies investigated the real potential of smart grids solutions as an alternative to network reinforcement, which was one of the main motivation of this thesis. Indeed, while the voltage control concepts presented previously in chapter 3.2 have been tested under real conditions in various projects [80], [85], [91], [153], [154], they mainly remain at the pilot level and the large scale deployment potential has not been fully investigated.

In this chapter, the results from a work presented in *Publication 3* [3] and *Publication 4* [4] are summarized.

3.3.1 Statistical analysis of low voltage feeders

In *Publication 4* [4], the statistical method used to analyse a large set of LV feeders (more than 24.000) is presented. The network data has been obtained from the geographical information system (GIS) of the two participating DSOs. After a validation phase, they have been used to compute two types of feeder parameters:

- descriptive indicators or explanatory variables (which are mostly used for classification purpose – see chapter 3.3.2)
- hosting capacity related indicators.

These indicators have been computed for every single feeder and for a number of different scenarios (e.g. location of the generator along the feeder, use of control, …). The most important indicators related to the hosting capacity are the hosting capacity itself as well as the constraint limiting the hosting capacity (for each scenario).

Figure 21 shows the distribution of the LV feeders on the U-I plane (x-axis for the maximal voltage I and y-axis for the maximal loading Λ) obtained with the dataset from one of the two DSOs (DSO1). Every single feeder is coloured according to the hosting capacity constraint: blue for voltage and red for current. The points are located either along the U_{max} = 1.03 % or the Λ_{max} = 100 % lines (planning limits). This figure shows that the vast majority (about 90 %) of the feeders are voltage-constrained (blue) and that most of the voltage-constrained feeders are far from the upper-right corner (where both constraints are reached at the same time). This means that most of the (voltage-) constrained feeders are "clearly" voltage-constrained. For such feeders, smart grids solutions aiming at controlling the voltage (and resulting from an increase of the loading) are not expected to create on over-loading.

The same analysis has been conducted for the second DSO (see Figure 22). The feeder distribution for the two DSOs is significantly different, confirming that they supply different areas: the share of current-constrained feeders of DSO2 is about the double of the one of DSO1.

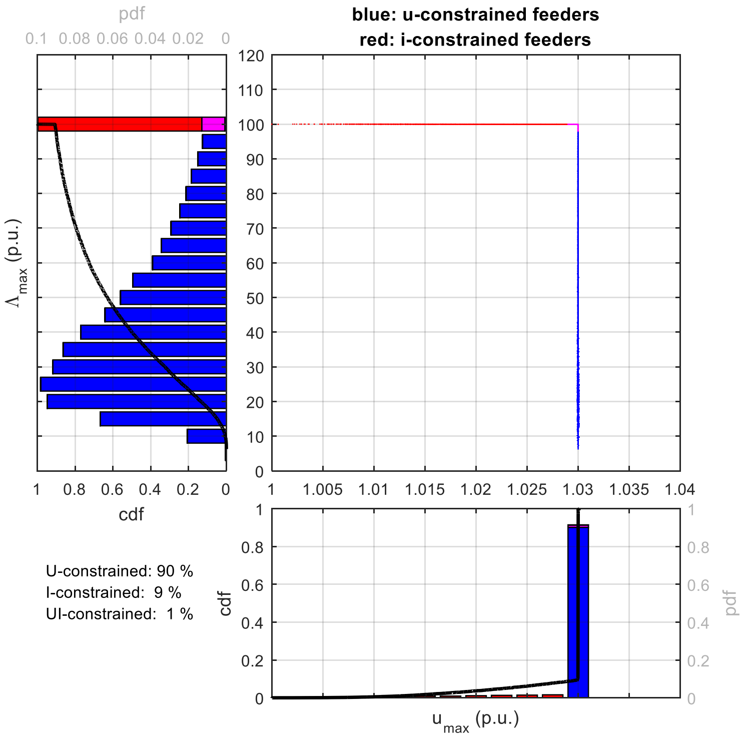


Figure 21: Share of voltage and current-constrained feeders – DSO1 [3]

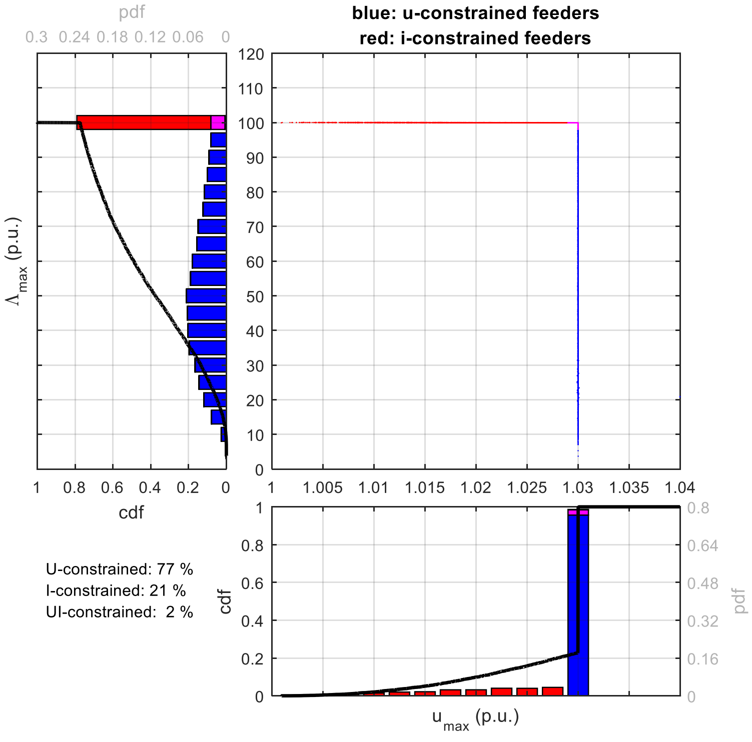


Figure 22: Share of voltage and current-constrained feeders – DSO2 [3]

In a second step, the expected deployment potential of the two considered voltage controls (use of a VRDT and Volt/var control) has been estimated by determining the share of the voltage and current constrained feeders, after implementation of the control (i.e. extension of the voltage band to 8 % or reactive power control [3]). The results are presented in Table 5. In addition, the average hosting capacity increase is given for each solution for comparison purpose. This average is built only on the basis of the feeders remaining voltage-constrained for which the solution can actually be used. The reader should keep in mind that the hosting capacity increase varies strongly from feeder to feeder (e.g. from 0 % to 80 % for Volt/var control for DSO1 as visible on Figure 15). The average value should be therefore used carefully.

Table 5: Share (%) of U/I constraints without and with voltage control and average hosting capacity (HC) increase for the two DSOs (results from [3])

DSO	**Share of U/I-constraint w/o control**	**Share of U/I-constraint with Volt/var control**	**Share of U/I-constraint with ext. voltage band (VRDT)**
DSO1	90/10	81/19 ➔ + 25 % HC_{av}	43/57 ➔ + 179 % HC_{av}
DSO2	77/23	61/39 ➔ + 23 % HC_{av}	21/79 ➔ + 179 % HC_{av}

As expected, the share of voltage-constrained feeders drops for both DSOs when implementing the considered voltage controls. While the Volt/var control can be used in more than half of the feeders for both DSOs (81 % for DSO1 and 61 % for DSO2), the most effective control (use of a VRDT which leads to the highest hosting capacity increase: 179 %) can only be implemented in 43 % of the feeders for DSO1 and 21 % of the feeders for DSO2. This table shows, that although the share of the voltage and current-constrained feeders is different for both DSOs (due to the different structure of the supplied areas), the average hosting capacity increase are almost identical for both types of control: the feeder behaviour of voltage-constrained feeds is comparable for both DSOs.

3.3.2 Classification of low voltage feeders

As previously mentioned, *Publication 4* [4] presents the data, method and assumptions used to perform the statistical analysis summarized in chapter 3.3.1 and the classification attempts summarized in this chapter. Some insights on the tools developed to conduct this work are presented in [155].

The main objective of the classification work was to investigate whether the behaviour of LV feeders, in terms of hosting capacity constraint, can be predicted on the sole basis of descriptive indicators. A further objective was to compare two methods [4]:

- *“Clustering which consists in grouping a set of observations into clusters, on the unique basis of some observed variables, and without knowing a priori the number of clusters.*

Observations within a cluster should have at the same time a high similarity between each other and a high dissimilarity with observations in other clusters".

- *"Classification which consists in finding a way to identify to which sub-set of observations (category or class) a new observation belongs, on the basis of an algorithm trained on a set of data containing observations whose category or class is known".*

In order to classify LV feeders, the two types of parameters mentioned previously in chapter 3.3.1 (descriptive indicators and hosting capacity related indicators) have been used.

An initial set of more than 80 indicators has been reduced to a subset of 12 indicators (the most relevant to characterize feeders in terms of hosting capacity – see Table 6). This set of parameters includes most of the parameters used in the relevant literature – see chapter 2.1.6 with some additional ones.

Table 6: Feeder parameters (variables) used for the classification ([4])

Feeder parameter (variable)	Description
ADTN	Average Distance To Neighbours (m)
ANON	Average Number of Neighbours (-)
LastBusDist.	Path length between secondary substation and the bus with the lowest voltage (last bus[1]) under the considered scenario[2] (m)
Feeder Length	Feeder length: largest distance between the secondary substation and any of the busses (m)
TotLineLength	Algebraic sum of the cable or overhead line length in the whole feeder (m)
km/load	Quotient between TotLineLength and the number of loads (km)
Rsc	Short-circuit resistance at the last bus[1] (Ω)
Rsum	Equivalent sum resistance: see explanation below and equation (9) (Ω)
kWm	see equation (10) (kWm)
kWΩ	see equation (11) (kWΩ)
In_avg	Average nominal current for all the cable or lines of the feeder (A)
In_max	Maximum nominal current for all the cable or lines of the feeder (A)

[1] the "last bus" is the bus with the lowest voltage in the feeder under the considered scenario

[2] the three considered scenarios are: „uniform", „weighted" and „eof (end of feeder)"

The equivalent sum-impedance Rsum can be computed on the basis of the network data alone for several scenarios. It gathers the information about the feeder impedance and the distribution of the generation along the feeder (e.g. beginning / end / uniform) [113]. For a radial feeder with a uniform generation distribution (N generators), Rsum can be computed by equation (9):

$$Rsum = \frac{1}{N}\sum_{k=1}^{k=N}\left(R'_k \cdot l_k \cdot (N-k+1)\right), \quad (9)$$

where R'_k and l_k are the specific resistance and length of segment k.

The parameters kWm and kWΩ can be computed by equations (10) and (11) respectively:

$$kWm = \sum_{k=1}^{k=N}(P_k \cdot d_k), \quad (10)$$

$$kW\Omega = \sum_{k=1}^{k=N}(P_k \cdot R_k), \quad (11)$$

where P_k is the power of the generator connected to node k, d_k the distance between node k and the secondary substation and R_k the short-circuit resistance at node k.

Having defined all these indicators for the feeder data set, a workflow including data import, validation, preparation, exploration, clustering and classification has been used (see *Publication 4* [4]). In this chapter, only the main results related to the clustering and the classification are summarized.

Once all the parameters are available, several data exploration techniques have been used to analyze the data structure. For this, three methods have been implemented: *correlation analysis*, *variable clustering* and *Principal Component Analysis* (PCA). In addition to these classical techniques, an analysis of the *predictor importance* has been done. Thanks to these analyses, the parameters from which the best discrimination can be expected have been identified (those showing the poorest correlation). However, for the further investigations, the whole variable set has been used to avoid information loss (12 variables).

3.3.2.1 Classification of low voltage feeders with classification trees

The feeders classification has been performed with classification trees, which are, together with e.g. neural networks or discriminant analysis, a popular supervised machine learning technique. They have been chosen in this work for their simplicity and interpretability.

Several options have been investigated. In a first try, a fully-grown classification tree using all the 12 parameters without limitation on the tree depth) has been implemented. Such deep classification trees are however prone to over-fitting: the very good fitting obtained with a training set is significantly les good for a different set (testing set). Over-fitting occurs when a classification tree has memorized the learning set, instead of learning the general data structure. In order to avoid over-fitting, several techniques can be used. In this work, classification trees have been pruned (merging leaves) to reduce their complexity.

The performance of the classification trees has been evaluated for various parametrizations (e.g. level of pruning), with the resubstitution error and the cross-validation error. The resubstitution error is given by the percentage of misclassified observations on the whole data set, whereas the cross-validation error requires to separate the data set into a training set and a testing set (usually with the share 90 % / 10 %). By evaluating the cross-validation error, over-fitting can be detected and avoided. Even with simple classification trees (pruning level smaller than 5), a rather low cross-validation error has be obtained (about 3 %). This is however mainly due to the fact that the data set is heavily skewed (unbalanced), with about 90 % of voltage-constrained feeders and 10 % of current-constrained feeders. Under such circumstances, a random guess would even lead to a good result. The corrected cross-validation error obtained by using unequal misclassification costs increases to about 15 %.

For the classification problem considered in this work (classify LV feeders into voltage- and current-constrained feeders), misclassifying current-constrained feeders does not have the same implication as misclassifying voltage-constrained feeders. As explained in chapter 3.2.3.2, one of the side effects of increasing the hosting capacity with voltage control (e.g. the use of a VRDT or Volt/var control), is the increase of the feeder loading. Since the loading is usually not monitored for the considered control concepts in a way that over-loading could be prevented, the deployment of these smart grids solutions must be limited to voltage-constrained feeders. To do so, a heavily unsymmetrical misclassification cost function can be used.

With such a heavily unsymmetrical cost function, none of the current-constrained feeder is classified as voltage-constrained feeder, but at the same time, many voltage-constrained feeders are classified as current-constrained feeders. The results are analysed with the confusion matrix, given in Table 7. The first main column shows the “legend”, the second shows the confusion matrix with “balanced” misclassification costs and the third shows the confusion matrix with heavily unbalanced misclassification costs.

Table 7: Confusion matrix (%) for a pruned classification tree with “balanced” (reflecting the data structure) and “unbalanced” (to avoid misclassification I→U) misclassification costs ([4])

	“Legend”		**“Balanced” miscl. costs**		**“Selective” miscl. costs**	
Actual→ Predicted ↓	**U**	**I**	**U**	**I**	**U**	**I**
U	TU[1]	**FI[2]**	88.6	**11.4**	46.2	**53.8**
I	**FU[3]**	TI[4]	**3.3**	96.7	**0**	100

[1] TU: true U-constrained feeders (normalized to the actual number of U-constrained feeders)
[2] FI: false I-constrained feeders (normalized to the actual number of U-constrained feeders)
[3] FU: false U-constrained feeders (normalized to the actual number of I-constrained feeders)
[4] TI: true I-constrained feeders (normalized to the actual number of I-constrained feeders)

For the “balanced” misclassification costs, the misclassified feeders (I→U) represent about 3.3 %. In order to bring this ratio to 0, very high (I→U) misclassification costs are specified. However, the number of (U→I) misclassified feeders increases strongly from 11.4 % to 53.8 %, which represents a loss of potential. For such misclassified feeders, voltage control options would be wrongly discarded.

A careful analysis of the misclassified feeders U→I which represent as previously mentioned a loss of potential, shows that the majority of these feeders (70 %) have a loading greater than 70 % when fully using the hosting capacity, before implementing the voltage control. These feeders are voltage-constrained but have a high loading, meaning that part of these feeders would turn to be current-constrained when implementing a voltage control. Indeed, only about one third of these misclassified feeders U→I are still voltage-constrained after implementation of Volt/var control. This means that the loss of deployment potential is not 53.8 % but “only” about 18 %.

3.3.2.2 Clustering of low voltage feeders with the k-means algorithm

All the studies on the classification of distribution feeders analysed in the previous work are based on clustering analysis (i.e. process of grouping a set of observations into clusters – see chapter 2.1.6). In order to compare the results from the classification with those from the clustering an *external validation* has been performed. Unlike in the previous studies, the class membership (voltage or current-constrained feeders) was known through the comprehensive simulations performed and an external validation was therefore possible.

The feeders have been clustered with the k-means clustering, and the number of variables used as well as the number of clusters have been varied. In order to quantify the clustering performance (and select the “appropriate” number of clusters), the following two metrics have been evaluated for each clustering attempt: the silhouette value, and the normalized sum of squared errors (nSSE) [4].

The selection of the “optimal” number of clusters for the considered data set is, as expected, not straight forward. While the normalized sum of squared errors decreases monotonously when increasing the number of clusters, the silhouette value does not. A number of clusters between 6 and 16 (range observed in most previous studies) could be somehow justified.

The clustering result (shown here for four clusters) is shown on Figure 23.

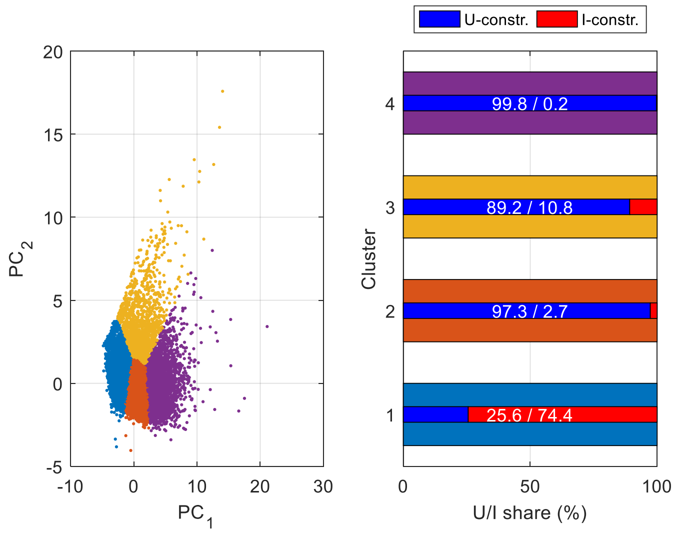


Figure 23: External validation of the clusters – cluster vs. classes – DSO1 [4]

The left part shows the clusters of feeders, using a projection on the first two principal components (PC) obtained from a principal component analysis (PCA). The right part shows the results of the external validation: for each cluster, the share of voltage (blue) and current (red)-constrained feeders is shown as a bar and a numerical value. This share can be interpreted as a "partial purity" level (for each cluster) [4].

The more dissymmetric the ratio (the purest), the better the clustering succeeds in separating both classes. The fourth cluster (purple on Figure 23) is the purest since it almost only contains voltage-constrained feeders (99.8 %). On the contrary, the cluster 1 (blue) has a lower level of purity with a share of 25.6 % and 74.4 % of voltage and current-constrained feeders respectively.

Following the same approach as for the classification (avoiding "misclassification" of current-constrained feeders), the purest cluster is the fourth. However, this cluster is rather small (about 16 % of the whole feeder population or 18 % of the voltage-constrained feeders), which means that the clustering result is rather poor. Its ability to discriminate between the two classes is low, even when accepting a "risk" ("impurity" of 0.2 %).

When comparing clustering and classification, the expected benefits of the classification over the clustering are significant since the share of voltage-constrained feeders safely identified as such is about 46 % for the decision tree-based classification against only 18 % for the clustering.

Concluding, even with a modest performance from a generic point of view, the benefits of the feeder classification are significant. Distribution system operators can deploy voltage control solutions in the group of the feeders identified with a very high confidence level as voltage-constrained, without having to perform time-consuming studies.

3.4 Technical and non-technical issues hindering a deployment of Volt/var control in distribution networks

As explained in the introduction (chapter 1) and in the state of the art (chapter 2), clear requirements on how to implement Volt/var control in e.g. PV inverters have been missing in connection guidelines, thus hindering distribution system operators to deploy these solutions on a large scale. In particular, two issues have been identified as not sufficiently investigated in research studies, and properly addressed in relevant standards:

- the issue of stability of distribution networks with a high share of generators with Volt/var control, and
- the issue of generator behaviour and control performance under unbalanced conditions.

The next two sub-chapters summarize the research work conducted on these issues.

3.4.1 Stability of Volt/var control

As mentioned in chapter 2.1.5.3, previous studies have not systematically analyzed the problem and did not formulate clear recommendations. One of the main objectives of the work conducted on this issue was to fill this gap.

In [6], the stability problem of the *Q(U)* control has been investigated with a simplified inverter model (ideal current source), together with a detailed model of the *Q(U)* controller and a network model. In a first step, the system has been linearized:

- Network model with a linear equivalent (see e.g. equation (1) in chapter 2.1.1)
- *Q(U)* characteristic: only the linear (droop) area has been considered since interactions are only possible in this area
- Time behaviour of the inverter: the time delays present in the current control have been linearized with a Padé approximation [6].

Having linearized the whole system, classical stability analysis tools have been used in a parametric study, varying all the parameters that influence the stability of the system:

- the rated power of the inverter,
- the network impedance (reactance),
- the controller droop (steepness of the *Q(U)* control),
- the time response τ of the outer-controller, and
- the unwanted time delay T_D in the inner-controller.

The first three parameters can in fact be combined into the open-loop gain, see equation (12) which can be rearranged to equation (13).

$$K_{ol} = \frac{k.X}{U_N^2} \tag{12}$$

$$K_{ol} = \frac{\Delta U_{PV}}{\Delta U_{droop}} \cdot \frac{\tan \varphi_{max}}{R/X} \tag{13}$$

with

K_{ol}	Open-loop gain of the system (including inverter and network)
k	Droop of the *Q(U)* control
ΔU_{droop}	Voltage range of the droop area
$\tan \varphi_{max}$	Maximal tanφ of the control
ΔU_{PV}	Voltage rise caused by the PV infeed
R	Equivalent resistance of the network
X	Equivalent reactance of the network
U_N	Nominal voltage

By varying all these parameters, the stability of the system can be analyzed by e.g. determining the poles of the system. Figure 24 shows for example the stability locus (path of the most critical pole when varying one parameter) for two scenarios. The red, brown and green lines correspond to damping factors of 0 % (stability limit), 5 % and 10 %. The upper part of the figure shows the impact of the delay on the stability. When increasing the delay, the most critical pole moves to the right: the system damping is decreased and the system can become unstable (for delays greater than 250 ms in this case).

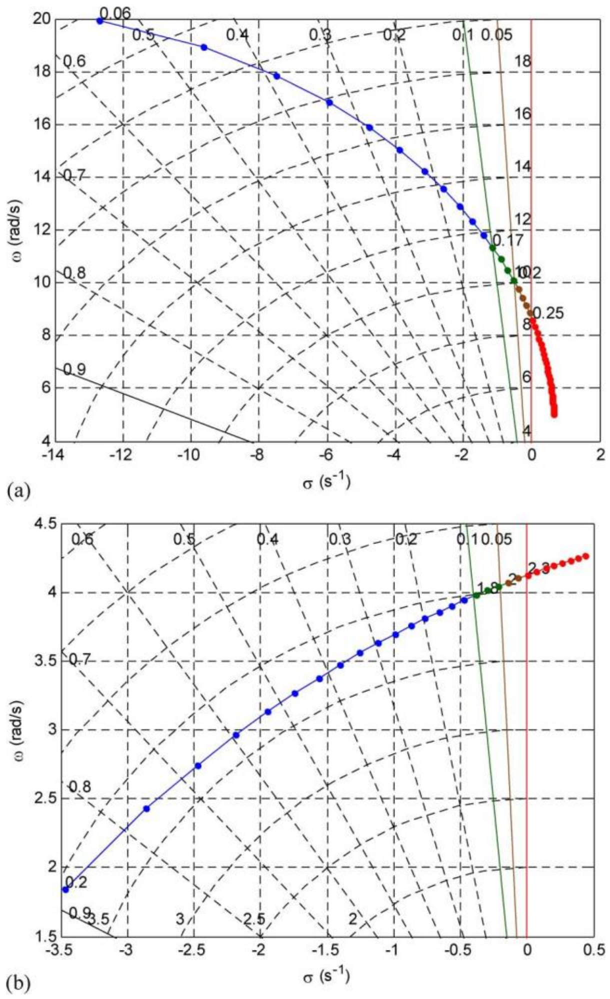


Figure 24: Stability locus. (a) τ = 0.2 s, T_D variable and K_{ol} = 2
(b) τ = 0.2 s, T_D = 0.5 s and K_{ol} variable [6]

As a result of the parametric study, a stability criterion has been derived (equation (14)) where a_ζ and b_ζ are linear equation coefficients (constant only depending on the (desired) damping factor ζ).

$$\frac{T_D}{\tau} \leq \frac{1}{a_\zeta \cdot \frac{\Delta U_{PV}}{\Delta U_{droop}} \cdot \frac{\tan \varphi_{max}}{R/X} + b_\zeta} \tag{14}$$

According to this equation, the ratio between T_D (delay) and τ (desired time response) must be “small enough” to ensure stability. This holds in particular when:

- the inverter has a large impact on the network (high voltage rise due to e.g. a large power and/or a weak network),
- the network has a small R/X ratio (a large reactance),
- the droop area of the controller is steep, or when
- the inverter is able to inject or consume a large amount of reactive power.

The constants a_ζ and b_ζ have been determined empirically (analyzing the results of the parametric study), and a worst-case has been considered to formulate a generic recommendation: assuming a case with a generator causing a voltage rise of 6 % (two times more than the current planning level according to [54], [55]), a R/X ratio of only 1 (rather high for LV networks), a droop area of 1 % of the nominal voltage (steep (*Q(U)* characteristic) and a $cos\varphi$ of 0.90, the maximal ratio between T_D and τ is 0.64. Assuming a response time of about 3.3 s to reach, as required in some connection guidelines (see chapter 2.1.3) the steady-state within 10 s, the maximal allowable delay to ensure a damping of 10 % would be 1.4 s, which is a very large value.

The analysis has been extended to cases with multiple inverters connected at different nodes along a feeder, with different parameterization of their controllers. A generalization of the stability criterion has been obtained and verified through further simulations. Finally, all the work has been validated through laboratory tests. The test set-up includes two inverters connected to two different nodes of a feeder. The comparison between the simulated and the measured response of the inverters shows a very good agreement (Figure 25).

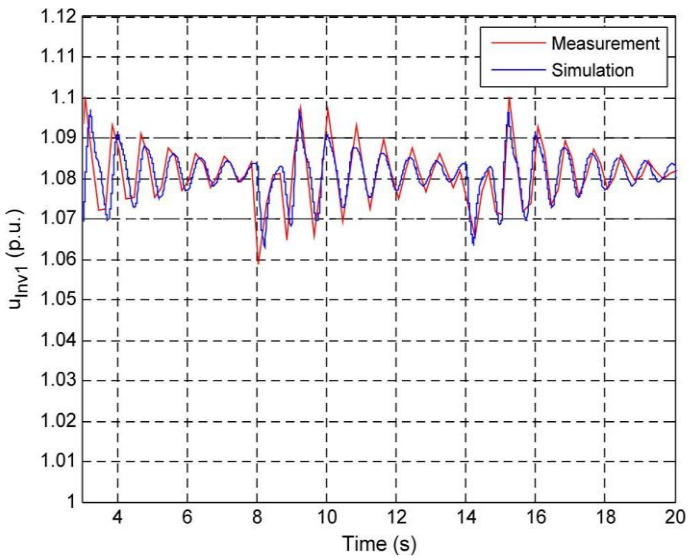


Figure 25: System response to voltage steps (comparison between simulation and lab tests) [6]

One of the main outcome of this work is the formulation of a clear stability criterion which can be used for feeders with several inverters. This stability criterion can be considered as “weak”: the requirements on the controller design are not severe since the maximal allowable delay is large. For example, to reach a response time of 5 s with a damping of 10 %, the maximal allowable delay is about 0.8 s. However, for systems relying on a plant controller (with remote sensing of the voltage and remote control of the inverters), larger delays can appear and the system design should be done carefully.

Further work on the stability of voltage control has been performed on the interaction of *Q(U)* control and OLTC control. In [156], three types of adverse interactions between OLTC control (at primary and secondary substations) and local Volt/var control have been identified and discussed. Some recommendations on how to avoid such adverse interactions have been formulated.

3.4.2 Performance of Volt/var control under unbalanced conditions

As mentioned in chapter 2.1.5.2, the behaviour of generators under unbalanced conditions and the mitigation of voltage unbalance have been investigated in a number of studies. However, as mentioned in chapter 2.1.3, only a few connection guidelines address this issue, and the requirements are inhomogeneous.

In the frame of this thesis, significant efforts have been devoted to this issue, by analyzing:

- the basic issue of voltage balance in LV networks and its consequences on the hosting capacity [106], [109]
- the way unsymmetrical infeed is considered in planning practices of distribution system operators [106]
- how different implementations of Volt/var control performs under unbalanced conditions [7]
- how voltage unbalance can be mitigated [8], [157].

Unsymmetrical infeed by distributed generators (e.g. single-phase (photovoltaic) generators) results in two effects:

- unsymmetrical power flows

These unsymmetrical power flows can results in a faster increase of the loading and therefore a faster exhausting of the hosting capacity of LV feeders. In addition, the unequal distribution of the current over the three phases leads to increased losses (in the phase and neutral conductors).

- unsymmetrical voltages

The unsymmetrical power flows results in unsymmetrical voltages (voltage unbalance), which have two implications: the voltage limit (and therefore the hosting capacity) is reached significantly faster (with a factor close to 6 [106], [109]), and the voltage phasors are no longer balanced. A short description of the causes and consequences of voltage unbalance is provided in *Publication 7* [7].

Since voltage unbalance is inherent to LV distribution (e.g. due to unsymmetrical loads or generators), several implementation of Volt/var control have been investigated in [7]. On the basis of a large number of simulations to consider many different load / generation conditions, the following controls have been analyzed (the details of the simulations are explained in [7]):

- Symmetrical *cosφ(P)*
- *Q(U)*
    - Unsymmetrical (individual) Q-control ("$Q(U_{ind})$")
    - Symmetrical Q-control using:
        - the maximal of the three phase-to-neutral voltages ($Q(U_{max})$)
        - the average phase-to-neutral voltage ($Q(U_{mean})$)
        - the positive sequence voltage ($Q(U_{+})$)

These different options have been implemented into the controller of a simulation model and a LV network with a long over-head line feeder has been considered. In total, 3.000 load / generation cases have been considered and 19 different parameterizations have been investigated by analyzing the maximal voltage, the loading, the unbalance factor.

Figure 26 shows the cumulative distribution function of the maximal voltage rise obtained from analysing all the load / generation scenarios, for the five considered control modes. It shows that the control leading to the smallest voltage rise – i.e. the most effective control – is the unsymmetrical control ($Q(U(_{ind})$). Leaving out the 1 % most extreme conditions, the maximal voltage rise can be reduced by about 12 % (relative reduction) with the control $Q(U_{max})$ and 19 % (relative reduction) with the individual control ($Q(U_{ind})$) – representing about 1.3 % (percentage points) of the nominal voltage.

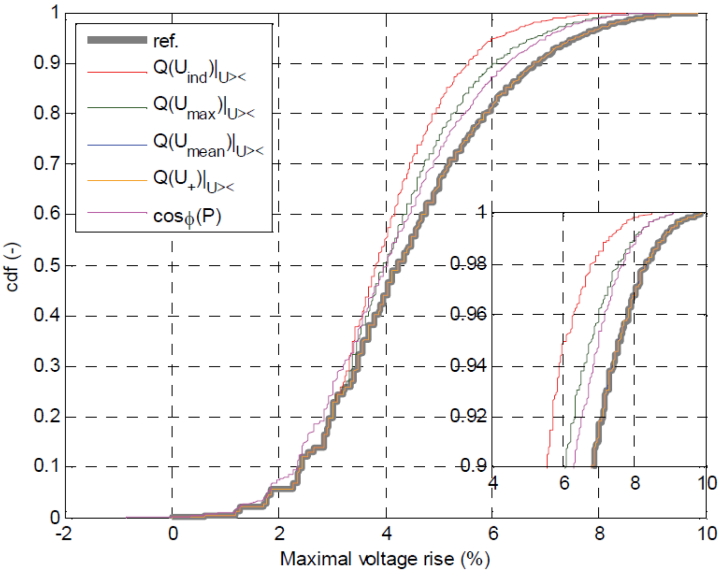


Figure 26: Maximal voltage rise for all load / generation combinations [7]

Through further analyses, two side effects of different Volt/var controls have been identified:

- the control $Q(U_{max})$ leads to a decrease of the maximal voltage but leads also to a further decrease of the lowest voltage, which can be problematic
- the most effective control ($Q(U_{ind})$) leads for some scenarios to a significant rotation of the phasors, which leads to an increase of the voltage unbalance factor (ratio between negative and positive sequence).

The simulations showed that an individual control of each phase is the most effective control. This type of control tends to reduce the spreading between the phase magnitudes, which results however in an increase of the voltage unbalance factor (ratio negative to positive sequence) due to the phasor rotation. In very unsymmetrical cases, the 2 % limit specified in [53] can be exceeded and the control should be limited. From an inverter design point of view, an individual control of each phases imposes stronger requirements on the software and hardware of the inverter.

In addition to these investigations, the effects of unsymmetrical control have been investigated in [109]. According to one of the case studies analyzed in this paper, a single-phase active power infeed results in a voltage rise on the corresponding phase and, at the same time, to a voltage drop in one of the remaining two phases due to the neutral point displacement. Moreover, the effectiveness of voltage control for balanced and unbalanced conditions has been compared, showing that the maximal voltage can be decreased to a greater extent under unbalanced conditions (single-phase infeed in this case). However, a significant side effect of the control has been observed. In the case of a single-phase active power infeed, the voltage on the phase with the maximal voltage is decreased but at the same time, the voltage at the phase with the lowest voltage is further decreased, due to the stronger neutral point displacement. In the considered case study, while the voltage rise can be decreased by 33 %, the voltage range (difference between the highest and lowest voltage) is decreased by only 20 % (both relative decrease). In another case study with two single-phase generators, another side effect has been observed: the maximal voltage is no longer reached at the “end of the feeder” but at a phase and node to which no generator is connected (see Figure 27). This means that over-voltage situations might even appear since the generator control would not observe these high voltage values. In fact, even the over-voltage protection implemented in the connection interface of the generators would not prevent this over-voltage.

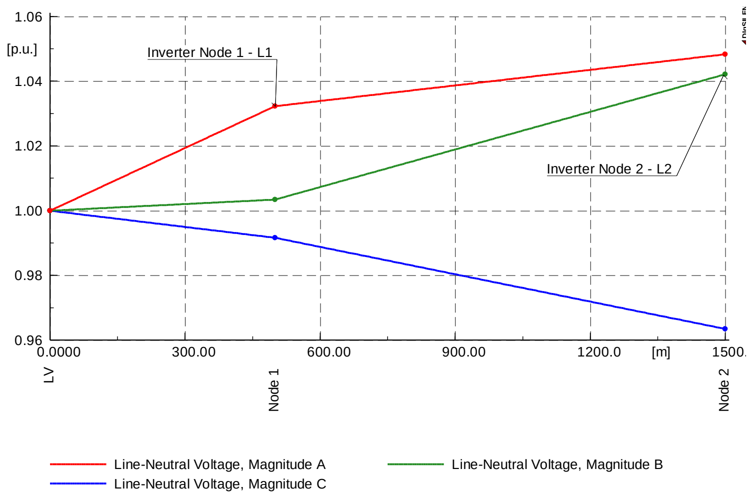


Figure 27: Voltage profile along a feeder with two PV generators with reactive power-based voltage control [8]

In [141], a novel concept for combining network system service-orientated functions in grid storage systems is presented. Among others, a control actively reducing the voltage unbalance has been proposed. This control allows to reduce the voltage unbalance to the greatest extent possible, under consideration of further (system services) having potentially a higher priority.

An alternative to reduce the voltage unbalance and therefore increase the hosting capacity is to tackle the unbalance directly at its origin and try to balance the active power infeed over the three phases. In [8], a Pareto-optimal concept for balancing the power infeed has been proposed.

As prerequisite of the proposed concept, the information about the phase connection must be known. Nowadays, this information can be obtained from the advanced meter infrastructure (AMI) if available [8], [114]. Further “indirect” concepts to identify the phase connection via data analysis (voltages) have also been proposed recently [158]. Once this information is available, the status quo can be analyzed and the network planner can evaluate the current situation (e.g. how unbalanced the network is, and whether it is worth to try to reduce the unbalance).

In a first step, a Monte-Carlo simulation is used to compute the expectable voltage rise caused by all the generators. The result of this computation is a cumulative density function curve showing the probability of reaching a given voltage rise – see Figure 28.

In a second step, the possible improvement (reduction of the voltage rise) is evaluated by another Monte-Carlo simulation in which the phase allocation is randomly modified. Since switching the connection phase of single-phase generators (or more generally modifying the phase allocation – keeping of course the direction of the rotating field) implies additional work for labour force, the number of changes should be kept low. The concept of Pareto-efficiency has been proposed to identify the most efficient switching for a given number of changes. For each number of changes (e.g. up to 5 on Figure 28), the combination leading to the lowest voltage rise is stored and at the end, a sorted list of improvements (with increasing “cost”) is obtained (Pareto curve). This Pareto curve can be used to take the decision on a compromise between efforts and improvement (reduction of the voltage rise). In the example analyzed in [8], a reduction of the voltage rise of more than 1 % can be achieved with a single switch (see Figure 28). With three switches, a reduction of about 2 % can be achieved.

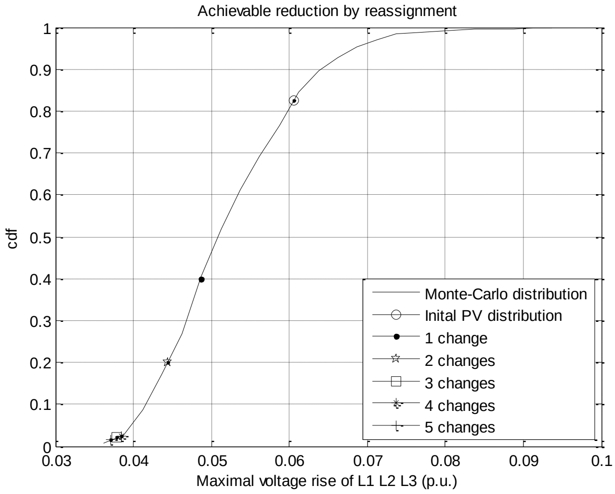


Figure 28: Pareto-efficient minimization of the voltage rise (with up to five phase changes) [8]

The simulation tools developed to perform the analyses presented in [8] (e.g. import smart meter data, run Monte-Carlo simulations, and present the results) have been gathered into a user-defined tool. This tool has been presented in [157].

3.4.3 Non-technical barriers

Finally, this chapter discusses non-technical issues, which can potentially hinder the deployment of Volt/var control in distribution networks, thus explaining the rather low level of adoption by distribution system operators.

3.4.3.1 Cost-benefit analysis of smart grids solutions

The very first non-technical issue which is not in the scope of this thesis but which definitely affects the deployment potential of smart grids solutions is the cost. A detailed economic evaluation (cost-benefit analysis) of different smart grids solutions (including Volt/var control and the use of voltage regulated distribution transformers) has been presented in [96], showing that the implementation of voltage control to enhance the hosting capacity can be a viable alternative to network reinforcement, but that a case-by case evaluation is necessary. Similar conclusions have been formulated in [90]. An interesting finding from the project DG DemoNet [134] is the impact of the age structure of network assets. As discussed in [159], the age of the assets (e.g. distribution lines) which must be reinforced in order to reach the same hosting capacity as with a smart grids solution, can have a significant impact on the cost-benefits analysis. In “old” networks, the actual costs of reinforcement must be evaluated with a lower level than in “new” networks due to the the low remaining value of existing assets (which would need anyway to be renewed soon since they are close to the end of their technical life expectancy). Such aspects make an economical evaluation even more complex.

3.4.3.2 Network planning getting more complex

As mentioned in chapter 3, even before deploying smart grids solutions, having a better knowledge of the actual network situation (e.g. expected hosting capacity and its constraint) already allows to better use the infrastructure. In a second step, the decision of implementing smart grids solutions in some particular networks can be taken. This implies an increase of the complexity of network planning, requiring on the one side, the collection and analysis of an increasing amount of data (e.g. voltage statistics from smart meters [113], [160]) and on the other side, the analysis of more scenarios as well as the implementation of the considered smart grids solutions into the planning tools. The new functionalities needed to perform the necessary analyses (e.g. local Volt/var control, probabilistic load flows) only appeared recently in network planning tools as standard functions. Before this, specific tools such as those presented in [139] had to be developed.

In [96], another factor making network planning, under consideration of smart grids solutions more complex, has been presented. Volt/var control is, as explained in chapters 3.2.3 and 3.3, significantly more effective for over-head feeders than for cable feeders. However, in addition to the effect of the network age mentioned previously, several aspects can affect the deployment decision. One of these is for example the trend to replace over-head lines by cables at distribution level, to improve the continuity of supply. This trend means in general, that the effectiveness of Volt/var control can be expected to decrease when more and more overhead lines are replaced by cables.

Another factor worth mentioning is that the need to consider different voltage levels at the same time (e.g. LV, MV but also HV) increases with the use of smart grids solutions. Indeed, when increasing the hosting capacity significantly, effects on upstream networks are observed (e.g. modification of the inter-regional load flows, appearance of new (uncontrolled) reactive power flows). An example of this is the fact that On Load Tap Changers at primary substations might come to the limit due to increasing reverse power flows together with reactive power surplus or deficit [161].

Moreover, as mentioned in [96], the current DSO regulation schemes may hinder the deployment of smart grids solutions since implementing these solutions generally result in an increased OPEX compared to the network reinforcement resulting in a CAPEX increase.

3.4.3.3 Organizational complexity

In [96], several organizational issues have been identified as additional burden hindering the deployment of smart grids solutions.

For example, the use of Volt/var control implies for DSOs to be relying on a solution implemented at the customer side, which represents a risk as such. In case control parameters must be modified after the commissioning, DSOs need to deploy considerable efforts to organize a visit to each affected customer. An example of this (at another scale) is the retrofitting of PV inverters in Germany for the “50.2 Hz problem”. In fact, even the commissioning process can be complex for DSOs due to the lack of clear requirements in standards. An example of this is how to specify the settings of a local Volt/var controller at a (PV) generator. Manufacturers have different parametrization approaches (e.g. definition of capacitive / inductive, voltage values in % or V, normalization to the maximal inverter power or actual PV array power, etc.). Another issue requiring special attention is the risk that controller settings are not kept when the generator (e.g. PV inverter) is renewed (after e.g. 15 years).

All these issues result in an increase of the risk and an increase of work for the DSOs, which can partly explain the low adoption rate of Volt/var control.

3.4.3.4 Changing regulatory framework

The newly published Network Code on Demand Connection (Demand Connection Code - DCC) [162] will be implemented at national level in all the countries of the European Union. One particular issue of interest for Volt/var control is the amount of reactive power which can be exchanged between transmission and distribution networks without special dispositions. While this issue has already been covered for many years in some countries (e.g. Belgium [163], France [164]), many countries lack clear and transparent rules about the reactive power exchange. The relevance of this issue has been stated in several papers in the last years (e.g. [165]).

The variability of renewable energy resources can make it difficult for DSOs to try to achieve the „neutral behaviour“ targeted by the Demand Connection Code, even if distributed energy resources can offer additional degrees of freedom (provision of reactive power independently from the active power for modern photovoltaic or wind generators [166]–[168]), even “at night” or “at calm”.

Finally, some new control options such as Volt/Watt control have direct implications in the earnings of the generators and deserve special attention. Even if already mentioned in standards (e.g. [64]), the issue of non-discriminatory handling of generators might be a serious barrier to the deployment of this solution.

4 Discussions and conclusions

The main conclusions and main contributions of this work are summarized in a concise way in chapters 4.1 and 4.2. More detailed conclusions as well as the methods and assumptions used to draw them can be found in chapter 3 or in the corresponding papers (chapter 6). An outlook on future research is suggested in chapter 4.3.

4.1 Main conclusions of this work

- ⇨ **Conclusion 1: Hosting capacity constraint as useful indicator to predict the feeder behaviour.**

In this thesis, the concept of hosting capacity has been used by considering the main two constraints limiting the amount of generation which can be hosted by distribution networks: the maximal voltage and the maximal current. The focus has been laid on the voltage rise issue, being identified in the previous work as the most limiting factor for distribution networks.

On the basis of comprehensive simulations for different types of generic feeders, general conclusions on the behaviour of low voltage feeders have been formulated (whether feeders are expected to experience the voltage or the current constraint).

Moreover, an indicator has been defined and used to further characterize the network behaviour: the *dynamic voltage control need DVCN* quantifies the need for controlling the feeders differently instead of using e.g. the On-Load-Tap-Changer (optionally with a voltage set-point determined from measurements at *critical nodes*).

- ⇨ **Conclusion 2: Volt/var control allowing deferring or limiting network reinforcement.**

In this work, the most popular voltage control concepts have been investigated in details (using exemplary networks, generic feeders and large sets of real low voltage networks). The analyses showed that the hosting capacity of low voltage networks can be increased to an amount which strongly depends on the network. Although low voltage feeders are known to have a rather high R/X ratio, the expected compensation of the voltage rise is about 19 % for 150 mm^2 cable feeders and 34 % for 70 mm^2 overhead lines (for purely radial feeders and aluminium conductors), leading to an increase of hosting capacity of about 23 % and 52 % respectively.

Another promising solution is the use of voltage regulated distribution transformers. Installing such assets leads to significantly higher increase of hosting capacity (up to 180 %).

⇨ **Conclusion 3: The *critical feeder length* is a good indicator for a first prediction of the feeder behaviour in terms of hosting capacity constraint.**

Detailed analyses of generic feeders with different scenarios in terms of generation location, allowed to determine the *critical length* which is defined for each type of generic feeder (cable or overhead line of a given cross-section) as the feeder length for which both constraints (voltage and current) are reached at the same time. Feeders longer than the critical length are expected to be subject to voltage problems and feeders shorter than the critical length are expected to be subject to current problems. In order to quantify the expected potential of voltage regulated distribution transformers, the critical length has been computed for generic feeders with an extended voltage band (from 3 % to 8.5 %): about 500 m for a generic overhead feeder (70 mm^2 AL) and more than 700 m for a generic cable feeder (150 mm^2 AL). The combined use of voltage regulated distribution transformers with Volt/var control further increases the critical length (about 1000 m for the considered cable feeder), meaning that only very long feeders (rather unusual in European low voltage networks) can actually fully benefit from such a voltage control.

⇨ **Conclusion 4: The feeder behaviour can be predicted, to a certain extent, with classification techniques using indicators available without network simulations.**

The comparison between clustering and classification showed as expected the greater added value of classification. Special care has been devoted to over-fitting and to problematic misclassification (i.e. classifying current-constrained feeders as voltage-constrained feeders). The downside of using highly unsymmetrical misclassification costs is necessarily the loss of potential, some voltage-constrained feeders being misclassified as current-constrained feeders. The actual loss of potential is however limited: about 18 % of the voltage-constrained feeders which could actually benefit from voltage control are dismissed. Despite the “modest” performance of the classification, the added value is significant. DSOs can deploy voltage control solutions in the group of feeders identified as suitable with a very high confidence level and without needing time-consuming studies.

⇨ **Conclusion 5: The achievable hosting capacity increase with *cosφ(P)* and *Q(U)* control is comparable. With voltage regulated distribution transformers, the achievable hosting capacity is significantly higher.**

A detailed comparison between the two most popular types of Volt/var controls (*cosφ(P)* and *Q(U)*) has been performed with a parametric study for generic feeders. While defaults settings are mentioned in several connection guidelines for the control *cosφ(P)*, default settings for the *Q(U)* control are missing in almost all the European countries. The settings have therefore been varied in a parametric study. A new index has been introduced to characterise the expected effectiveness of the *Q(U)* control: the Volt Var Index (VVI) which is the ratio between the area below the *Q(U)* curve and the total area. This index proved to have a good correlation with the actual effectiveness (voltage rise reduction) and with the side effects (amount of reactive energy consumed and additional network losses). A comparison between the *Q(U)* and the cosφ(P) control shows that they have a similar effectiveness for an "average" *Q(U)*-parameterization (VVI about 0.5). A comprehensive analysis of a large set of low voltage feeders (>37 000) confirmed this result.

In addition to the Volt/var control, the benefits of using voltage regulated distribution transformers have been quantified. With the extension of the voltage band made possible by such assets, the hosting capacity can be increased to a significantly higher extent as with Volt/var control: about 180 % against up to 80 % for Volt/var control (with however large differences from feeder to feeder).

⇨ **Conclusion 6: The side effects of *cosφ(P)* and *Q(U)* are significantly different. An extension of the voltage band can lead to even stronger side effects.**

The analyses performed with generic feeders showed that the increase of losses due to the Volt/var control is not negligible but limited (increase of +33 % in the considered worst case). For low voltage networks in which the available voltage band is extended through a voltage regulated distribution transformer and used to connect more distributed generators, the increase of losses is significantly higher (up to a factor of about 4).

In terms of reactive energy consumption, *cosφ(P)* and *Q(U)* have again a similar performance. However, since further effects have not been considered to allow an unbiased comparison (e.g. voltage decrease due to the loads), the *Q(U)* control would, in general, lead to lower reactive energy consumption and lower network losses than the *cosφ(P)* control. It should therefore be preferred. The analyses showed that high VVI values (which allow to increase the effectiveness) lead to a strong increase of the reactive energy consumed. For this reason, the settings should be carefully be selected and an "average" parameterization is recommended.

⇨ **Conclusion 7: *P(U)* as an "emergency solution" only, or limited to special cases.**

The P(U) control has been introduced recently in the Austrian connection guideline. Accepting even a small amount of curtailment can allow increasing significantly the hosting capacity. However, due to the impossibility to accurately predict and even measure the curtailed energy, worst-case assumptions are necessary (e.g. record the number of hours for which the power has been reduced). These worst-case assumptions scrap the potential of increasing the hosting capacity by this soft curtailment. Additional barriers to a generalized use of the *P(U)* control for hosting capacity extension, is the problem of unequal (discriminatory) curtailment along feeders.

However, this control can be interesting since it guarantees that the maximal voltage will not be exceeded (which is not guaranteed by Volt/var control alone). Moreover, it could be used in special cases such as for customers connected to dedicated feeders for which the unequal curtailment would not occur (for example for a generator already connected through a dedicated feeder applying for an increase of power requiring a feeder reinforcement).

⇨ **Conclusion 8: Actual potential of Volt/var control and voltage regulated distribution transformers for two DSOs.**

The statistical analyses conducted on the large set of real low voltage feeders (>37 000) allowed to determine the actual deployment potential of the considered voltage control solutions. For DSO1, 81 % of the feeders would benefit from Volt/var control and about 43 % would benefit from an extension of the voltage band (through the use of voltage regulated distribution transformers). The supply area of DSO2 is slightly different since “only” 61 % of the feeders would benefit from Volt/var control and “only” about 21 % from an extension of the voltage band. For both DSOs, the average hosting capacity increase achieved by Volt/var control and by voltage band extension is similar: about +25 % and +180 % respectively (with a strong variation from feeder to feeder).

⇨ **Conclusion 9: A stability criterion has been established for networks with generators operating with *Q(U)* control. Stability issues (poorly damped oscillations) are not expected.**

The stability of feeders with generators operating in *Q(U)* mode is mainly determined by the rated power of the generators, the network impedance (reactance), the controller droop, the time response of the outer-controller and the unwanted time delays in the inner-controller. The investigations showed that the system remain stable (or well damped) as long as the ratio between the unwanted delay and the controller time constant does not exceed a value, which depends on the factors previously mentioned. This result has been generalized to feeders with multiple generators (with different *Q(U)*-settings) and validated through laboratory simulations. Even considering worst-case conditions, stability issues (poorly damped oscillations) are not expected. For example, a delay in the control loop of about 0.8 s would still allow reaching a response time of 5 s with a damping of 10 %. Special attention should however be given to plant controllers using a remote sensing of the voltage due to the communication delays.

⇨ **Conclusion 10: From all the most common *Q(U)* implementations under unbalanced conditions, the use the maximal of the phase-to-neutral voltages is recommended.**

Unbalanced power infeed from generators significantly limit the hosting capacity. The impact of different ways of controlling the voltage under unbalanced conditions has been investigated through Monte Carlo simulations. The $Q(U_{max})$ implementation leads (after the individual control of each phase) to the best performance in terms of maximal voltage and maximal spreading. However, under very unsymmetrical conditions, the negative sequence voltage might exceed the normative limit of 2 %.

⇨ **Conclusion 11: A concept for identifying highly unbalanced feeders with a high improvement potential using Monte Carlo simulations to determine the Pareto-curve has been proposed.**

Feeders with a very unsymmetrical distribution of the generation over the three phases should be identified and handled accordingly. Indeed, implementing unsymmetrical voltage control would lead to strong side effects such as increased negative sequence component, and increased losses. In order to identify highly unbalanced feeders, a new functionality of the automated metering infrastructure can be used: the ability to determine the connection phase for every single smart meter. Once this information is available, the improvement potential can be calculated with a Monte Carlo simulation aiming a limiting the number of phase changes. On the basis of the Pareto curve, the DSO can decide on the trade-off efforts / unbalance reduction. The simulations showed promising results and a specific tool has been developed and made available.

⇨ **Conclusion 12: Besides the costs, several non-technical issues still represent a barrier to the deployment of Volt/var control in distribution networks.**

Evaluating the cost-benefits of smart grids solutions is a challenging task. One of the less discussed aspects in the literature, which has however a strong impact on the economic viability of smart grids solutions against network reinforcement, is the age of assets. Further barriers to the deployment of voltage control in distribution networks are the increase of complexity in the network planning, the fact that networks are evolving, the impact of DSO regulation schemes, and the organizational complexity.

4.2 Main contributions of this work

The results presented in this thesis have supported demonstration activities (in the frame of the projects *MetaPV* [147], *morePV2grid* [80] and *DG DemoNet - Smart LV grid* [95]). Some of the findings have been supporting the development of new control concepts for photovoltaic inverters by the manufacturers participating in the research projects mentioned previously.

Moreover, some of the results have been brought into standardization groups such as CENELEC TC8X / WG03, which was in charge of developing the standard EN 50438 [66] and the technical specifications TS 50549-1 and -2 [67], [68], or into the last connection guideline in Austria [64] (e.g. the recommendation to use the maximal of the three phase-to-neutral voltages for the *Q(U)* control).

Besides the published papers, some of the developed tools have been made available to other researchers (e.g. phase balancing tool [157] or *Q(U)* controller for unbalanced conditions [139]).

Finally, some of the concepts developed by the research group to which the applicant belonged have been patented (see chapter 7).

4.3 Future research

Besides the results obtained from the work presented here, several additional questions would deserve further investigations.

First, the performance and benefits of the classification of low voltage feeders should be further investigated on the basis of large data sets from different DSOs, from different countries. With the open data initiatives followed by different DSOs (e.g. by Enedis [169]), the access to very large data sets is nowadays possible. The importance of this type of work has been stressed by the project launched by the European Commission “Distribution system operators observatory” [170] which could benefit from the classification method proposed in this thesis.

Another aspect which would deserve more research efforts, is the fact that distribution and transmission networks can no longer be analyzed separately. Even if this has been recognized some years ago, simulation methods to reduce the complexity and support the scenario building are still necessary. In particular, for planning (and operation) purpose, an increasing amount of data must be exchanged between distribution and transmission operators, as acknowledged and required by the System Operation Guideline [171].

A further aspect going beyond the voltage control with reactive power in distribution networks is the provision of reactive power at distribution level (for e.g. sub-transmission and transmission networks). In particular, with the decommissioning of large power generation units, some areas of the transmission network lack reactive power. For example, a few generators from nuclear power stations which have been shut down in Germany, operate as synchronous condensers to further support the transmission network (e.g. *Biblis* and *Grafenrheinfeld*). Further reactive power resources will be needed in the future and further studies such as [172], [173] quantifying the geographical need and potential from renewable generation will be necessary.

5 References

[1] B. Bletterie, J. Le Baut, S. Kadam, R. Bolgaryn, and A. Abart, 'Hosting capacity of LV networks with extended voltage band', in *Proc. 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*, Vienna, 2015.

[2] B. Bletterie *et al.*, 'Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks', *Prog. Photovolt. Res. Appl.*, vol. 20, no. 6, pp. 747–759, Sep. 2012.

[3] B. Bletterie, S. Kadam, A. Abart, and R. Priewasser, 'Statistical analysis of the deployment potential of Smart Grids solutions to enhance the hosting capacity of LV networks', in *Proc. 14. Symposium Energieinnovation*, Graz, 2016.

[4] B. Bletterie, S. Kadam, and H. Renner, 'On the Classification of Low Voltage Feeders for Network Planning and Hosting Capacity Studies', *Energies*, vol. 11, no. 3, p. 651, Mar. 2018.

[5] B. Bletterie, S. Kadam, R. Bolgaryn, and A. Zegers, 'Voltage control with PV inverters in low voltage networks – In depth analysis of different concepts and parameterization criteria', *IEEE Trans. Power Syst.*, pp. 1–1, 2016.

[6] F. Andren, B. Bletterie, S. Kadam, P. Kotsampopoulos, and C. Bucher, 'On the Stability of local Voltage Control in Distribution Networks with a High Penetration of Inverter-Based Generation', *IEEE Trans. Ind. Electron.*, pp. 1–1, 2014.

[7] B. Bletterie, S. Kadam, A. Zegers, and Z. Miletic, 'On the effectiveness of voltage control with PV inverters in unbalanced low voltage networks', in *Proc. Electricity Distribution (CIRED 2015), 23rd International Conference and Exhibition on*, Lyon, 2015.

[8] B. Bletterie, S. Kadam, R. Pitz, and A. Abart, 'Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters', in *Proc. PowerTech 2013 IEEE Grenoble*, 2013, pp. 1–6.

[9] IRENA, 'Renewable capacity statistics 2018'. 2018.

[10] European Commission, *Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions - A policy framework for climate and energy in the period from 2020 to 2030*. 2014.

[11] *Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare- Energien-Gesetz - EEG 2017*. 2017.

[12] WindEurope, 'Wind in power 2017 - Annual combined onshore and offshore wind energy statistics'. Feb-2018.

[13] 'Bundesverband WindEnergie e.V.' [Online]. Available: https://www.wind-energie.de/themen/statistiken/bundeslaender. [Accessed: 13-Jun-2018].

[14] IG Windkraft, 'Windfakten - Windenergie in Österreich'. [Online]. Available: https://windfakten.at/?xmlval_ID_KEY[0]=1234. [Accessed: 06-Jun-2018].

[15] 'Agentur für Erneuerbare Energien - Installierte Leistung Photovoltaik - Solar - Übersicht zur Entwicklung Erneuerbarer Energien in allen Bundesländern - Föderal Erneuerbar'. [Online]. Available: https://www.foederal-erneuerbar.de/uebersicht/bundeslaender/BW|BY|B|BB|HB|HH|HE|MV|NI|NRW|RLP|SL|SN|ST|SH|TH|D/kategorie/solar/auswahl/183-installierte_leistun/jahr/2017/#goto_183. [Accessed: 13-Jun-2018].

[16] A. Buttler, F. Dinkel, S. Franz, and H. Spliethoff, 'Variability of wind and solar power – An assessment of the current situation in the European Union based on the year 2014', *Energy*, vol. 106, pp. 147–161, Jul. 2016.

[17] BDEW, ‘Redispatch in Deutschland Auswertung der Transparenzdaten - April 2013 bis einschließlich Januar 2018’. 12-Feb-2018.

[18] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen, ‘Quartalsbericht zu Netz- und Systemsicherheitsmaßnahmen - Gesamtjahr und Viertes Quartal 2017’. 18-Jun-2018.

[19] ‘APG - Marktinformationen’. [Online]. Available: https://www.apg.at/de/markt/Markttransparenz/Uebertragung/Engpassmanagementkosten. [Accessed: 06-Jun-2018].

[20] T. Stetz, ‘Autonomous Voltage Control Strategies in Distribution Grids with Photovoltaic Systems: Technical and Economic Assessment’, Kassel University press GmbH, 2014.

[21] M. Sterner, ‘Notwendigkeit und Chancen für power-to-x-technologien’. Oct-2017.

[22] ‘Home - ETIP’. [Online]. Available: https://www.etip-snet.eu/. [Accessed: 15-Jun-2018].

[23] European Commission, Ed., *European technology platform SmartGrids: vision and strategy for Europe’s electricity networks of the future*. Luxembourg: Office for Official Publications of the European Communities, 2006.

[24] F. Gangale, J. Vasiljevska, C. F. Covrig, A. Mengolini, and G. Fulli, ‘Smart grid projects outlook 2017’, p. 91.

[25] J. A. P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, ‘Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities’, *Electr. Power Syst. Res.*, vol. 77, no. 9, pp. 1189–1203, Jul. 2007.

[26] C. J. Wallnerstrom, Y. Huang, and L. Soder, ‘Impact From Dynamic Line Rating on Wind Power Integration’, *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 343–350, Jan. 2015.

[27] M. Tschampion, M. A. Bucher, A. Ulbig, and G. Andersson, ‘N- 1 security assessment incorporating the flexibility offered by dynamic line rating’, in *Power Systems Computation Conference (PSCC), 2016*, 2016, pp. 1–7.

[28] Joint Working Group B5/C6.26/CIRED, ‘Protection of Distribution Systems with Distributed Energy Resources’, Mar. 2015.

[29] G. Lammert, T. He\s s, M. Schmidt, P. Schegner, and M. Braun, ‘Dynamic grid support in low voltage grids—fault ride-through and reactive power/voltage support during grid disturbances’, in *Power Systems Computation Conference (PSCC), 2014*, 2014, pp. 1–7.

[30] VDE, Frankfurt am Main - Germany, ‘VDE-AR-N 4105 Generators connected to the low-voltage distribution network - Technical requirements for the connection to and parallel operation with low-voltage distribution networks’. Jul-2017.

[31] M. Lave, J. Kleissl, A. Ellis, and F. Mejia, ‘Simulated PV power plant variability: Impact of utility-imposed ramp limitations in Puerto Rico’, in *Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th*, 2013, pp. 1817–1821.

[32] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, ‘A novel approach for ramp-rate control of solar PV using energy storage to mitigate output fluctuations caused by cloud passing’, *Energy Convers. IEEE Trans. On*, vol. 29, no. 2, pp. 507–518, 2014.

[33] V. Salehi and B. Radibratovic, ‘Ramp rate control of photovoltaic power plant output using energy storage devices’, in *PES General Meeting| Conference & Exposition, 2014 IEEE*, 2014, pp. 1–5.

[34] J. Marcos, O. Storkël, L. Marroyo, M. Garcia, and E. Lorenzo, ‘Storage requirements for PV power ramp-rate control’, *Sol. Energy*, vol. 99, pp. 28–35, Jan. 2014.

[35] M. Braun, *Provision of ancillary services by distributed generators: Technological and economic perspective*, vol. 10. kassel university press GmbH, 2009.

[36] nationalgrid, ‘Enhanced Frequency Response - Invitation to tender for pre-qualified parties’. 08-Jul-2016.

[37] ENTSO-E, ‘Need for synthetic inertia (SI) for frequency regulation - ENTSO-E guidance document for national implementation for network codes on grid connection’. 29-Mar-2017.

[38] 50hertz, Amprion, Tennet, and Transnetz BW, ‘Auswirkungen reduzierter Schwungmasse auf einen stabilen Netzbetrieb’, Apr. 2014.

[39] P. Tielens and D. Van Hertem, ‘The relevance of inertia in power systems’, *Renew. Sustain. Energy Rev.*, vol. 55, pp. 999–1009, Mar. 2016.

[40] ENTSO-E, ‘High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS) - ENTSO-E Guidance document for national implementation for network codes on grid connection’, Mar. 2017.

[41] A. B. Attya, O. Anaya-Lara, and W. E. Leithead, ‘Novel Metrics to Quantify the Impacts of Frequency Support Provision Methods by Wind Power’, in *Proc. IEEE Innovative Smart Grid Technologies ISGT Europe*, Ljubljana, 2016.

[42] G. Delille, B. François, and G. Malarange, ‘Dynamic frequency control support: A virtual inertia provided by distributed energy storage to isolated power systems’, in *Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES*, 2010, pp. 1–8.

[43] P. Wall *et al.*, ‘Smart Frequency Control for the Future GB Power System’, in *Proc. IEEE Innovative Smart Grid Technologies ISGT Europe*, Ljubljana, 2016.

[44] J. N. Sakamuri *et al.*, ‘Improved frequency control from wind power plants considering wind speed variation’, in *Power Systems Computation Conference (PSCC), 2016*, 2016, pp. 1–7.

[45] A. S. Øverjordet, ‘Synthetic inertia from wind farms-Impacts on rotor angle stability in existing synchronous generators’, NTNU, 2014.

[46] H. E. Brown and C. L. DeMarco, ‘Synthetic inertia and small signal instability’, in *North American Power Symposium (NAPS), 2016*, 2016, pp. 1–6.

[47] N. Jenkins, R. Allan, P. CROSSLEY, D. Kirschen, and G. Strbac, *Embedded Generation*. The Institution of Engineering and Technology, 2000.

[48] B. Bletterie *et al.*, ‘Enhancement of the network hosting capacity – clearing space for/with PV’, presented at the 25th European Photovoltaic Solar Energy Conference and Exhibition, Valencia, Spain, 2010, pp. 4828–4834.

[49] D. Mende *et al.*, ‘Reactive power control of PV plants to increase the grid hosting capacity’, in *Proc. 28th European Photovoltaic Solar Energy Conference and Exhibition*, Paris, 2013, pp. 4225–4230.

[50] C. Schwaegerl, M. H. J. Bollen, K. Karoui, and A. Yagmur, ‘Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources’, in *Proc. Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on*, 2005, pp. 1–5.

[51] J. W. Smith and D. L. Brooks, ‘Voltage impacts of distributed wind generation on rural distribution feeders’, in *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES*, 2001, vol. 1, pp. 492–497.

[52] T. Gonen, *Electrical power Distribution System Engineering*. CRC Press, 2008.

[53] CENELEC, ‘Voltage characteristics of electricity supplied by public electricity networks’. 01-Mar-2011.

[54] E-CONTROL, ‘Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt2: Richtlinie zur Beurteilung von Netzrückwirkungen’. Nov-2017.

[55] VDE-FNN, ‘VDE-AR-N 4105:2011-08 Power generation systems connected to the low-voltage distribution network’. Aug-2011.

[56] ‘Generating Plants Connected to the Medium-Voltage Network’, Jun. 2008.

[57] ‘Spannungsbandproblem | Informationsportal regelbare Ortsnetztransformatoren’. [Online]. Available: http://ront.info/systemwirkung-ront/probleme-und-losungen/spannungsbandproblem/. [Accessed: 05-Jul-2018].

[58] ‘Google Scholar’. [Online]. Available: https://scholar.google.at/. [Accessed: 10-Jul-2018].

[59] M. Braun *et al.*, ‘Is the distribution grid ready to accept large-scale photovoltaic deployment? State of the art, progress, and future prospects: Distribution grid and large-scale PV deployment’, *Prog. Photovolt. Res. Appl.*, vol. 20, no. 6, pp. 681–697, Sep. 2012.

[60] R. Bründlinger, ‘Review and Assessment of Latest Grid Code Developments in Europe and Selected International Markets with Respect to High Penetration PV’, in *Proc. 6th Solar Integration Workshop*, Vienna, 2016.

[61] E-CONTROL, ‘Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen’. 2008.

[62] E-CONTROL, ‘Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen - Teil B: Technische Tegeln für Netze mit Nennspannung >= 110 kV’. 2008.

[63] E-CONTROL, ‘Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen’. 2013.

[64] E-CONTROL, ‘Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen’. 22-Feb-2016.

[65] CEI, ‘CEI 0-21 - Reference technical rules for the connection of active and passive users to the LV electrical Utilities’. Jul-2016.

[66] CENELEC, ‘EN 50438:2013 Requirements for micro-generating plants to be connected in parallel with public low-voltage distribution networks’. 2013.

[67] CENELEC, ‘CLC/TS 50549-1:2014-10 Requirements for the connection of a generating plant to a distribution system - Part 1: Connection to a LV distribution system and above 16A’. 2015.

[68] CENELEC, ‘CLC/TS 50549-2:2014-10 Requirements for the connection of a generating plant to a distribution system - Part 2: Connection to a MV distribution system’. 2015.

[69] European Commission, *COMMISSION REGULATION (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators*. 2016.

[70] R. Bründlinger, B. Bletterie, G. Arnold, T. Degner, and C. Duvauchelle, ‘PV inverters supporting the grid – First experiences with testing and qualification according to the new grid interconnection guidelines in Germany, Austria and France’, in *Proc. 24th European Photovoltaic Solar Energy Conference*, Hamburg, 2009, pp. 3170–3178.

[71] ENEDIS, ‘Principe et conditions de mise en oeuvre d’une régulation locale de puissance réactive pour les Installations de Production raccordées au Réseau Public de Distribution HTA’. 01-Mar-2017.

[72] Synergrid, ‘Prescriptions techniques spécifiques de raccordement d’installations de production décentralisée fonctionnant en parallèle sur le réseau de distribution’. 04-Jun-2012.

[73] ENEDIS, ‘Principes d’étude et de développement du réseau pour le raccordement des clients consommateurs et producteurs BT’. 15-Feb-2017.

[74] P. Esslinger, ‘Studie Q(U)’, Munich, Aug. 2012.

[75] M. Rylander, J. Smith, and W. Sunderman, ‘Streamlined Method for Determining Distribution System Hosting Capacity’, 2015, pp. 3–9.

[76] Math Bollen and Sarah Rönnberg, ‘Hosting Capacity of the Power Grid for Renewable Electricity Production and New Large Consumption Equipment’, *Energies*, vol. 10, no. 9, p. 1325, Sep. 2017.

[77] M. Rossi, G. Vigano, and D. Moneta, ‘Hosting capacity of distribution networks: Evaluation of the network congestion risk due to distributed generation’, in *Clean Electrical Power (ICCEP), 2015 International Conference on*, 2015, pp. 716–722.

[78] dena, ‘dena-Verteilernetzstudie. Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030’, Dec. 2012.

[79] G. Schlömer and L. Hofmann, ‘Eine Heuristik zur Umbauplanung von Niederspannungsnetzen ganzer Ortschaften’, in *Proc. 14. Symposium Energieinnovation*, Graz, 2016.

[80] M. Heidl, ‘morePV2grid - More functionalities for increased integration of PV into grid’, Dec. 2013.

[81] E. Demirok, P. C. González, K. H. B. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, ‘Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids’, *IEEE J. Photovolt.*, vol. 1, no. 2, pp. 174–182, Oct. 2011.

[82] G. Kerber, R. Witzmann, and H. Sappl, ‘Voltage limitation by autonomous reactive power control of grid connected photovoltaic inverters’, in *Proc. Compatibility and Power Electronics, 2009. CPE’09.*, 2009, pp. 129–133.

[83] E. Demirok, D. Sera, P. Rodriguez, and R. Teodorescu, ‘Enhanced local grid voltage support method for high penetration of distributed generators’, in *Proc. IECON 2011-37th Annual Conference on IEEE Industrial Electronics Society*, 2011, pp. 2481–2485.

[84] M. Stifter *et al.*, ‘DG DemoNet validation: Voltage control from simulation to field test’, in *Innovative Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition on*, 2011, pp. 1–8.

[85] S. Kadam *et al.*, ‘Evaluation of voltage control algorithms in smart grids: results of the project: morePV2grid’, in *Proc. 29th European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, 2014.

[86] N. Etherden and M. H. Bollen, ‘Increasing the hosting capacity of distribution networks by curtailment of renewable energy resources’, in *Proc. 2011 IEEE Power Tech.*, Trondheim, 2011.

[87] S. Alyami, Y. Wang, C. Wang, J. Zhao, and B. Zhao, ‘Adaptive Real Power Capping Method for Fair Overvoltage Regulation of Distribution Networks With High Penetration of PV Systems’, *IEEE Trans. Smart Grid*, vol. 5, no. 6, pp. 2729–2738, Nov. 2014.

[88] R. Tonkoski, L. A. C. Lopes, and T. H. M. EL-Fouly, ‘Coordinated Active Power Curtailment of Grid Connected PV Inverters for Overvoltage Prevention’, *IEEE Trans. Sustain. Energy*, vol. 2, no. 2, pp. 139–147, Apr. 2011.

[89] FNN, ‘Voltage Regulating Distribution Transformer (VRDT) – Use in Grid Planning and Operation’, Jul. 2016.

[90] T. Stetz, K. Diwold, M. Kraiczy, D. Geibel, S. Schmidt, and M. Braun, 'Techno-Economic Assessment of Voltage Control Strategies in Low Voltage Grids', *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 2125–2132, Jul. 2014.

[91] T. Stetz, F. Marten, and M. Braun, 'Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany', *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 534–542, Apr. 2013.

[92] FNN, 'Schlussbericht Vergleich von technischer Wirksamkeit sowie Wirtschaftlichkeit zeitnah verfügbarer Verfahren zur Sicherung der statischen Spannungshaltung in Niederspannungsnetzen mit starker dezentraler Einspeisung', Dec. 2014.

[93] M. Brenna *et al.*, 'Automatic Distributed Voltage Control Algorithm in Smart Grids Applications', *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 877–885, Jun. 2013.

[94] A. Einfalt, F. Zeilinger, R. Schwalbe, B. Bletterie, and S. Kadam, 'Controlling active low voltage distribution grids with minimum efforts on costs and engineering', in *Proc. Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE*, 2013, pp. 7456–7461.

[95] A. Einfalt, F. Kupzog, H. Brunner, and A. Lugmaier, 'Control strategies for smart low voltage grids — The project DG DemoNet — Smart LV Grid', in *Proc. CIRED Workshop*, Lisbon, 2012, pp. 1–4.

[96] B. Bletterie and I. Urcola, 'Technical & economic evaluation of replicability and scalability of solutions to increase the DER', Apr. 2016.

[97] G. C. Kryonidis, N. V. Theologou, A. I. Chrysochos, C. S. Demoulias, and G. K. Papagiannis, 'An Enhanced Decentralized Voltage Regulation Scheme for the Reduction of Tap Changes in HV/MV Transformers Under High DG Penetration', in *Proc. IEEE Innovative Smart Grid Technologies ISGT Europe*, Ljubljana, 2016.

[98] W. Xiao, K. Torchyan, M. S. El Moursi, and J. L. Kirtley, 'Online Supervisory Voltage Control for Grid Interface of Utility-Level PV Plants', *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 843–853, Jul. 2014.

[99] ENTSO-E, 'Dynamic Line Rating for overhead lines'. 30-Mar-2015.

[100] R. Stephen, 'Guide for thermal rating calculations of overhead lines: working group 22.12'. Cigré, 2002.

[101] J. Iglesias and F. Jakl, 'Guide for thermal rating calculations of overhead lines: working group B2.43'. Cigré, 2014.

[102] IEEE, 'IEEE Std 738-2012 IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors'. 2013.

[103] T. B. Phillips, 'Dynamic Rating of Transmission Lines for Improved Wind Energy Integration in Complex Terrain', 2014.

[104] F. Teng, R. Dupin, A. Michiorri, G. Kariniotakis, Y. Chen, and G. Strbac, 'Understanding the Benefits of Dynamic Line Rating under Multiple Sources of Uncertainty', *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3306–3314, 2018.

[105] D. Habijan, M. Cavlović, and D. Jaksić, 'The issue of asymmetry in low voltage network with distributed generation', in *Proc. 22nd International Conference on Electricity Distribution CIRED*, Stockholm, 2013.

[106] B. Bletterie, A. Gorsek, A. Abart, and M. Heidl, 'Understanding the effects of unsymmetrical infeed on the voltage rise for the design of suitable voltage control algorithms with PV inverters', in *Proc. 26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, 2011, pp. 4469–4478.

[107] L. Degroote, B. Renders, B. Meersman, and L. Vandevelde, 'Neutral-point shifting and voltage unbalance due to single-phase DG units in low voltage distribution networks', in *Proc. PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1–8.

[108] E. De Jaeger, A. DU BOIS, and B. Martin, 'Hosting capacity of LV distribution grids for small distributed generation units, referring to voltage level and unbalance', in *Proc. Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[109] B. Bletterie *et al.*, 'Local voltage control by PV inverters first operating experience from simulation, laboratory tests and field tests', in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4574–4581.

[110] R. Salustiano, E. Neto, and M. Martinez, 'The unbalanced load cost on transformer losses at a distribution system', in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–3.

[111] L. F. Ochoa, R. M. Ciric, A. Padilja-Feltrin, and G. Harrison, 'Evaluation of distribution system losses due to load unbalance', in *Proc. 15th Power Systems Computation Conference PSCC 2005*, Liège, 2005.

[112] A. Siddique, G. S. Yadava, and B. Singh, 'Effects of voltage unbalance on induction motors', in *Proc. Electrical Insulation, 2004. Conference Record of the 2004 IEEE International Symposium on*, 2004, pp. 26–29.

[113] B. Bletterie, A. Abart, S. Kadam, D. Burnier, M. Stifter, and H. Brunner, 'Characterising LV networks on the basis of smart meter data and accurate network models', in *Proc. Integration of Renewables into the Distribution Grid, CIRED 2012 Workshop*, 2012, pp. 1–4.

[114] G. Roupioz, X. Robe, and F. Gorgette, 'First use of smart grid data in distribution network planning', in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[115] S. Weckx, C. GonzalezDeMiguel, P. Vingerhoets, and J. Driesen, 'Phase switching and phase balancing to cope with a massive photovoltaic penetration', in *Proc. Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[116] R. D. Lazar and A. Constantin, 'Voltage balancing in LV residential networks by means of three phase PV inverters', in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4068–4071.

[117] S. Weckx and J. Driesen, 'Load Balancing With EV Chargers and PV Inverters in Unbalanced Distribution Grids', *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 635–643, Apr. 2015.

[118] J. Fernandez, S. Bacha, D. Riu, H. Turker, and M. Paupert, 'Current unbalance reduction in three-phase systems using single phase PHEV chargers', in *Industrial Technology (ICIT), 2013 IEEE International Conference on*, 2013, pp. 1940–1945.

[119] A. Constantin and R. D. Lazar, 'Open Loop Q(U) Stability Investigation in Case of PV Power Plants', in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 3745–3749.

[120] H. L. Willis, H. N. Tram, and R. W. Powell, 'A Computerized, cluster based method of building representative models of distribution systems', *IEEE Trans. Power Appar. Syst.*, no. 12, pp. 3469–3474, 1985.

[121] K. P. Schneider, Y. Chen, D. P. Chassin, R. G. Pratt, D. W. Engel, and S. Thompson, 'Modern grid initiative: Distribution taxonomy final report', Pacific Northwest National Laboratory, 2008.

[122] M. Nijhuis, M. Gibescu, and S. Cobben, 'Clustering of low voltage feeders from a network planning perspective', in *Proc. CIRED 23rd International Conference on Electricity DistributionProc. CIRED 23rd International Conference on Electricity Distribution*, Lyon, 2015.

[123] Kerber, 'Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen', 2011.

[124] M. Lindner *et al.*, 'Aktuelle Musternetze zur Untersuchung von Spannungsproblemen in der Niederspannung', in *Proc. 14. Symposium Energieinnovation*, Graz, 2016.

[125] dena, 'dena-Verteilernetzstudie. Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030', Dec. 2012.

[126] J. Dickert, M. Domagk, and P. Schegner, 'Benchmark low voltage distribution networks based on cluster analysis of actual grid properties', in *PowerTech (POWERTECH), 2013 IEEE Grenoble*, 2013, pp. 1–6.

[127] R. J. Broderick and J. R. Williams, 'Clustering methodology for classifying distribution feeders', in *Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th*, 2013, pp. 1706–1710.

[128] G. Gust, 'Analyse von Niederspannungsnetzen und Entwicklung von Referenznetzen'. 09-Jul-2014.

[129] J. Cale, B. Palmintier, D. Narang, and K. Carroll, 'Clustering distribution feeders in the Arizona Public Service territory', in *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, 2014, pp. 2076–2081.

[130] Y. Li and P. J. Wolfs, 'Taxonomic description for western Australian distribution medium-voltage and low-voltage feeders', *IET Gener. Transm. Distrib.*, vol. 8, no. 1, pp. 104–113, Jan. 2014.

[131] G. Walker, H. Nägele, F. Kniehl, A. Probst, M. Brunner, and S. Tenbohlen, 'An application of cluster reference grids for an optimized grid simulation', in *Proc. CIRED 23rd International Conference on Electricity DistributionProc. CIRED 23rd International Conference on Electricity Distribution*, Lyon, 2015.

[132] F. Dehghani, H. Nezami, M. Dehghani, and M. Saremi, 'Distribution feeder classification based on self organized maps (case study: Lorestan province, Iran)', in *Electrical Power Distribution Networks Conference (EPDC), 2015 20th Conference on*, 2015, pp. 27–31.

[133] N. Hatziargyriou, E. Karfopoulos, A. Tsitsimelis, D. Koukoula, M. Rossi, and V. Giacomo, 'On the der hosting capacity of distribution feeders', in *Proc. CIRED 23rd International Conference on Electricity Distribution*, Lyon, 2015.

[134] H. Brunner, A. Lugmaier, B. Bletterie, H. Fechner, and R. Bründlinger, 'Aktiver Betrieb von elektrischen Verteilnetzen mit hohem Anteil dezentraler Stromerzeugung – Konzeption von Demonstrationsnetzen', Jun. 2008.

[135] J. Le Baut *et al.*, 'Probabilistic evaluation of the hosting capacity in distribution networks', in *Proc. IEEE Innovative Smart Grid Technologies ISGT Europe*, Ljubljana, 2016.

[136] EPRI, 'Stochastic Analysis to Determine Feeder Hosting Capacity for Distributed Solar PV', EPRI, Dec. 2012.

[137] M. Stifter *et al.*, 'DG DemoNet: Experiences from volt/var control field trials and control algorithm advancements', in *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Berlin, Germany, 2012, pp. 1–7.

[138] 'PowerFactory - DIgSILENT Germany', 2017. [Online]. Available: http://www.digsilent.de/index.php/products-powerfactory.html. [Accessed: 06-Nov-2015].

[139] F. M. Gonzalez-Longatt and J. Luis Rueda, Eds., *PowerFactory Applications for Power System Analysis*. Cham: Springer International Publishing, 2014.

[140] B. Bletterie, S. Kadam, and J. Le Baut, 'Increased hosting capacity by means of active power curtailment', in *Proc. CIRED Workshop 2016*, Helsinki, 2016.

[141] B. Bletterie, A. Tayyebi, S. Kadam, J. L. B. J. Stöckl, J. Kathan, and A. Einfalt, ‘A novel concept for combining distribution network and system support services for storage systems’, in *PowerTech, 2017 IEEE Manchester*, 2017, pp. 1–6.

[142] B. Bletterie, A. Latif, P. Zehetbauer, S. M. Villanueva, E. Romero-Ramos, and H. Renner, ‘On the impact of load modelling on distribution network studies’, in *Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2017 IEEE PES*, 2017, pp. 1–6.

[143] G. C. Calafiore and M. C. Campi, ‘The Scenario Approach to Robust Control Design’, *IEEE Trans. Autom. Control*, vol. 51, no. 5, pp. 742–753, May 2006.

[144] H. Yu, C. Y. Chung, K. P. Wong, H. W. Lee, and J. H. Zhang, ‘Probabilistic Load Flow Evaluation With Hybrid Latin Hypercube Sampling and Cholesky Decomposition’, *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 661–667, May 2009.

[145] J. Varela, N. Hatziargyriou, L. J. Puglisi, M. Rossi, A. Abart, and B. Bletterie, ‘The IGREENGrid Project: Increasing Hosting Capacity in Distribution Grids’, *IEEE Power Energy Mag.*, vol. 15, no. 3, pp. 30–40, May 2017.

[146] ‘MATLAB and Simulink for Technical Computing - MathWorks Deutschland’, 05-Nov-2015. [Online]. Available: http://de.mathworks.com/?refresh=true. [Accessed: 05-Nov-2015].

[147] C. Dierckxsens *et al.*, ‘Cost-effective integration of photovoltaics in existing distribution grids: results and recommendations’, Mar. 2015.

[148] P. Kotsampopoulos, F. Lehfuss, G. Lauss, B. Bletterie, and N. Hatziargyriou, ‘The limitations of digital simulation and the advantages of PHIL testing in studying Distributed Generation provision of ancillary services’, *IEEE Trans. Ind. Electron.*, pp. 1–1, 2015.

[149] ‘MetaPV’, 08-Mar-2017. [Online]. Available: http://www.metapv.eu/. [Accessed: 08-Mar-2017].

[150] R. Schwalbe, M. Stifter, B. Bletterie, A. Abart, R. Pointer, and F. Herb, ‘DG DemoNet: impact of volt/VAR control on increasing the voltage band reserve-results from field trial validations’, 2013.

[151] ‘IGREENGrid - Home’, 23-Sep-2015. [Online]. Available: http://www.igreengrid-fp7.eu/. [Accessed: 23-Sep-2015].

[152] ENEDIS, ‘Offres de raccordement intelligentes | Enedis’. [Online]. Available: http://www.enedis.fr/actualites/offres-de-raccordement-intelligentes. [Accessed: 06-May-2018].

[153] T. Stetz, J. von Appen, F. Niedermeyer, G. Scheibner, R. Sikora, and M. Braun, ‘Twilight of the Grids: The Impact of Distributed Solar on Germany?s Energy Transition’, *IEEE Power Energy Mag.*, vol. 13, no. 2, pp. 50–61, Mar. 2015.

[154] J. Witkowski, E. Lejay-Brun, G. Malarange, and L. Karsenti, ‘Field demonstration of local voltage regulation on ERDF MV network’, in *Proc. 22nd International Conference on Electricity Distribution CIRED*, Stockholm, 2013.

[155] S. Kadam, B. Bletterie, and W. Gawlik, ‘A Large Scale Grid Data Analysis Platform for DSOs’, *Energies*, vol. 10, no. 8, p. 1099, Jul. 2017.

[156] A. Kulmala, S. Repo, and B. Bletterie, ‘Avoiding adverse interactions between transformer tap changer control and local reactive power control of distributed generators’, in *PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2016 IEEE*, 2016, pp. 1–6.

[157] F. Gonzalez-Longatt and J. L. Rueda Torres, Eds., *Advanced Smart Grid Functionalities Based on PowerFactory*. Cham: Springer International Publishing, 2018.

[158] F. Olivier, D. Ernst, and R. Fonteneau, ‘Automatic phase identification of smart meter measurement data’, in *proc. 24th International Conference on Electricity Distribution*, Glasgow, 2017.

[159] W. Prüggler, ‘Ökonomische Kostenvalidierung und mögliche Auswirkungen auf die Erneuerbarenentwicklung in Österreich’, Wien, Aug. 2013.

[160] A. Abart *et al.*, ‘Power Snapshot Analysis: A new method for analyzing low voltage grids using a smart metering system’, in *Proc. Electricity Distribution (CIRED 2011), 21st International Conference and Exhibition on*, Frankfurt, 2011.

[161] J. Morin, F. Colas, X. Guillaud, and S. Grenard, ‘Determination and origins of reactive power flows in HV/MV substations’, in *Proc. Electricity Distribution (CIRED 2015), 23rd International Conference and Exhibition on*, Lyon, 2015.

[162] EC, *Network Code on Demand Connection*. 2016.

[163] Elia, ‘Tariffs transport 2016-2019’. 03-Dec-2015.

[164] RTE, ‘TURPE 5: Fiche tarifaires - HTA (<63 kV)’. 01-Aug-2017.

[165] P. Vermeyen and P. Lauwers, ‘Managing reactive power in MV distribution grids containing distributed generation’, in *Proc. CIRED 23rd International Conference on Electricity Distribution*, Lyon, 2015.

[166] G. Monfredini, Martini, S. Grotti, S. Soldani, and M. Trova, ‘PV Inverter Extended Grid Services – From “Day-Time” to “Full-Time” Operation’, in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 3811–3821.

[167] A. Maknouninejad, N. Kutkut, I. Batarseh, and Z. Qu, ‘Analysis and control of PV inverters operating in VAR mode at night’, in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*, 2011, pp. 1–5.

[168] L. F. N. Lourenco, M. B. C. Salles, R. M. Monaro, and L. Queval, ‘Technical Cost of Operating a Photovoltaic Installation as a STATCOM at Nighttime’, *IEEE Trans. Sustain. Energy*, pp. 1–1, 2018.

[169] ‘Enedis Open Data — Explore’. [Online]. Available: https://data.enedis.fr/explore/?sort=modified. [Accessed: 24-May-2018].

[170] G. Prettico, F. Gangale, A. Mengolini, A. Lucas, and G. Fulli, ‘Distribution system operators observatory’, 2016.

[171] European Commission, ‘COMMISSION REGULATION (EU) 2017/ 1485 - of 2 August 2017 - establishing a guideline on electricity transmission system operation’. Official Journal of the European Union, 02-Aug-2017.

[172] Institut für Netz- und Anwendungstechnik GmbH, ‘Zukünftige Bereitstellung von Blindleistung und anderen Maßnahmen für die Netzsicherheit’, Sep. 2016.

[173] D. Uber and M. Pöller, ‘Studie zur Berechnung von Wirkarbeitsverlusten durch Blindarbeit’, Sep. 2016.

6 Compiled publications

The publications forming part of this doctoral thesis are provided in this chapter (four journal papers and four conference papers). For each paper, a brief description of the personal contribution of the applicant is provided. Further papers related to the topics, but not fully addressing the research questions, are listed in chapter 7 (conference papers, book chapters, journal papers).

Publication 1

"Hosting capacity of LV networks with extended voltage band"

B. Bletterie, J. Le Baut, S. Kadam, R. Bolgaryn, and A. Abart, "Hosting capacity of LV networks with extended voltage band," in Proc. 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), Vienna, 2015.

Own contribution

This paper presents the expectable benefits of voltage control for different types of low voltage networks, in particular for voltage regulating distribution transformers and volt/var control.

The results summarised in this article emerged mainly out of the European project IGREENGrid (FP7 - Project ID 308864) in which the applicant was one of the key researcher.

The applicant initiated and coordinated the paper. He proposed a standardised method to analyse the behaviour of feeders in terms of hosting capacity constraint, introduced the concept of "critical length", supervised the simulation work carried out by the fourth author, analysed the results and performed most of the writing of the paper.

Hosting capacity of LV networks with extended voltage band

Benoît Bletterie, Julien Le Baut, Serdar Kadam
Energy department
Austrian Institute of Technology,
Vienna Austria
benoit.bletterie@ait.ac.at

Roman Bolgaryn
UAS Technikum Wien
Vienna, Austria

Andreas Abart
Netz Oberösterreich GmbH
Linz, Austria
andreas.abart@netzgmbh.at

***Abstract*—This paper presents the results of investigations on the voltage band management in low voltage networks considering two promising network integration solutions to enhance the hosting capacity for e.g. high PV penetrations. The critical length defined as border between current and voltage constraints is calculated for typical overhead lines and cables. The extension of the available voltage band by the use of e.g. on load tap changers in secondary substations allows a substantial increase of the hosting capacity which can be further increased by the use of reactive power based voltage control. However, the actual benefits of a voltage band extension or voltage control measures can only be used for feeders exceeding the critical length. In this paper, the critical length for different types of feeders is calculated and the implications are discussed. In addition, the impact of an extension of the voltage band and of the use of network integration solutions on network losses is investigated.**

***Index Terms*— Distributed power generation, Power quality, Smart grids, Solar power generation**

I. Introduction

Solar photovoltaic (PV) power is considered in most scenarios as an important energy resource to meet the medium and long term renewable energy targets. In [1], a growth of around 6 GW per year between 2011 and 2013 is reported for Europe, with five countries exceeding 1 GW despite the clear market decline, especially in Germany and Italy. One of its main characteristics is its distributed nature: in fact more than 70 % of the PV capacity is connected to the low voltage (LV) network [2], and a large growth is expected in the distribution network, especially in rural areas.

In some networks, the hosting capacity (HC) is already exhausted, mainly due to the voltage rise caused by the PV generation. In the last five years, extensive research has been done on the enhancement of the hosting capacity of rural feeders by voltage control through active and reactive power management or with new network assets such as distribution transformers with On-Load-Tap-Changer (OLTC) [3][4][5][6]. With these methods, the part of the voltage band allocated to generators can be considerably increased. With the use of these new control tools extending the available voltage band (OLTC) or partly compensating the voltage rise (e.g. reactive power based voltage control by photovoltaic inverters), the loading of low voltage feeders increases. Against this background, feeders in which the hosting capacity was considered to be mainly limited by the voltage might turn to be constrained by the maximal loading. Due to the absence of monitoring in LV networks (especially loading), sufficient reserve should be foreseen to the border between voltage and loading constraint.

This paper addresses the potential implications of an extended voltage band on overloading risk and on network losses. For this, a simple feeder has been used and several scenarios with different controls and voltage bands are considered.

II. Hosting Capacity In LV Networks

A. Limiting factors of the hosting capacity

In terms of network planning and operation, the most basic requirements consist in not exceeding component's rating and fulfilling the voltage quality standards (in particular the voltage level according to EN 50160 in Europe [7]). The hosting capacity of a network defines the maximal amount of generation that can be connected to it without violating the

978-1-4799-7736-9/15/$31.00 ©2015 IEEE

applicable planning criteria. This paper investigates the hosting capacity of LV feeders considering the two previously mentioned factors (current and voltage), as proposed in [5].

B. *Enhancement of the hosting capacity*

Since the hosting capacity is in many cases limited by the maximal admissible voltage rise [5][8][9], several voltage control options have been investigated in the last years. A part from a possible classification based on the general architecture of the voltage control concepts (e.g. local / centralized / distributed), these voltage control concepts can be differentiated on the basis of the components they rely on. In particular, the following two components are considered in this paper:

- PV inverters: local voltage control through reactive and active power management as investigated in [3][2][10][11]
- Distribution transformers with On-Load-Tap-Changer as proposed and investigated in [12][13]

Local voltage control by inverters has been already required in some countries for many years [14][15][16][17] with the following prevailing concepts: *cosφ(P), Q(U), P(U)*. The effectiveness of these controls has been investigated in [18].

Distribution transformers with OLTC allow decoupling the low voltage (LV) from the medium voltage (MV). With the use of a distribution transformer with OLTC, the voltage band allocated to generators connected to the LV network can be significantly increased. This part of the available voltage band (±10 % in total according to EN 50160 [7], shared between MV and LV) which is allocated to generators connected to the LV network (which amounts for example 3 % in Germany [15] and Austria [19]) can be doubled or even tripled depending on the characteristics of the OLTC.

III. Impact Of An Extended Voltage Band On the Hosting Capacity And Network Performance

The investigations presented in this paper try to answer the following questions:

a) To which extend are LV feeders with extended voltage band (e.g. through the use of a distribution transformer with an OLTC) more prone to current constraints?
And therefore to which extend is this voltage band extension actually usable due to the general lack of observability (and especially for loading) in LV networks?

b) What is the impact of using an extended voltage band to enhance the hosting capacity on network losses?

A. *General assumptions*

For this study, two types of feeders have been considered (Figure 1):

- LV feeder with a single PV generator located at the end of the feeder (*punctual generation*);
- LV Feeder with a continuous and uniform PV power density as proposed in [20] (*uniform generation*).

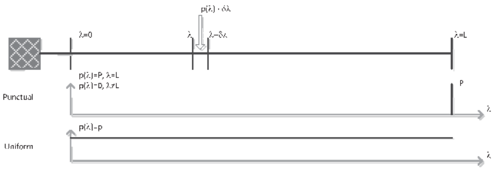


Figure 1. Considered feeders (punctual / continuous uniform distribution)

In reality, feeders are more complex and neither the single generator located at the end, nor the uniform distribution of several generators along it are usual. Moreover, different cable types might be used along feeders. The objective of this paper is to provide some understanding on the impacting factors and general trends. Moreover, simple investigations show that feeders with 10 nodes behave almost like continuous feeders (the feeder with continuous and uniform generation has been approximated with 100 nodes in this study). The investigations are performed for the most common types of overhead lines and cables (aluminum conductor) –see Table 1. For both types of feeders, the length and the PV penetration have been considered as variable. Using this simple feeder model allows getting a good understanding of the problem, of the influencing factors and of the causal relations.

Table 1: Considered overhead lines and cables (OL: Overhead Line, CBL: Cable)

Cross-section (mm^2)	Overhead Line (OL)	Cable (CBL)
50	OL_Al_4x50	CBL_4x50
70	OL_Al_4x70	CBL_4x70
95	OL_Al_4x95	CBL_4x95
120	OL_Al_4x120	CBL_4x120
150		CBL_4x150
240		CBL_4x240

The main assumptions used for the simulations (load flow computation as a snap-shot) are briefly summarized here:

- The feeder starts at the secondary side of the distribution transformer for the sake of simplicity.
- PV generation is considered to be uniformly distributed or located at the end of the feeder (see previous explanation).
- PV generators are considered to be balanced, the maximal output power is considered. Some investigations about voltage control under unsymmetrical conditions have been published in [21][22].
- Loads are not considered, they would increase the calculated hosting capacity.
- The admissible voltage rise is considered to be 3 % according to the current rules in Germany [15] and Austria [19]

532

- With the use of an OLTC at the secondary substation, the voltage band available for LV feeders is considered to be 17 % assuming a dead-band of 3 % for the OLTC (20 %–3 %=17 %). Assuming an equal allocation between allowed voltage rise (caused by generators) and voltage drop (caused by loads), the admissible voltage rise is extended from 3 % to 8.5 %.
- The maximal loading of cables and overhead lines is considered to be 100 % of the rated current.

B. Hosting capacity determination

In order to answer question a), the *critical feeder length* is introduced. It is defined as the feeder length for which the loading and voltage constraints are simultaneously limiting the hosting capacity. This *critical length* has been determined for the two types of feeders (*punctual generation* and *uniform generation*) and for different types of cables and overhead lines (see Table 1). If the *critical length* is larger than the *maximal expected length* of LV feeders, the extended voltage band cannot be fully used and attention must be paid to the overload risk.

The *critical length* has been calculated according to the procedure shown in Figure 2. Figure 3 illustrates the functioning of the procedure graphically. The procedure consists of two main parts which are briefly explained hereafter.

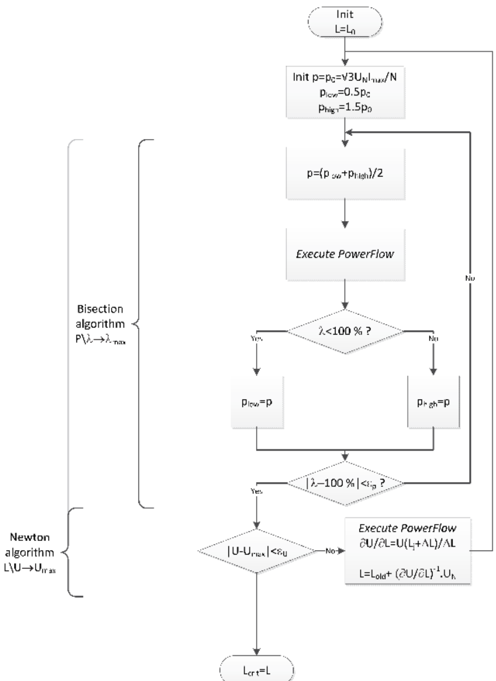


Figure 2. Algorithm flow chart for the determination of the "critical length"

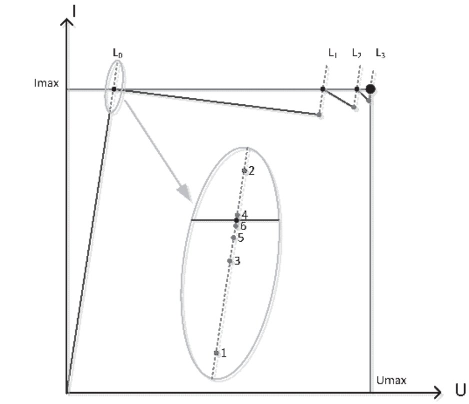


Figure 3. Illustration of the algorithm used to determine the "critical length"

The inner part varies the generation power until the maximal loading λ=100 % is reached (at the beginning of the feeder). This is done by a bisection algorithm ($P\backslash\lambda\rightarrow\lambda_{max}$ in Figure 2 and dashed grey lines in Figure 3). The outer part varies the feeder length until the maximal voltage (U_{max}=1.10 p.u.) is reached. This is done by a Newton algorithm ($L\backslash U\rightarrow U_{max}$ in Figure 2 and solid back lines in Figure 3). Note that the slack voltage is set to 1.015 p.u. to ensure an admissible voltage rise of 8.5 % (1.10 p.u.–0.085 p.u.=1.015 p.u.).

The results for a *punctual generation* are shown in Figure 4 (*critical length*) and Figure 5 (hosting capacity) for the 10 different types of cables/lines. The bars on the left of each cross-section value correspond to the overhead line (OL) and the bars on the right to the cables (CBL). In addition, the results are shown for two different power factors: 1 (black) and 0.9 (grey/white) to quantify the impact of reactive power-based voltage control on the *critical length* and on the hosting capacity. Figure 4 shows as expected that the *critical length* of cables or overhead lines increases with increasing cross-section due to the fact that the conductor resistance decreases faster than the current capacity increases (relatively).

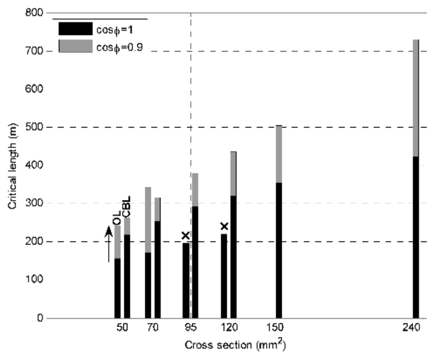


Figure 4. "Critical length" with two different power factors for a *punctual generation* (OL: Overhead Line | CBL: CaBLe)

533

This figure shows that the *critical length* remains below about 350 m/500 m without/with additional reactive power except for the cable with the largest cross-section (240 mm^2). As an example, for a standard LV cable of 150 mm^2 shorter than 353 m, the extended voltage band (8.5 % instead of 3 %) cannot be used without overloading the cable. When considering in addition reactive power control (cosφ=0.9–under excited), the *critical length* increases to about 504 m (black bars extended to the grey bars in Figure 4). For 70 mm^2 overhead lines, only feeders longer than 253 m without reactive power control or 316 m with reactive power control would actually benefit from the voltage band extension and the reactive power control. Extending the available voltage band (8.5 % instead of 3 %) and compensating part of the voltage rise by reactive power control is therefore only suitable for feeders with a total length above the *critical length*. This limits the actual potential of voltage control to rather long feeders (which are not unusual in European rural networks). In order to fully avoid the overloading risk, the feeder length should be significantly above this *critical length*.

For the overhead lines of high cross-section (95 mm^2 and 120 mm2), the voltage stability limit is reached due to the large reactance compared to the small resistance (black cross for OL_Al_4x95 and OL_Al_4x120) and the border between over-voltage and over-current does not exist. This is shown in Figure 4 and Figure 5 by black and white crosses respectively.

Figure 5 shows the hosting capacity per feeder type and for both power factors. For a 150 mm^2 cable, the hosting capacity equals 206 kW (single generator at the end of the feeder). With a power factor of 0.90 (under-excited) to limit the voltage rise, the current is increased and the hosting capacity is lowered to 185 kW (-10 %). This is shown by the reduction of the black bars by the white area in Figure 5.

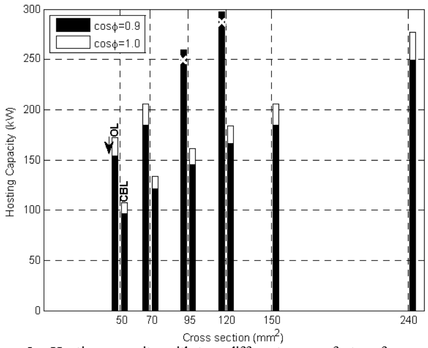


Figure 5. Hosting capacity with two different power factors for a *punctual generation* (OL: Overhead Line | CBL: CaBLe)

The results for the *uniform generation* along the feeder have been obtained in a similar way. Due to the distribution of the PV power along the feeder, the *critical length* is significantly higher since the PV penetration is on average connected closer to the feeder begin. In fact, it can be demonstrated (e.g. with the equivalent load location, [23]) that the voltage rise caused by the *uniform generation* is half of the voltage rise caused by a *punctual generation* of the feeder or the same length. For the 150 mm^2 cable, the critical length is for the *uniform generation* about 705 m (353 m for the *punctual generation*).

As observed in Figure 6, the *critical length* exceeds (considering a compensation of the voltage rise by reactive power control) 750 m for all feeder types except for the two overhead lines with the lowest cross-section (50 mm^2 and 70 mm^2). As explained before, this means that an extension of the voltage band with reactive power control is only suitable for feeders of this type longer than 750 m. Moreover, some reserve should be considered to avoid overloading which cannot be easily observed. Standard cable feeders (150 mm^2) with *uniform generation* can only benefit from a voltage band extension when longer than 705 m or 991 m with reactive power control.

For 70 mm^2 overhead lines, only feeders longer than 506 m without reactive power control or 625 m with reactive power control would actually benefit from the voltage band extension and the reactive power control.

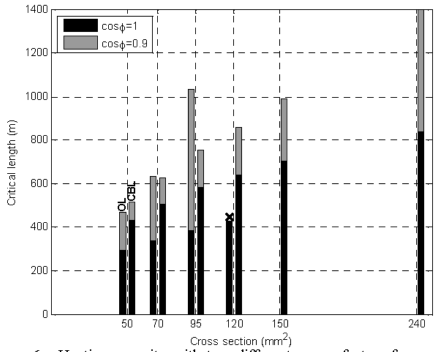


Figure 6. Hosting capacity with two different power factors for a *uniform generation* (OL: Overhead Line | CBL: CaBLe)

Considering 70 mm^2 overhead lines which can typically be found in rural areas prone to experience more severe voltage constraints and accordingly exhibit a low hosting capacity, only feeders longer than 253 m (*punctual generation*) or 506 m (*uniform generation*) without reactive power control and 316 m (*punctual generation*) or 625 m (*uniform generation*) with reactive power control would benefit from the extended voltage band. An extension of the voltage band in the considered amount is meaningful but can be used only for rather long feeders (are not unusual in European rural areas). When approaching the critical length, the risk of running into overloading raises.

C. Impact of the extended voltage band on the losses

After having identified the hosting capacity and the border current / voltage limitation (*critical length*), the question b) on the impact on network losses has been investigated for a long continuous feeder (cable 150 mm^2 - 1000 m). Several network integration alternatives have been considered:

1. reference case without any control;
2. limitation of the active power output to 70 % of the installed power (acc. to one option in the current German regulation [24]);
3. cosφ(P) control according to [15].

In order to quantify the losses, representative PV profiles have been used. These profiles which have been proposed and used in [25] are based on one year-measurements in Vienna and lead to an annual yield of 997 full load equivalent hours.

Table 2 and Table 3 summarize the results of the simulations for the three network integration alternatives, considering the current admissible voltage rise (3 %) and an extended voltage rise (8.5 %). For all these alternatives, the PV generation was designed to fully exhaust the available voltage band (the feeder is not overloaded since the length exceeds the *critical length*). With the second alternative (limitation of the output power to 70 %), the installed power was multiplied by 1.43 (1/0.70) compared to the reference scenario to make use of the power limitation. The expected impact of this measure is an increase of the losses due to the fact that the shape of the duration curve is modified (larger number of hours with high generation values). This is confirmed and quantified in Table 2 and Table 3. The third scenario also exhibits a higher hosting capacity due to the reactive power control for which also an increase of losses can be expected.

For the limitation of the output power to 70 %, a yield reduction of about 6 % was obtained which is in line with values reported in the literature. Authors in [26] report for example of a yield reduction between 1 % and 7 %, depending on the location (Germany) and PV installation properties (e.g. orientation).

These tables confirm the expectations. They show however that the increase of losses due to the implemented controls is rather limited (from 1.2 % to 1.6 % for the limited voltage band and from 3.4 % to 4.6 % for the extended voltage band). This represents an increase of about 33 % for both cases. The impact of the extended voltage band on the losses is larger: enhancing the hosting capacity by allowing a larger admissible voltage rise (8.5 % instead of 3 %) leads to almost three times higher network losses (Figure 7).

TABLE 2: RESULTS FOR THE THREE DIFFERENT SCENARIOS FOR THE CABLE (CURRENT VOLTAGE BAND = 3 %)

Test case	*Inst. power (kWp)*	*Annual yield (MWh)*	*Losses (MWh)*	*Losses/yield (%)*
No control	60.4	60.2	0.7	1.2
P<70 %×P_{max}	86.3	86.0	1.1	1.4
cosφ(P)	74.8	74.5	1.2	1.6

TABLE 3: RESULTS FOR THE THREE DIFFERENT SCENARIOS FOR THE CABLE (EXTENDED VOLTAGE BAND = 8.5 %)

Test case	*Inst. power (kWp)*	*Annual yield (MWh)*	*Losses (MWh)*	*Losses/yield (%)*
No control	169.4	168.8	5.7	3.4
P<70 %×P_{max}	242.0	241.2	8.9	4.0
cosφ(P)	214.5	213.8	9.9	4.6

The extension of the voltage band to 8.5 % (instead of currently 3 %) allows significantly increasing the hosting capacity of rural feeders (provided that they are longer than the critical length). This is reached at the costs of a non-negligible increase of network losses (by a factor of almost 4).

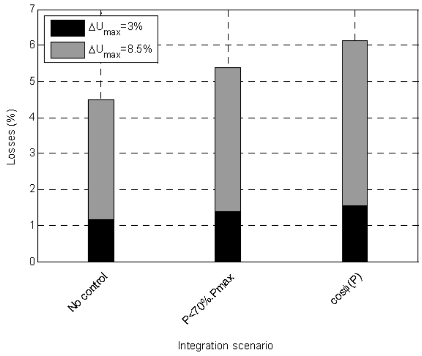


Figure 7. Network losses for the three network integration alternatives for a *uniform generation* for the current and an extended voltage band

IV. CONCLUSION

The extension of the voltage band made feasible by the use of distribution transformers with OLTC allows enhancing significantly the hosting capacity. In addition, reactive power control can also further extend the hosting capacity provided that the thermal limit of the feeder is not reached. In order to characterize feeders in this regard, the concept of the *critical length* has been introduced. It is defined as the feeder length for which both constraints (voltage and current) are actually limiting the hosting capacity.

The investigations presented in this paper tend to show that the extension of the voltage band can actually be used only for rather long feeders (longer than 506 m for 70 mm^2 overhead feeders with a *uniform generation*). While such feeders are not unusual in European rural areas), the real potential of this measure to enhance the hosting capacity is limited.

The investigations performed to quantify the impact of different network integration alternatives showed that the increase of losses due to the implemented controls (curtailment to 70 % or reactive power control) is rather limited (factor 1.3) while the increase of the losses due to the use of an extended voltage band are significant (factor of almost 4).

V. ACKNOWLEDGMENTS

This work as partly done within the project IGREENGrid which has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 308864.

VI. REFERENCES

[1] G. Masson, S. Orlandi, and M. Rekinger, "Global market outlook for Photovoltaics 2014-2018." 2014.

[2] Stetz, "Autonomous Voltage Control Strategies in Distribution Grids with Photovoltaic Systems: Technical and Economic Assessment," Kassel University press GmbH, 2014.
[3] E. Demirok, P. C. González, K. H. B. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, "Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids," *IEEE J. Photovolt.*, vol. 1, no. 2, pp. 174–182, Oct. 2011.
[4] T. Stetz, F. Marten, and M. Braun, "Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 534–542, Apr. 2013.
[5] B. Bletterie, A. Gorsek, B. Uljanic, B. Blazic, A. Woyte, T. Vu Van, F. Truyens, and J. Jahn, "Enhancement of the network hosting capacity – clearing space for/with PV," in *Proceedings 25th European Photovoltaic Solar Energy Conference and Exhibition*, Valencia, Spain, 2010, pp. 4828 – 4834.
[6] B. Bletterie, A. Stojanovic, S. Kadam, G. Lauss, M. Heidl, C. Winter, D. Hanek, A. Pamer, and A. Abart, "Local voltage control by PV inverters first operating experience from simulation, laboratory tests and field tests," in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4574–4581.
[7] CENELEC, "Voltage characteristics of electricity supplied by public electricity networks." 01-Mar-2011.
[8] C. Schwaegerl, M. H. J. Bollen, K. Karoui, and A. Yagmur, "Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources," in *Proc. Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on*, 2005, pp. 1–5.
[9] D. Mende, J. Schwarz, S. Schmidt, D. Premm, V. Sakschewski, M. Pfalzgraf, H. Homeyer, J. Schmiesing, and J. Brantl, "Reactive power control of PV plants to increase the grid hosting capacity," in *Proc. 28th European Photovoltaic Solar Energy Conference and Exhibition*, Paris, 2013, pp. 4225 – 4230.
[10] B. Bletterie, A. Goršek, T. Fawzy, D. Premm, W. Deprez, F. Truyens, A. Woyte, B. Blažič, and B. Uljanič, "Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks," *Prog. Photovolt. Res. Appl.*, vol. 20, no. 6, pp. 747–759, Sep. 2012.
[11] E. Demirok, D. Sera, P. Rodriguez, and R. Teodorescu, "Enhanced local grid voltage support method for high penetration of distributed generators," in *Proc. IECON 2011-37th Annual Conference on IEEE Industrial Electronics Society*, 2011, pp. 2481–2485.
[12] M. Joorabian, M. Ajodani, and M. Baghdadi, "A method for voltage regulation in distribution network equipped with OLTC transformers and DG units," in *Proc. Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific*, 2010, pp. 1–5.
[13] A. Einfalt, F. Kupzog, H. Brunner, and A. Lugmaier, "Control strategies for smart low voltage grids — The project DG DemoNet — Smart LV Grid," in *Proc. CIRED Workshop*, Lisbon, 2012, pp. 1–4.
[14] BDEW, "Generating Plants Connected to the Medium-Voltage Network." Jun-2008.
[15] VDE-FNN, "VDE-AR-N 4105:2011-08 Power generation systems connected to the low-voltage distribution network." Aug-2011.
[16] E-CONTROL, "Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen." 2013.
[17] CEI, "CEI 0-21 - Reference technical rules for the connection of active and passive users to the LV electrical Utilities." Dec-2013.
[18] S. Kadam, B. Bletterie, G. Lauss, M. Heidl, C. Winter, D. Hanek, and A. Abart, "Evaluation of voltage control algorithms in smart grids: results of the project: morePV2grid," in *Proc. 29th European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, 2014.
[19] E-CONTROL, "Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt2: Richtlinie zur Beurteilung von Netzrückwirkungen." Sep-2006.
[20] M. H. J. Bollen and A. Sannino, "Voltage Control With Inverter-Based Distributed Generation," *IEEE Trans. Power Deliv.*, vol. 20, no. 1, pp. 519–520, Jan. 2005.
[21] E. De Jaeger, A. DU BOIS, and B. Martin, "Hosting capacity of LV distribution grids for small distributed generation units, referring to voltage level and unbalance," in *Proc. Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.
[22] B. Bletterie, A. Gorsek, A. Abart, and M. Heidl, "Understanding the effects of unsymmetrical infeed on the voltage rise for the design of suitable voltage control algorithms with PV inverters," in *Proc. 26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, 2011, pp. 4469 – 4478.
[23] B. Bletterie, A. Abart, S. Kadam, D. Burnier, M. Stifter, and H. Brunner, "Characterising LV networks on the basis of smart meter data and accurate network models," in *Proc. Integration of Renewables into the Distribution Grid, CIRED 2012 Workshop*, 2012, pp. 1–4.
[24] Bundesministerium für Wirtschaft und Energie, *Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG)*. .
[25] B. Bletterie, S. Kadam, M. Heidl, C. Winter, D. Hanek, and A. Abart, "Techno-Economic Evaluation of Voltage Control in LV Networks: A Smart Grid Case Study," in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Paris, 2013, pp. 4210 – 4216.
[26] J. von Appen, M. Braun, B. Zin\s ser, and D. Stellbogen, "Leistungsbegrenzung bei PV-Anlagen-Anpassung der Modellierungsmethoden und Vergleich verschiedener Standorte," in *Proc. 27th Symp. Photovoltaic Solar Energy*, 2011, pp. 47–52.

Publication 2

"Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks"

B. Bletterie et al., "Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks" Prog. Photovolt. Res. Appl., vol. 20, no. 6, pp. 747–759, Sep. 2012.

Own contribution

This paper investigates the suitability of different voltage control concepts to mitigate voltage rise and increase the hosting capacity of distribution networks. This work is mostly based on a comprehensive simulation work with load and generation profiles for a whole year, including a sensitivity analysis.

The results summarised in this article emerged mainly out of the European project MetaPV (FP7 - Project ID 239511) in which the applicant was one of the key researcher.

The applicant initiated and coordinated the paper among the project consortium including a research centre, a university, equipment manufacturers and a distribution system operator. He introduced several metrics to quantify the impact of a high solar penetration on the distribution network (e.g. local/dynamic voltage control need) and designed most of the simulation cases. The applicant supervised a junior researcher in charge of running the simulations, analysed the results and coordinated the writing of the paper.

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2011)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.1222

PAPER PRESENTED AT 26TH EU PVSEC, HAMBURG, GERMANY 2011

Development of innovative voltage control for distribution networks with high photovoltaic penetration

B. Bletterie[1]*, A. Goršek[2], T. Fawzy[3], D. Premm[3], W. Deprez[4], F. Truyens[4], A. Woyte[5], B. Blazič[6] and B. Uljanič[6]

[1] Austrian Institute of Technology, Energy Department, Vienna, Austria
[2] Austrian Institute of Technology, Energy Department, Wien, Austria
[3] SMA Solar Technology AG, Niestetal, Germany
[4] Infrax cvba, Hasselt, Belgium
[5] 3E sa/nv sa, Brussels, Belgium
[6] University of Ljubljana, Ljubljana, Slovenia

ABSTRACT

The voltage rise caused by photovoltaic (PV) power feed-in is one of the main network constraints limiting the PV penetration in distribution networks. In this paper, a local voltage control approach for PV inverters based on reactive power management is proposed and investigated into detail. Through a parametric study, various inverter settings are considered and compared for a real medium voltage network with a high PV penetration level and for which a demonstration is planned within the project MetaPV. The purpose of this work is to investigate the suitability of such control concepts to compensate the voltage rise caused by the PV power feed-in and to provide some guidance on the adjustment of the settings of such control mechanisms. For the assessment of the performance of the control concept with different settings, extensive load flow simulations have been performed for a voltage-dependent reactive power control (Q(V) characteristics) on the basis of 15-minute profiles. As a result, voltage time-series over a period of 1 year are obtained for each case and analysed into details. Apart from the voltage profiles, other features such as network losses and reactive energy import have been quantified because they are also of noticeable importance for network operators. The simulation results show that suitable settings are necessary to maintain the voltage within the prescribed limits. A comparison between the considered cases shows that reactive power control Q(V) with a power factor down to 0.9 is necessary to achieve satisfying results. The use of a dead-band is recommended for the voltage-dependent reactive power control in order to limit the losses and reactive energy import. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
local voltage control; reactive power control; PV inverters; smart grids

***Correspondence**
B. Bletterie, Austrian Institute of Technology, Energy Department, Vienna, Austria.
E-mail: benoit.bletterie@ait.ac.at

Received 15 May 2011; Revised 1 September 2011; Accepted 12 September 2011

1. INTRODUCTION: IMPACT OF PHOTOVOLTAIC GENERATION ON THE DISTRIBUTION NETWORK

The increasing integration of distribution generation (DG) and particularly photovoltaics (PV) leads to technical challenges, specifically in how to maintain a high level of quality of supply with reasonable network costs. With the increase of the PV penetration in the last decade, leading for example to an installed capacity exceeding 17 GW at the end of 2010 in Germany [1], bottlenecks are locally expected and even already experienced. Most of the installed PV capacity is connected to the distribution network, and to a great extent, even to the low-voltage (LV) network. Although the size of the individual units is rather small compared to conventional power stations, the cumulated effect of a high number of PV installations can have a noticeable impact on the distribution networks, which were not designed to accommodate such a generation. A large DG penetration may cause power flows to reverse and become bidirectional depending on the loading and generation conditions. Among all the possible effects that DG units can have on the network operation, the voltage rise caused by the local active power feed-in is one of the major concerns in medium-voltage (MV) and LV networks. For the scope of this work, the European standard EN 50160 [2] has been used as background (i.e. limits of ±10% of the nominal voltage during 95% of 1 week). In this study, the available voltage band of ±10% has been assumed to be equally distributed between medium voltage and low voltage, leading to ±5% as planning limits.

For the quantification of the impact of distributed generation on the network, the concept of hosting capacity introduced in [3] and refined in [4] and [5] is briefly explained. The hosting capacity is defined as the maximum distributed generation (DG) penetration for which the power system still operates satisfactorily. It is determined by comparing a performance index with its limit, which represents the limit of satisfactory operation of the network. The hosting capacity is therefore the DG penetration level for which the performance index falls below the limit (see Figure 1).

Among the different possible definitions of the PV penetration, the following one has been used in this work: the PV penetration is the ratio between the installed PV power and the maximal network load. This concept can be applied to a whole MV or LV network or to particular feeders.

In [4], the hosting capacity of a particular MV network has been quantified on the basis of detailed simulations and considering the voltage constraints as limiting factor. For the considered network, the hosting capacity has been already exhausted due to the combined presence of loads and generation in the same MV network but located on different feeders.

Once the hosting capacity of a network is exhausted, suitable countermeasures are necessary. Through network reinforcement, for example upgrade of overhead lines or cables, the hosting capacity can be extended. However, because network reinforcement costs are generally costly, some alternative solutions based on automation and communication can be implemented at a lower cost. Bletterie *et al.* [6] show that smart grid concepts applied to the voltage control can lead to savings of more than 50% compared to network reinforcement. For the particular case of

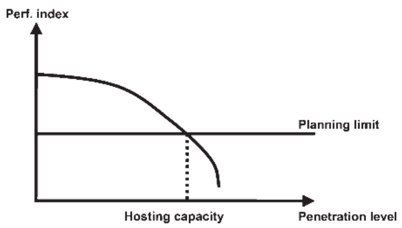


Figure 1. Concept of hosting capacity (illustration from [5]).

PV installations, suitable control mechanisms can be implemented into PV inverters, enabling them to contribute to the network operation and to maintain the voltage within the limits.

One of the core objectives of the previously mentioned project MetaPV is to develop and demonstrate the suitability of advanced voltage control concepts for PV inverters, making photovoltaics a cornerstone of smart grids.

A few studies covered the issue of voltage control with reactive power management. Kerber *et al.* [7] investigate for example a characteristic Q = f(V) (reactive power as function of the voltage at the point of connection) on a small LV network. In addition, a concept for a location-based parameterisation is proposed. The main conclusion is that the voltage rise caused by a PV feed-in can be partly compensated by operating PV inverters with a power factor down to 0.90. The impact on the sizing of PV inverters is briefly mentioned, and the impact on the additional reactive power flow and the network losses are considered to be limited to uncritical levels.

Stetz *et al.* [8] explain the basis of a reactive power controller in PV inverters, considering three different implementations based on the recommendation of [9]. Results are in this paper also presented for a small LV network, showing that the hosting capacity of the considered network could be extended by a factor two by applying the proposed control. The impact of the control on the inverter efficiency has also been investigated, showing a rather large impact due to the fact that only a summer week has been considered. Stetz *et al.* [10] focus on the optimal sizing of PV inverters connected to the LV network and featuring reactive power control. On the basis of a simplified network model, this paper concludes that inverters shall be oversized by more than 10% in comparison with inverters not featuring reactive power control.

For the improvement of the integrations of PV generation into distribution networks, the work presented here investigates the performance of newly developed solution of reactive power management with the example of a real MV network using accurate inverter models and accurate load and generation profiles. Through a parametric study, conclusions are drawn on the performance of the different controller settings. Because the simulations have been made for a whole year with 15-minute profiles, sound conclusions can be drawn on the impact of the proposed control on network losses. In the scope of the MetaPV project [1], the study will be extended to LV networks.

2. INVESTIGATED NETWORK AND PHOTOVOLTAIC INVERTER MODEL

This section introduces the investigated medium voltage network as well as the inverter model.

2.1. Investigated Network

The considered MV network is a 10-kV cable network situated in the Lommel municipality in Belgium. The detailed network, load and generation data were provided by the Belgian network operator Infrax. The weakest feeder of this network has been chosen for the investigation on the basis of a voltage sensitivity analysis. This feeder is made of various cables (cross-section starting from 240 mm^2 and ending with 25 mm^2) and is almost 14-km long.

Figure 2 presents the feeder selected for the investigations with seven industrial and three residential PV installations. The existing PV installations, which are connected to one of the LV networks supplied by this feeder, have been aggregated into one equivalent MV installation (one generator). All the other installations have been defined considering a realistic distribution and leading to a high local penetration of PV generation.

Within the MetaPV project, scenarios for generation and consumption have been developed until 2020 [5] and [4]. The PV power installed in the whole MV network according to these scenarios is briefly summarised in Table I.

The presented study is based on the scenario 2011, including the installations planned within the project (more than 6 MW for the whole demonstration area). For the achievement of a higher but still realistic penetration, a total of seven PV installations have been integrated into the considered feeder (Figure 2 and Table II), thus creating locally a large PV penetration. The total considered generation of about 3 MW overpasses the maximal load of the feeder by 35%, which locally represents a high PV penetration (135%). The minimal load of this feeder represents about 37% of the maximal load.

Table II shows the installed power summing more than 3 MW on this feeder. It also shows the voltage sensitivity factor at the point of connection, which quantifies the strength of the network at this point. With both information (connected power and voltage sensitivity factor), the cumulated impact of the PV generation along the feeder can be easily calculated. On Figure 3, it can be seen that the weakest node (at 13.8 km distance from the substation) has a sensitivity factor of almost 4.5%/MW. Furthermore, it can be seen that the R/X ratio at the weakest node is quite high (about 2.8), meaning that active power variations have a larger impact on the voltage than reactive power variations.

For each PV installation on this feeder, a generation profile with a time step of 15 min on the basis of real measurements from the automated metering system (AMS) for the year 2009 has been used. For loads, standard profiles have been applied for public distribution transformer stations, and a power factor of 0.90 has been assumed. For industrial customers, the profiles from AMS have been used.

2.2. Inverter model

For the investigations, an inverter model in the PowerFactory® software has been used. Each PV installation of the selected feeder has been fitted with a detailed model of a smart inverter. A smart inverter is an inverter that is able to contribute to the network operation by the following features (list not exhaustive) [11]:

- reactive power control
- voltage control
- fault-ride-through
- feed-in curtailment in case of congestion
- feed-in curtailment in case of over-frequency

Figure 4 provides an overview of the functions available in the inverters used in this project and available in the models for the simulations. In addition to the voltage control functions, the active power can be reduced in case of network over-

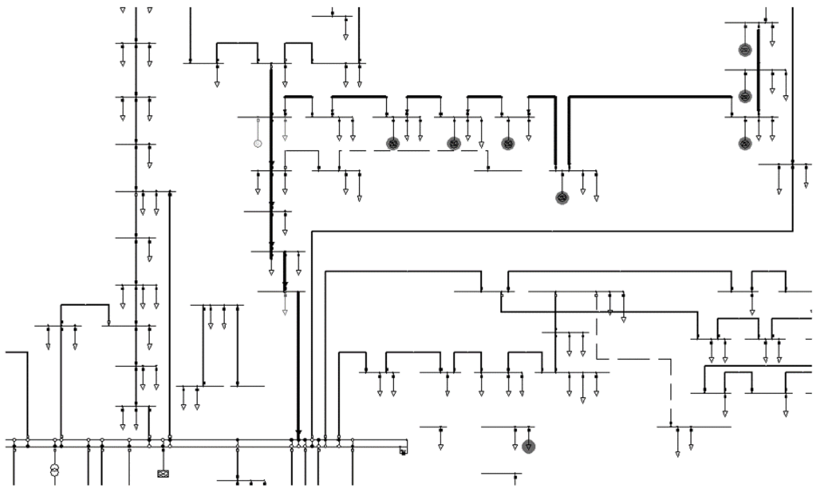


Figure 2. Considered feeder (marked bold) from the demonstration network with seven photovoltaic installations (grey circles).

Prog. Photovolt: Res. Appl. (2011) © 2011 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

Table I. Installed photovoltaic (PV) capacity for the whole photovoltaic (MV) network from 2010 to 2020 (Source: [4]).

Year	2010	2011	2012	2013	2014	2015	2020
PV on MV network (MW)	3.1	5.6	8.2	10.8	13.3	15.9	28.7

frequency P(f), through feed-in management commands (P_{max}) or as a function of the grid voltage P(V). The model can also be parameterised to reflect the behaviour of the inverter in case of voltage dips through the dynamic grid support algorithm. The control structures can be implemented locally as standalone control concepts or with a central supervisory control unit, sending operation commands to the inverter via a suitable communication interface. The main function used in the analyses summarised in this report is the function Q = f(V), meaning that the voltage at the point of connection of the inverter will be controlled by consuming or injecting reactive power. Figure 5 shows a basic Q(V) characteristic. More details are provided in the next chapter. The smart inverter can be parameterised to control the voltage according to the particular requirements of the distribution network operator (DNO) and depending on the network characteristics.

Inverter models have been implemented as static generators in the simulation environment, where detailed capability diagrams reflecting the inverter capabilities in terms of active and reactive power are implemented. Figure 6 shows the structure of the inverter model, which contains a standard phase-locked loop (PLL) module as well as a dedicated current control. Each of the seven implemented generators is fed with an external 15-minute profile for active power. Loads are similarly fed with consumption profiles for active and reactive power, as previously explained.

The objective of investigations presented in this paper is to propose a set of suitable settings (voltage set-point, dead-band, droop factor…) to maintain the voltage within the limits defined by the network planning practices and basically based on the EN 50160 [2].

Two types of investigations have been performed: steady-state simulations to study the impact of the controller settings on the overall performance, and stability simulations aiming at demonstrating that several inverters can operate as stable systems. This paper focused on the results of the steady-state simulation, which are based on load flow computation for each15-minute interval of a year.

Table II. Generation location and size for the test feeder.

PV generator	Distance from substation (km)	Sensitivity (%/MW)	Generator power (kW)
Node 1	8.6	1.3	200
Node 2	9.5	1.9	800
Node 3	10.8	2.7	380
Node 4	11.6	3.2	380
Node 5	12.3	3.6	200
Node 6	13.2	4.0	380
Node 7	13.8	4.4	380

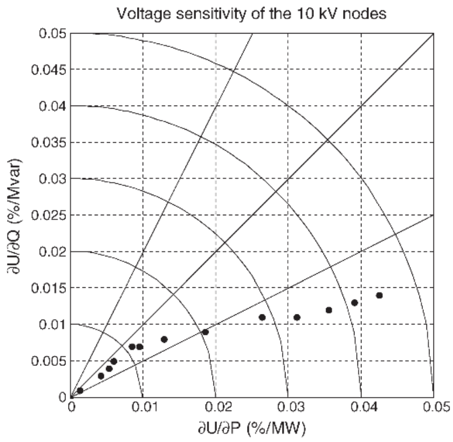


Figure 3. Voltage sensitivity diagram for all nodes located on the test feeder.

3. INVESTIGATED SCENARIOS AND SIMULATION ASSUMPTIONS

This section introduces the assumptions used for the study of the selected medium voltage feeder. Further on, a short description of the investigated cases is provided.

All simulations have been performed on the basis of the previously mentioned scenario 2011. In addition, seven industry-scale PV systems have been integrated into the selected feeder. The simulations are conducted using measured and standard profiles (15 min) for load and generation. The voltage has been assumed to be constant at the substation (here 1.05 p.u.) because it is controlled to a

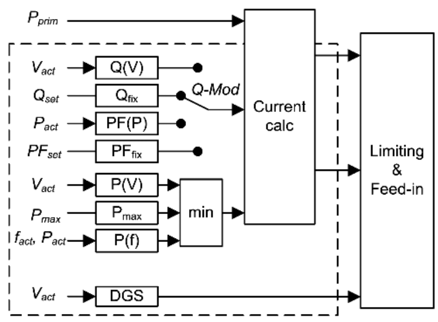


Figure 4. Grid management and feed-in structure of a smart photovoltaic inverter [11].

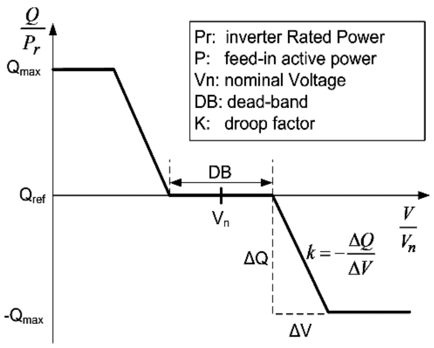


Figure 5. Considered Q(V) characteristic for the voltage control.

constant set-point with the on-load-tap-changer (OLTC). The investigations are based on load flow computations with the software PowerFactory®, using the generation and load profiles for 1 year.

Before running the simulations, the hosting capacity of the considered feeder has been estimated, on the basis of the work presented in [5] and [4]. One of the indicators proposed to quantify the hosting capacity from the voltage band point of view is the local control need (LVCN). The need for locally controlling the voltage at some nodes of the network is quantified through Equations (5) and (6). The *LVCN*(*t*) is the difference between the maximum and the minimum instantaneous voltage and the available voltage band. It says whether the voltage in the whole considered area (i.e. the whole MV network) could be controlled by adjusting the voltage set-point with the OLTC to a suitable value at the substation. Figure 7 provides an example for which there is no need to control the voltage locally. It shows the locus of the maximal voltage and the minimal voltage over the network for the whole year. It can be seen that for each time step, it is possible to shift both curves up and down to bring them into the limits, meaning that a central voltage control through the OLTC would be sufficient to control the voltage. In some situations, it is not possible to maintain the voltage within the limits due to the large difference between heavy-loaded feeders supplying mainly loads and feeders to which many PV installations are connected. This indicator is based on the analysis of the voltage profiles of all the nodes and relies on an estimation based on linearization whose accuracy is fully acceptable for voltage values within the usual voltage (i.e. ±5%).

U_{maxlim} and U_{minlim} are the operational voltage limits. For the considered network, a voltage band of 10% (U_{maxlim}–U_{minlim}) has been assumed for the MV network.

$$u_{\max}(t) = \max\{u_k(t), k = 1..n\} \quad (1)$$

$$u_{\min}(t) = \min\{u_k(t), k = 1..n\} \quad (2)$$

$$U_{\max} = \max\{u_{\max}(t), t = 1..m\} \quad (3)$$

$$U_{\min} = \min\{u_{\min}(t), t = 1..m\} \quad (4)$$

$$LVCN(t) = (u_{\max}(t) - u_{\min}(t)) - (U_{\mathrm{maxlim}} - U_{\mathrm{minlim}}) \quad (5)$$

$$LVCN_{\max} = \max\{LVCN(t), t = 1..m\} \quad (6)$$

k is the index for nodes, n is the number of nodes in the network and m is the number of time-steps in a year (35040 15-minute intervals in a year).

$u_{\max}(t)$ and $u_{\min}(t)$ are the locus of the maximal and the minimal network voltage, respectively.

$U_{\max}$ and $U_{\min}$ are the maximal and the minimal network voltage values over the year.

U_{maxlim} and U_{minlim} are the used planning limits. Here, the limits have been set to 1.01 p.u. and 1.09 p.u.

$LVCN_{\max}$ is the maximum of the local voltage control need $LVCN(t)$ over 1 year. If the $LVCN_{\max}$ is positive, some

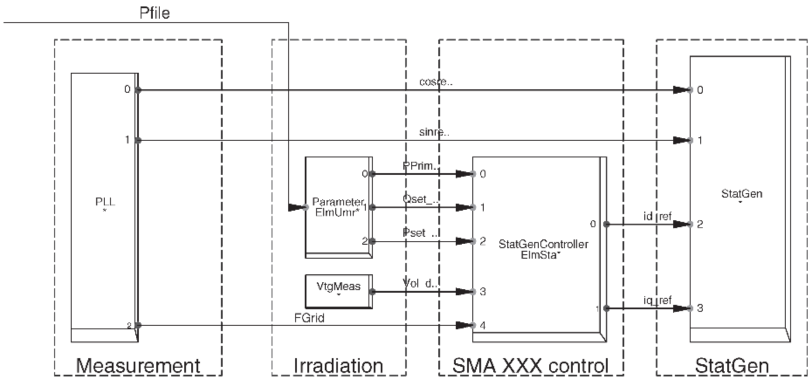


Figure 6. Model structure with phase-locked loop (PLL), StatGenController (main inverter model) and StatGen (connection with static generator).

Prog. Photovolt: Res. Appl. (2011) © 2011 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

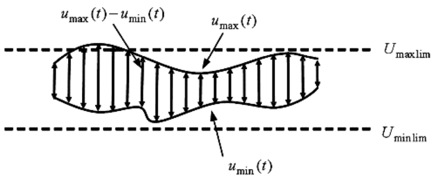


Figure 7. Definition of the local voltage control need.

countermeasures (local voltage control by generators) must be taken to maintain the voltage within the limits.

For the considered scenario, the local voltage control need is positive, meaning that some local control actions are necessary to maintain the voltage within the limits: the inverters connected to the feeder must regulate the voltage.

The Q(V) characteristic shown on Figure 5 has been implemented into the inverter models. It can be parameterised through the following settings:

- Voltage set-point (p.u.)
- Minimal power factor PF_{min}
- Droop factor (k, p.u./p.u.)
- Dead-band (ΔU_{DB}, p.u.)
- Maximal voltage for the linear range (U_{max})

The voltage set-point has been chosen to be the same as the set-point used for the OLTC at the substation (1.05 p.u.) to avoid any unnecessary offset.

The droop factor can be derived from Equation (7), showing that only three of these four parameters are needed to specify the characteristic (k, U_{max} and ΔU_{DB} are linked according to Equation (7)).

$$k = \frac{\tan(\arccos(PF_{min}))}{U_{max} - U_{set} - \Delta U_{DB}} \quad (7)$$

The minimal power factor is used to define the droop factor and does not reflect the smallest power factor at which the inverter is able to operate. The actual operation limits of the inverters have been specified in the static generator models through a capability diagram.

On the basis of the characteristic shown in Figure 5, a parametric study has been performed. Five different cases are investigated as follows. They are also summarised in Table III.

- Simulation case A0 (without control): In this case, the normal operation mode, without voltage control, is investigated. It serves as the reference case for the other cases and is used for comparison purpose.
- Simulation case A (PF_{min} = 0.85): this case represents a characteristic with a minimal power factor of 0.85, which means that relatively large amounts of reactive power (more than 60% of the active power) can be exchanged (consumed or injected) with the network. Nine different variations of dead-band and maximal voltage (ΔU_{DB} = 0–3% and U_{max} = 1.07–1.09 p.u.) are generated and evaluated.
- Simulation case B (PF_{min} = 0.90): this case represents a characteristic with a minimal power factor of 0.90. Nine different variations of dead-band and maximal voltage (between ΔU_{DB} = 0–3% and U_{max} = 1.07–1.09 p.u.) are generated and evaluated.
- Simulation case C (PF_{min} = 0.95): this case represents a characteristic with a minimal power factor of 0.95. Nine different variations of dead-band and maximal voltage (ΔU_{DB} = 0–3% and U_{max} = 1.07–1.09 p.u.) are generated and evaluated.
- Simulation case LDB (location-based dead-band): this case builds on case B and represents a characteristic with a minimal power factor of 0.90. However, a non-uniform dead-band has been used. Each inverter receives an own dead-band on the basis of the voltage sensitivity factor (Figure 3) to better distribute the contribution of the inverters to the voltage control [7]. By doing so, inverters whose connection point is located closer to the substation would start controlling reactive power for smaller voltages. In this way, the reactive power management is better distributed among all the inverters connected along the feeder. The dead-band has been distributed linearly between 1% and 3% over the nodes of the feeder. The closest the node is to the substation, the smallest the voltage sensitivity factor and therefore the smallest the dead-band.

In total, all 29 different simulation cases have been defined and parameterised into all the inverters of the considered feeder. For each of the cases, the simulations have been carried out on the basis of the yearly profiles and the following magnitudes have been exported:

- voltages
- network losses
- consumed power
- reactive and active power of each generator
- reactive power import
- cable loading

4. ANALYSIS OF THE IMPACT OF DIFFERENT INVERTER SETTINGS ON THE NETWORK PERFORMANCE

From Table III, a parametric study has been performed by simulating for each setting the selected feeder with the inverter models for a whole year. Before comparing all the results in terms of voltage profiles, reactive power import and network losses, some particular cases are taken as example to explain the results.

Figure 8 shows the yearly profile of the voltage at the weakest node without (left) and with (right) voltage control (settings according to case B5). It can be seen that without voltage control, the voltage at this node exceeds the planning limit of 1.10 p.u. EN 50160 [2] and the planning limit set to

Table III. Comparison of different simulation cases with different settings (grouped A0, A, B, C, LDB).

Case	Set-point	Maximal voltage	Dead-band	PF	Droop
	[p.u.]	[p.u.]	[%]	[-]	[p.u./p.u.]
A0					
A1	1.05	1.07	0	0.85	30.99
A2	1.05	1.07	1	0.85	61.97
A3	1.05	1.08	0	0.85	20.66
A4	1.05	1.08	1	0.85	30.99
A5	1.05	1.08	2	0.85	61.97
A6	1.05	1.09	0	0.85	15.49
A7	1.05	1.09	1	0.85	20.66
A8	1.05	1.09	2	0.85	30.99
A9	1.05	1.09	3	0.85	61.97
B1	1.05	1.07	0	0.90	24.22
B2	1.05	1.07	1	0.90	48.43
B3	1.05	1.08	0	0.90	16.14
B4	1.05	1.08	1	0.90	24.22
B5	1.05	1.08	2	0.90	48.43
B6	1.05	1.09	0	0.90	12.11
B7	1.05	1.09	1	0.90	16.14
B8	1.05	1.09	2	0.90	24.22
B9	1.05	1.09	3	0.90	48.43
C1	1.05	1.07	0	0.95	16.43
C2	1.05	1.07	1	0.95	32.87
C3	1.05	1.08	0	0.95	10.96
C4	1.05	1.08	1	0.95	16.43
C5	1.05	1.08	2	0.95	32.87
C6	1.05	1.09	0	0.95	8.22
C7	1.05	1.09	1	0.95	10.96
C8	1.05	1.09	2	0.95	16.43
C9	1.05	1.09	3	0.95	32.87
LDB	1.05	1.09	1–3	0.90	16.14–48.43

1.09 p.u. With the voltage control (DB = 2%, U_{max} = 1.08 p.u.), the voltage stays below the limit of EN 50160 [2] but still exceeds the planning limit of 1.09 p.u. for short duration. This figure further shows that reactive power is consumed in times where the PV generation is high and the load is low to keep the maximal voltage below the limit. Moreover, it can be seen that reactive power is injected into the network at times of low PV generation (winter months) for which the voltage is low. Due to the high load and low PV generation level, under-voltage conditions prevail in this period of the year. Over the whole year, inverters provide reactive power (due to the lower voltage) during more than 60% of the time. Further considerations related to this observation are presented later.

Figure 9 provides a summary of the performance of the voltage control for each setting in terms of maximal voltage. It shows that setting a minimum power factor of 0.95 does not allow keeping the voltage within the limits. As expected, the largest compensation of the voltage rise is obtained for the lower minimal power factor 0.85. This figure further shows that the control 'location-based dead-band' provides a better performance within the power factor category 0.90. This is due to the fact that generators connected at the beginning of the feeder contribute to the voltage control before reaching the planning limit.

A further analysis of the voltage profiles is provided through the 'box plot' representation in Figure 10. Each bar (colour black to white) represents a parameterization case. This statistical representation of the voltage time-series at the weakest node shows the median (middle line), 25th and 75th percentile (lower and upper parts of the box) and the outliers (crosses). From the figure, it can be seen that the voltage in the reference case (without control) is between 1.01 and 1.03 p.u. for 50% of the time. By comparing the simulation cases corresponding to different settings with this reference case, the following can be observed:

- the dead-band width has an impact on the voltage distribution (e.g. height of the box). The smaller the dead-band is, the lesser the dispersed voltage values are, but the outliers are not affected by the dead-band.
- the maximal voltage (highest outlier) is affected by the minimal power factor and the used maximal voltage.

Prog. Photovolt: Res. Appl. (2011) © 2011 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

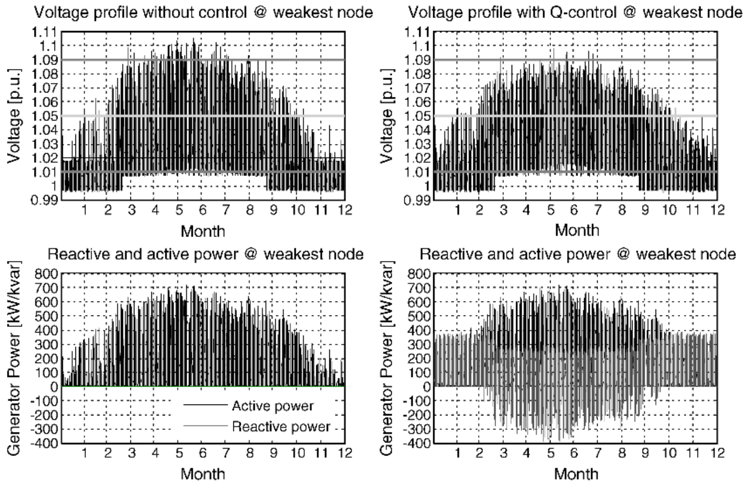


Figure 8. Voltage, active and reactive power of the weakest node 'Node 7' in normal operation (left) and control operation (right) for simulation case B3.

Apart from the voltage profiles, the network losses as well as the reactive energy import over the whole year have been considered. Figure 11 shows the reactive energy balance (integration of the reactive power flow through the substation). Positive values mean a consumption of reactive energy and negative values an excess. The imported and the exported reactive energy are shown separately (positive and negative part of the vertical axis), and the sum (balance over the year) is shown with the point. The reason for investigating the reactive energy balance for the whole feeder is that the DNO may be charged when importing large amounts of reactive

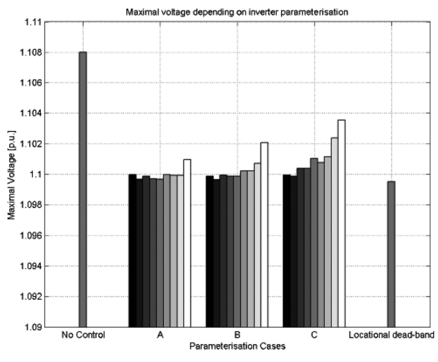


Figure 9. Maximal voltage values for the weakest node during different parameterisation settings according to Table III. Note that the diagram scale begins with 1.09 p.u.

energy, depending on the arrangements with the transmission system operator. Without voltage control, the balance of the reactive energy is positive, meaning that reactive energy is imported from the transmission network.

This figure shows that for all the investigated cases with voltage control, the reactive energy import is smaller than without voltage control. Although the reactive energy import is not significantly affected by the control, the reactive energy exports increases very strongly for some of the considered parameterisation cases, leading to an overall reactive energy export over the year (e.g. case A1). The case 'location-based dead-band' leads to an average result (average of the other cases). This figure further shows that simulation cases, with a lower minimal power factor (cases A), lead to a lower overall reactive energy import. This might seem to be a paradox but is in this case due to the fact that the PV generation causes high voltages only during part of the year (daytime in spring, summer and autumn). The rather small PV feed-in in combination with the larger load in winter leads to lower voltage values which, depending on the dead-band setting, also activates the voltage control, and causes an injection of reactive energy during this period. The increase of reactive energy import in times of high voltages is in this case smaller than the decrease of reactive energy import in times of low voltages. Furthermore, simulation cases with a smaller dead-band lead to smaller reactive energy import because they reinforce the effect previously explained. For two of the considered cases, the balance is even negative, meaning that over the year, a reactive energy surplus is fed into substation (small export).

This discussion points out the question whether PV generators shall, in addition to mitigating over-voltages, which is the

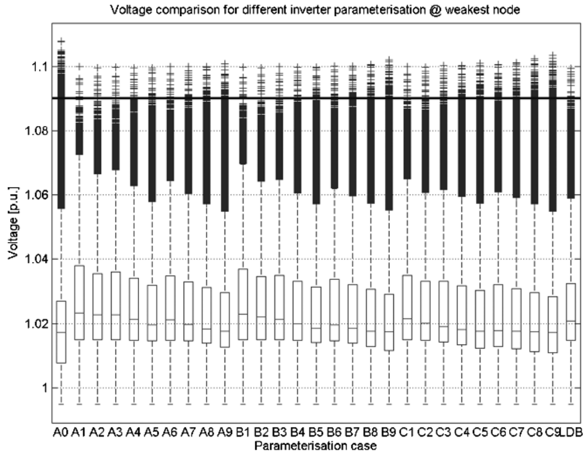


Figure 10. Voltage comparison for different inverter parameterisation on the weakest node.

primary task of this local voltage control, support the voltage in case of under-voltages. Although over-voltages caused by the high PV feed-in can be at least partly compensated by the inverters by consuming reactive power, under-voltages can only be compensated if they coincide with generation times.

On the basis of these observations, it can be concluded that the voltage control does not negatively impact the reactive power balance over the year. In this particular network, the voltage control even slightly improves the reactive power balance.

Finally, the performance of the different settings of voltage controller has been assessed in terms of network losses. Figure 12 shows total network losses in MWh for each case. As for the other figures, the reference case (without control, on the left) is shown for comparison purpose. The first observation, which can be made is that the activation of the voltage control has a limited impact on network loses. For this reason, the network losses for cases A1 to C9 have been normalised to the losses without control to allow a better comparison (Figure 13).

This figure shows that the use of a small minimal power factor (0.85), depending on the dead-band settings, leads to an increase of the losses of up to 5.5% (without dead-band). The feeder losses for the reference case (without voltage control) represent about 11.3% of the net-imported active energy (demand–generation). This increase brings the losses to 11.9% of the net-imported active energy, which represents an increase of less than 0.6 percentage points.

With an increasing dead-band, the network losses decrease because the voltage control is activated during a shorter period

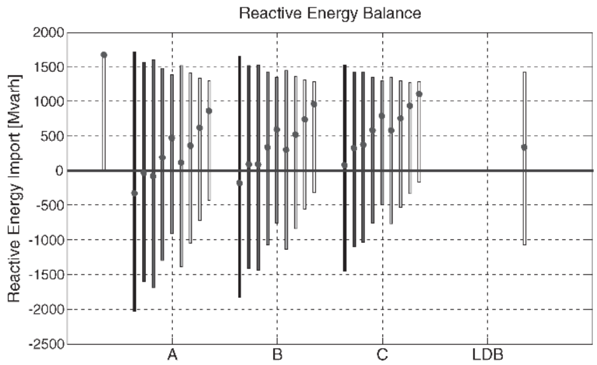


Figure 11. Reactive energy import and export for all the investigated cases in comparison with the case without voltage control.

Prog. Photovolt: Res. Appl. (2011) © 2011 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

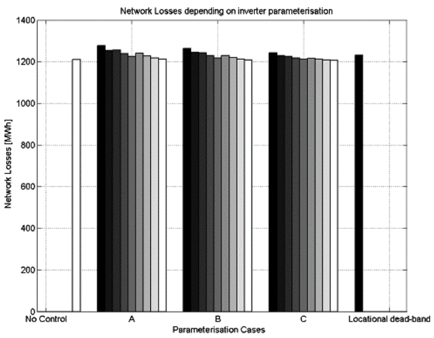


Figure 12. Network losses depending inverter setting in comparison with normal operational scenario.

of the year. For the cases operating with a minimal power factor of 0.90, the impact on the network losses is smaller. Case B8 (maximal voltage 1.09 and dead-band 2%) leads for example to a minimal increase of losses (relative increase <1%). The case 'location-based dead-band' leads again to an 'average' increase of the losses due to the distribution of the contribution.

The observation that the net-reactive energy import decreases while the network losses increase seems to be contradictory. By looking at Figure 11, it can be seen that for most cases, the reactive energy balance (point on Figure 11) is better than for the reference case but the absolute amount of reactive energy exchanged at the substation (total height of the bars) is significantly greater than for the reference case. In other words, the signed sum of the reactive energy consumption and injection is smaller, but the sum of the absolute values is larger, which has a negative impact on the losses. A further analysis is provided on the basis of case A1 (maximal voltage of 1.07 p.u. with a minimal power factor of 0.85 and without dead-band), which can be seen as an extreme case among the considered settings.

Figure 15 shows the relation between the voltage at the furthest node, the sum of the reactive power consumed by all the generators of the feeder and the feeder losses. On this figure, the grey points represent situations with over-voltage, and the black points represent situations with under-voltage.

The upper part of the figure shows that the total consumed or injected reactive power ranges between 1.7 and 1.6 Mvar, respectively, which is almost symmetrical. As previously explained, the balance over the year leads to an excess of more than 300 Mvarh. Moreover, this upper diagram shows that under some conditions, the sum of the generators consumes reactive power although the voltage is lower than the set-point (under-voltage) and vice versa provides reactive power although the voltage is greater than the set-point (over-voltage). This observation seems to be contradictory with the characteristic used for the voltage control (see Figure 5) but is in fact due to the non-homogeneity of the feeder. Indeed, the presence of loads and generators distributed along the feeder leads to a non-monotonous voltage diagram (see Figure 14). This means that, depending on the dead-band (0 in this case), some PV installations may inject reactive power (those that are close to the substation in the example of Figure 14) due to under-voltage, and others may consume reactive power (those that are far from the substation in the example of Figure 14) due to over-voltage. Depending on the conditions, the sum of these

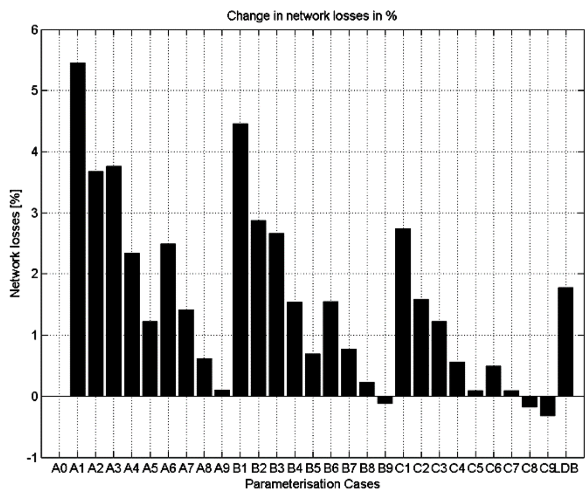


Figure 13. Active energy losses in comparison to the reference case without voltage control.

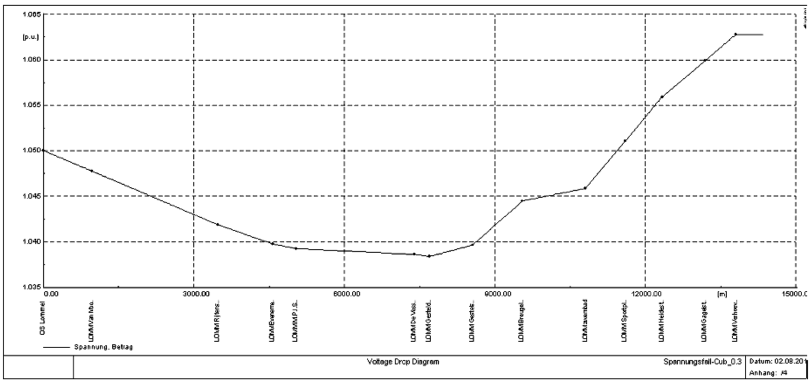


Figure 14. Example of non-monotonous voltage diagram for the considered feeder.

contributions may turn to be positive (consumption of reactive power) or negative (provision of reactive power).

The second part of Figure 15 shows that, in case of over-voltage, the losses can reach greater values than in case of under-voltage. This can also be seen on the third part of the figure in which the phenomenon described previously is also visible; some blue points (under-voltage) are located in the area of overall reactive power consumption by the generators and vice versa. About 6.5% of the annual feeder losses occur in such conditions (overall reactive power consumption although the voltage at the end of the feeder is lower than the set-point and overall reactive power provision although the voltage at the end of the feeder is greater than the set-point). With a coordinated voltage control approach, such situations could be avoided.

More than 85% of the feeder losses occur in under-voltage situations (with or without voltage control), which correlates with the fact that under-voltage situations represent about 85% of the year. With voltage control, feeder losses increase for under-voltage situations even more than for over-voltage situations. The feeder losses increase (about 1.276 Mvarh),

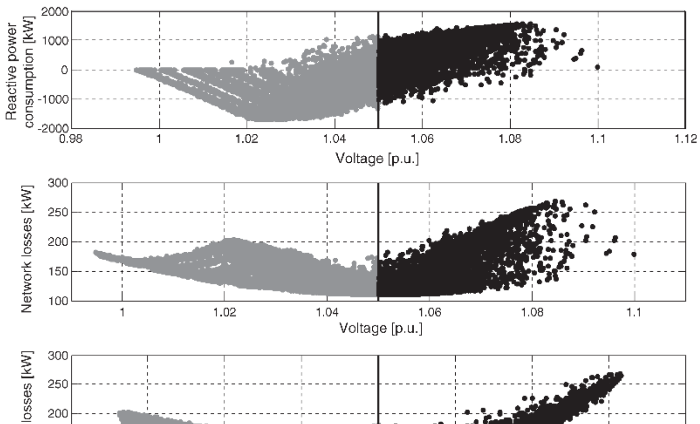


Figure 15. Relationship between voltage, sum of reactive energy consumed by the generators and losses for case A1.

Prog. Photovolt: Res. Appl. (2011) © 2011 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

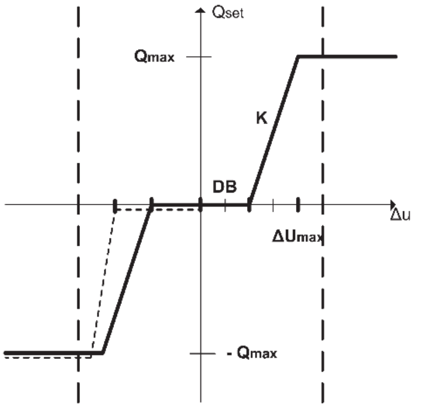


Figure 16. Proposed characteristic (with symmetrical and unsymmetrical control).

representing an increase of about 5.4% (see Figure 13) is mainly due to the voltage control operation for under-voltage mitigation (here 3.1%) than for over-voltage mitigation (here 2.3%).

The use of an unsymmetrical control (e.g. different dead-band for under and over-voltage) would lead to a better overall performance (less network losses, smaller impact on the reactive power balance).

5. CONCLUSION

The impact of different settings of the voltage control for PV installations connected to a medium voltage network has been investigated into details with a parametric study. For this, a feeder of a real 10-kV network and detailed inverter models has been used. The network performance has been considered in terms of voltage profiles on the one hand and reactive energy import and network losses on the other hand. The comparison between all the investigated cases leads to rather small differences because only realistic settings have been investigated.

Although further studies with other network types (e.g. other voltage levels such as 20 kV or 30 kV, other load/generation configurations) would be necessary to be able to generalise these findings, the following conclusions can be drawn from the analysis:

(i) With most of the investigated voltage control characteristics Q(V), the over-voltage caused by the high penetration of PV generation could be relieved. This would in practise mean that costly network reinforcement could be avoided or postponed, thanks to the control capabilities of smart inverters.

(ii) The effectiveness of the reactive power control is roughly proportional to the ratio between R/X and the relative amount of reactive power (tanφ). The investigations showed that the voltage can be kept below the upper voltage limit only by using a minimal power factor equal to or below 0.90. In cabled networks such as the one investigated, the R/X ratio of the network impedance is unfavourably high, meaning that larger amounts of reactive power are needed to compensate part of the voltage rise caused by the PV feed-in. For the limitation of the increase of network losses, it can be meaningful to limit the amount of reactive power to be exchanged with the network by specifying a minimal power factor of 0.90.

(iii) For the considered feeder, the use of a voltage control based on reactive power control significantly impacts the reactive energy balance over the year. In all the considered cases, the reactive energy import could be reduced because the inverters provide reactive power, which partly compensates the reactive power demand from the loads. This positive effect is mainly due to the symmetrical control (same dead-band for under/over-voltage) and could disappear for other network and load/generation configurations.

(iv) Lower minimal power factor leads, as expected, to higher network losses than higher power factors. This study showed however, that this impact is rather limited (maximal increase of the energy losses of about 5.4% for a minimal power factor of 0.85 without dead-band). For more suitable controller settings such as the one proposed hereafter, the increase of the feeder losses is small (relative increase of about 0.25%).

(v) The voltage set-point shall be adjusted to the network nominal voltage (set-point of the OLTC). Otherwise, inverters would try to offset the voltage by exchanging large amounts of reactive power with the network without real benefit.

(vi) Because of the Q(V) characteristic, the maximal voltage should be set close (to avoid unnecessary control action) but below the planning limits to ensure compliance under all the conditions. A reserve of 1% is proposed ($U_{max} = U_{lim} - 1\%$).

(vii) The use of a dead-band appears to be a positive feature from both the network and inverter point of view, avoiding unnecessary control actions.

(viii) The investigated case ‘location-based dead-band’ leads to slightly better voltage profiles although the performance in terms of reactive energy balance and network losses is similar to other cases. Even if this approach of setting a dead-band according to the network strength may appear to be more fair (not only generators at the end of the feeders are requested to contribute), its practical implementation is not straightforward. Indeed, by adjusting the dead-band according to the impedance (or sensitivity factor) at the point of connection, changes in the network such as feeder reconfiguration, network reinforcement and network extension would mean that the settings would need to be modified.

Prog. Photovolt: Res. Appl. (2011) © 2011 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

Because of the limited advantages of this solution against the more complex implementation, this solution is not recommended.

(ix) The problem of voltage control is not symmetrical. Indeed, because of the historical development (small amounts of generation until recently), DNOs have usually allocated a larger part of the available voltage band to loads and a smaller part to generators. The mitigation of under-voltage cannot be guaranteed due to the fact that under-voltage usually occurs when PV generation is low or zero. On the contrary, the mitigation of over-voltage can always, at least partly, be compensated by reactive power consumption from PV generators for they are the cause of the over-voltage. The effectiveness of this compensation can be easily estimated. For this reason, it could be meaningful to define unsymmetrical control characteristics (dotted line on Figure 16) or even use only half of the characteristic (over-voltage part only).

(x) Even if, as previously explained, the differences between the considered settings are rather limited, the following settings are proposed on the basis of the presented investigations:
- Voltage set-point: 1.05 p.u. (nominal voltage in this network)
- Maximal voltage: 1.09 p.u. (1% below the planning limit)
- Dead-band: 2%
- Minimal power factor: 0.90
- Resulting droop factor: 24.2

This work has shown that the use of a reactive power control for maintaining the voltage within the statutory limits can be an effective solution. Although the demonstration phase of the MetaPV project will allow validating these results, further studies with other types of networks and other configurations would allow validating these findings on a broader basis.

ACKNOWLEDGEMENT

The authors acknowledge the co-funding of the European Commission in the 7th Framework Programme (FP7) through grant agreement No TREN/FP7EN/239511/METAPV.

REFERENCES

1. Global market outlook for photovoltaics until 2015. European Photovoltaic Industry Association.
2. EN 50160:2011, Voltage characteristics of electricity supplied by public distribution networks.
3. Schwaegerl C, Bollen MHJ, Karoui K, Yagmur A. Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources. 18th International Conference on Electricity Distribution Turin, 6–9 June 2005.
4. MetaPV, Deliverable D3.1, Existing and Expectable bottlenecks for the integration of large PV generations amounts, Brussels, 2011. www.MetaPV.eu
5. Bletterie B, Gorsek A, Uljanic B, *et al.* Enhancement of the network hosting capacity – Clearing space for/with PV. *25th European Photovoltaic Solar Energy Conference and Exhibition*, Valencia, Spain, 6–10 September 2010; 4828–4834. ISBN: 3-936338-26-4, DOI: 10.4229/25thEUPVSEC2010-5AO.7.3T.
6. Bletterie B, Brunner H, Prüggler W. Aktiver Betrieb von elektrischen Verteilnetzen mit hohem Anteil dezentraler Stromerzeugung—Konzeption von Demonstrationsnetzen, DG DemoNet Project, BMVIT, Vienna, 2009
7. Kerber G, Witzmann R, Sappl, H. Voltage limitation by autonomous reactive power control of grid connected photovoltaic inverters. *Compatibility and Power Electronics, 2009. CPE '09*, Badajoz, 20–22 May 2009; 129–133. DOI: 10.1109/CPE.2009.5156024
8. Stetz T, Yan W, Braun M. Voltage control in distribution systems with high level PV-penetration—Improving absorption capacity for PV systems by reactive power supply. *25th European Photovoltaic Solar Energy Conference and Exhibition and 5th World Conference on Photovoltaic Energy Conversion*, Valencia, Spain, 6–10 September 2010. DOI: 10.4229/25thEUPVSEC2010-5BV.4.17
9. Technical Guideline—Generating Plants Connected to the Medium-Voltage Network. Guideline for generating plants' connection to and parallel operation with the medium-voltage network. BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., June 2008
10. Stetz T, Künschner J, Braun M, Engel B. Cost Optimal Sizing of Photovoltaic Inverters—Influence of New Grid Codes and Cost Reductions. *25th European Photovoltaic Solar Energy Conference and Exhibition and 5th World Conference on Photovoltaic Energy Conversion*, Valencia, Spain, 6–10 September 2010; 4633–4639. DOI: 10.4229/25thEUPVSEC2010-4BV.1.76
11. Fawzy T, Premm D, Bletterie B, Goršek A. Active contribution of PV inverters to voltage control—From a Smart Grids vision to a full-scale implementation. *e & i Elektrotechnik und Informationstechnik* 2011; **128**(4): 110–115. DOI: 10.1007/s00502-011-0820-z

Publication 3

"Statistical analysis of the deployment potential of Smart Grids solutions to enhance the hosting capacity of LV networks"

B. Bletterie, S. Kadam, A. Abart, and R. Priewasser, "Statistical analysis of the deployment potential of Smart Grids solutions to enhance the hosting capacity of LV networks," in Proc. 14. Symposium Energieinnovation, Graz, 2016.

Own contribution

This paper presents the results of a comprehensive statistical analysis of a large set of low voltage networks provided by two Austrian distribution network operators, with the objective to evaluate the potential of smart grids solutions to enhance the hosting capacity.

The results summarised in this article emerged mainly out of the European project IGREENGrid (FP7 - Project ID 308864) in which the applicant was one of the key researcher.

The applicant initiated and coordinated the research with the distribution system operators (data gathering, validation, analysis). Based on the simulations performed under his supervision by the second author, he performed the statistical analyses presented in the paper and presented the results to the distribution system operators for approval before writing the paper.

14. Symposium Energieinnovation, 10.-12.02.2016, Graz/Austria

Statistical analysis of the deployment potential of Smart Grids solutions to enhance the hosting capacity of LV networks

Benoît Bletterie[1], Serdar Kadam[1], Andreas Abart[2] Robert Priewasser[3]

[1]AIT Austrian Institute of Technology, Giefinggasse 2, 1210 Wien, benoit.bletterie@ait.ac.at,
[2]Netz Oberösterreich GmbH, Bahnhofstrasse 67, 4810 Gmunden
[3]Salzburg Netz GmbH, Bayerhamerstraße 16, 5020 Salzburg

Abstract: Several smart grids solutions to enhance the hosting capacity of LV networks have been proposed, investigated and successfully demonstrated. However, the real deployment potential remains unknown, which is a barrier to a systematic use of them by distribution network operators. This paper presents the results of the work done in the project IGREENGrid on the quantification of the potential of smart grids solutions in LV networks on the basis of a comprehensive statistical analysis of real datasets from two network operators. This work shows a moderate potential for reactive power-based voltage control and a significant potential for voltage regulated distribution transformer in the considered areas.

Keywords: Smart grids, scalability and replicability, voltage control, low voltage networks

1 Introduction

With the massive development of distributed renewable energy sources (DRES) in the last 15 years, the hosting capacity of distribution networks has been exhausted in some areas. In order to efficiently integrate this new generation into distribution networks, alternative solutions to network reinforcement (smart grids solutions) have been proposed in the last years. Voltage rise is often considered to be the main constraint limiting the hosting capacity. Many R&D efforts have been therefore devoted to the development of novel voltage control concepts [1][2]. While some of these concepts have been successfully tested under real conditions in various demonstrators [3], they remain at the case-study or pilot stage and their real potential for large scale deployment has not been fully studied so far.

On the one hand, the actual hosting capacity of low voltage (LV) networks is usually badly known. This is mainly due to their number, the number of loads connected to them and the general lack of detailed network models, making it difficult to estimate the hosting capacity of the potential of smart grids solutions to enhance it. On the other hand, a significant part of the installed photovoltaic capacity is connected to low voltage networks (e.g. about 70 % in Germany [4]), which justifies the need to have a better knowledge of low voltage networks.

Due to the very large number of LV networks, dedicated studies are not possible and statistical analysis are necessary. Considering the sustained growth of DER, the question of the actual replicability potential of smart grids solutions is raised and an answer is expected from different stakeholders (e.g. distribution system operators (DSOs), industry providers). In this context, the European project IGREENGrid [5] aims at assessing in a standardized way the replicability potential of smart grids solutions.

Due to the fact that the diversity of feeders among networks is very high (one network might have several very long feeders and a few very short feeders), the statistical analyses are performed at feeder level, which has also been proposed for example in [6].

The concept of hosting capacity introduced in [7] is restricted to the two most relevant limitations in distribution networks: the maximal admissible voltage rise and the maximal admissible loading. An illustration of this is shown on Figure 1.

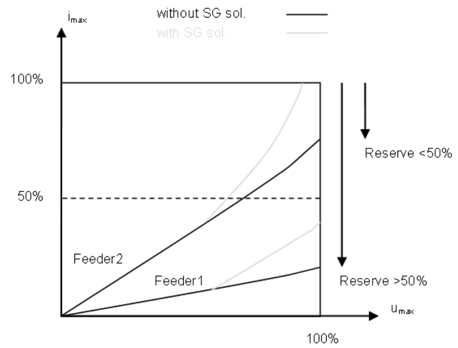


Figure 1 – Hosting capacity visualisation on the U-I plane

2 Method and data basis

In the framework of the project IGREENGrid, the LV networks of the two Austrian DSOs participating to the project (*Netz Oberösterreich GmbH* and *Salzburg Netz GmbH*) have been analysed extensively in order to evaluate the deployment potential of smart grids solutions. The data have been exported from the GIS-database and been imported into the simulation software DIgSILENT PowerFactory [8].

As explained in the introduction, the analysis of the LV networks has been done at feeder level. The first step has therefore been to define automatically feeders for each LV network and to run a series of automated scripts to verify the coherence of the data imported from the GIS-export. Among others, the validation included verifications on the following properties:

- Radiality
- Minimal short-circuit impedance
- Maximal geographical distance between nodes

After this initial validation, a set of about 11.000 LV networks and 37.000 LV feeders was available.

In order to characterise LV feeders and to quantify the potential deployment of smart grids solutions, suitable indicators have been introduced.

- Descriptive statistics-indicators
- Hosting capacity related indicators

The descriptive statistics-indicators include for example the short-circuit impedance at the weakest node, the R/X ratio, the feeder length, the equivalent sum impedance [9], the number of lines and network connections, the average number of and distance to neighbours, the mesh-factor…

The hosting capacity related indicators are based on a calculation of the hosting capacity for specific scenarios (assumptions). One of the basic assumptions is the distribution of the generation along the feeder (DRES scenario). In this work, 3 scenarios were defined for this purpose. They are briefly defined below, using the example of the indicator hosting capacity:

- "uniform": generation placed uniformly along the feeder (at all connection boxes) and then scaled-up to reach the hosting capacity (loading limit or voltage limit is reached).
- "weighted": generation distributed according to the summed annual consumption at the connection boxes) and then scaled-up to reach the hosting capacity. This scenario is relevant when assuming that most of the further DRES deployment will be close to the loads and driven by self-consumption.
- "eof" ("end of feeder"): generation connected at the "end node" which is defined as the node with the highest voltage for the uniform scenario.

Beside the DRES scenarios, smart grids solutions have been considered in a simple way:

- Reactive power-based voltage control (cosφ(P) and Q(U))
- Voltage band extension through the use of voltage regulated distribution transformer VRDT (transformer with On-Load-Tap-Changer (OLTC))

The control-cosφ(P) has been parametrised according to [10] and the Q(U)-control has been according to recommendations from previous projects [11], [12]. In order to investigate the benefits of a voltage regulated distribution transformer, the voltage limits have been extended as proposed in [13] (sensitivity analysis of the impact of the allowed voltage rise on the hosting capacity). Current connection rules [14], [15] foresee a maximal voltage rise of 3 % for the generation embedded in the LV network. In the sensitivity analysis on the impact of the voltage band on the hosting capacity, the maximal voltage rise has been increased up to +8 %. This value of 8 % has been chosen considering that a VRDT allows decoupling the LV from the MV network in terms of voltage level. With an equal allocation of the voltage band to loads (voltage drop) and generation (voltage rise) and a controller dead-band of ±2 %, the maximal voltage rise can be extended to +8 %.

For each of these scenarios, the indicators (e.g. hosting capacity) have been evaluated. Note that loads have not been considered in this work and that the generation is considered to be symmetrical (possible mitigation measures to voltage unbalance caused by unsymmetrical generation can be found in [16]–[19]).

3 Deployment potential of smart grids solutions

This section summarises the most interesting results of the analyses of the hosting capacity of LV feeders. In a first sub-section, a general characterisation of the LV feeders is done one their behaviour when reaching the hosting capacity.

3.1 Basic relevance of voltage control solutions

Figure 2 shows the location of the LV feeders on the U-I place (see Figure 1) for the dataset from the DSO1. The x-axis shows the maximal voltage and the y-axis the maximal loading. The planning limits considered here are 3 % voltage rise and 100 % loading). Each point on the main part of the graphic represents a feeder. The colouring is done according to the constraint reached first: blue if the voltage-constraint is reached first and red if the current-constraint is reached first. This colouring has been used in the whole paper.

The left part and the lower part of the diagram show the marginal distribution of the feeders (according to the maximal lading and voltage respectively). This figure shows that about 90 % of the feeders are voltage-constrained. In addition, this figure shows that most of the voltage-constrained feeders (blue) are far from the upper-right corner (voltage and current constraint): the maximal loading of most of the voltage-constrained feeders is not too close to the 100 %-limit. For 50 % of the voltage-constrained feeders, the maximal loading is below 37 % which means that there is a significant reserve to the over-loading. This means that there is, a priory, a large deployment potential of smart grids solutions aiming at controlling the voltage without taking the risk or reaching the overloading, which is unobserved in the considered solutions.

Figure 3 shows the same results for the DSO2. A comparison between Figure 2 and Figure 3 shows that the share of current-constrained feeder is more than twice larger for DSO2 which is due to the characteristic of the supplied area (significantly larger share of urban area). Further analyses showed that the impact of the DRES scenario (“uniform”, “weighted” and “eof”) is rather small.

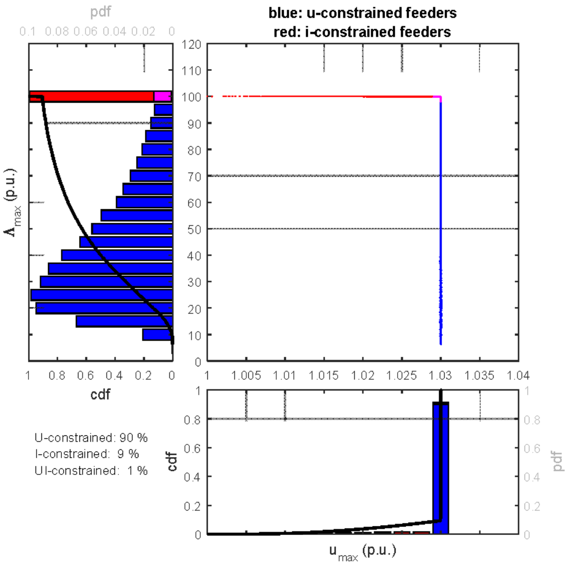


Figure 2 – Share of voltage and current-constrained feeders – DSO1

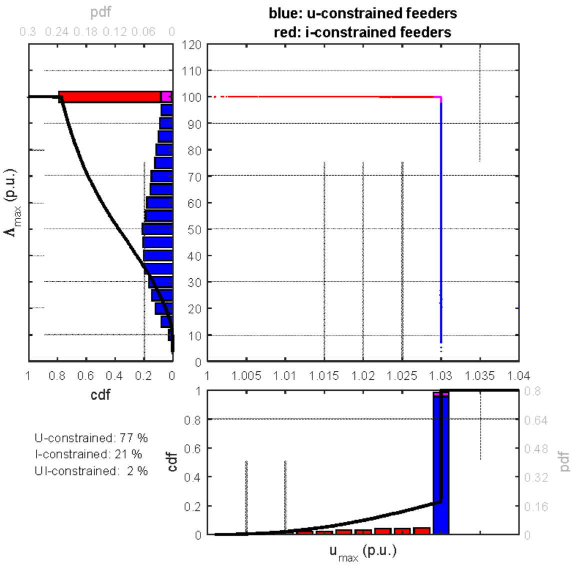


Figure 3 – Share of voltage and current-constrained feeders – DSO1

3.2 Deployment potential of voltage regulated distribution transformers

Figure 4 shows the result of a sensitivity analysis run to investigate the impact of the allowed voltage rise on the share of voltage and current-constrained feeders for the DRES scenario “uniform”. For this, the maximal voltage has been changed from 1.01 p.u. to 1.08 p.u. (meaning in fact that the allowed voltage rise has been varied between +1 % and +8 %).

As expected, the share of voltage-constrained feeders decreases when the allowed voltage rise increases. When doubling the voltage rise allowed according to current planning rules [14], [15] (+3 %), the share of voltage and current-constrained feeders changes from 90 % / 10 % to 60 % / 40 %. The extension of the allowed voltage rise to +8 % would correspond to a scenario in which all the secondary substations have a voltage regulated distribution transformers, reserving a voltage dead-band of ±2 %. In such as case, about 43 % of the feeders would still be voltage-constrained. In other words, this means that the maximal increase of the hosting capacity offered by a voltage regulated distribution transformers can be actually used in about 43 % of the feeders (large share due to the fact that most of the supplied area is rural).

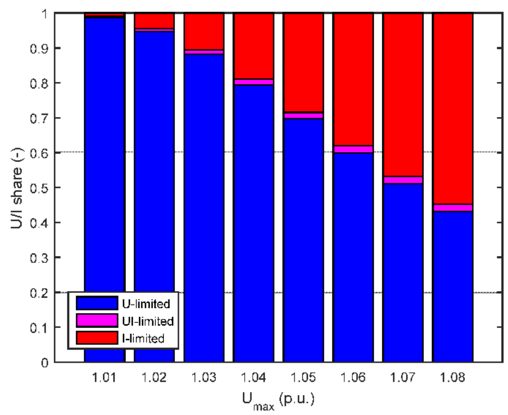


Figure 4 – Share of voltage and current-constrained feeders – sensitivity on the voltage band – DSO1

The average feeder hosting capacity increases for feeders which remain voltage-constrained from about 44 kW to 123 kW (+179 %) when increasing the allowed voltage rise from +3 % to +8 %. In other words, the expectancy value of the hosting capacity increase for an extension of the voltage band for feeders which can actually benefit from it is very high: +179 %.

3.3 Deployment potential of reactive power-based voltage control

Reactive power-based local voltage control has been intensively investigated in the last years [20]–[22]. The most two common forms of controlling the voltage according to current standards are cosφ(P) [10], [14] and Q(U) [23]. Before going into the details of the type of control, the basic benefits of reactive power-based voltage control has been evaluated.

Figure 5 shows the hosting capacity increase with cosφ=0.90 compared to the reference hosting capacity (without reactive power control). According to this figure, the expected hosting capacity increase

- exceeds +30 % for about 17 % of the feeders
- is between +20 % and 30 % for about 28 % of the feeders
- is below +20 % for about 31 % of the feeders
- is negative (decrease) for about 14 % of the feeders

Figure 5 should however be carefully interpreted since it does not take into account the constraint corresponding to the operation with reactive power control. The actual benefit of reactive power control should, only be evaluated for feeders remaining voltage-constrained when considering that the loading is unobserved. The inflexion point at a hosting capacity of about 23 % corresponds to 150 mm2 cables having a R/X ratio of 2.6 which leads to a hosting capacity increase of about 23 % at cosφ=0.90.

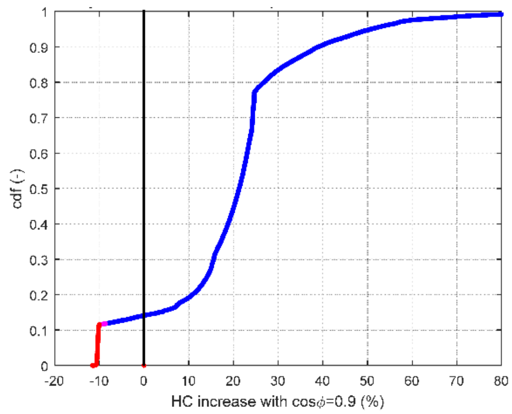


Figure 5 – Hosting capacity increase with cosφ=0.90 – DSO1

Figure 6 shows the distribution of the hosting capacity without reactive power control (x-axis) and with reactive power control (y-axis). The reactive power control implemented is a cosφ(P) control according to [10] and the colouring is done individually for both cases.

Figure 6 shows as expected an increase of current-constrained feeders. The full potential offered by reactive power control (cosφ=0.90) can be actually used in 81 % of the feeders (which remain voltage-constrained with reactive power control) and leads to an average increase of the hosting capacity by about +25 % (increase of the average feeder hosting capacity from 63 kW to 79 kW). In other words, the expectancy value of the hosting capacity increase for reactive power control for feeders which can actually benefit from it is moderate compared to the voltage band extension: +25 %. Note that transformers are not considered here and can lead in some cases to a non-negligible contribution (about 1 percentage point [12]). For the DSO2, the potential of reactive power-based voltage control is limited to 61 % of the LV feeders and represents on average an increase of hosting capacity of about +23 % (increase of the average feeder hosting capacity from 88 kW to 108 kW).

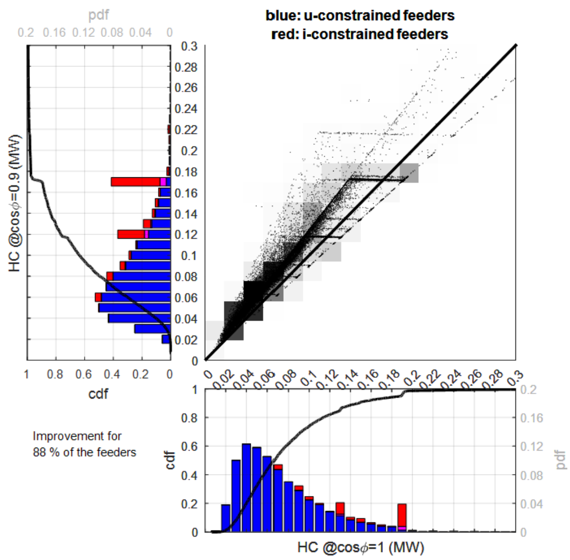


Figure 6 – Hosting capacity increase cosφ=0.90 vs. cosφ=1.0 – DSO1

Figure 7 shows a comparison between the effectiveness of the Q(U) and the cosφ(P) control. The Q(U) control generally leads to a lower reactive power consumption since reactive power is only consumed when the voltage is actually high. However, the effectiveness of the Q(U)-control is necessarily lower than the effectiveness of the cosφ(P) control since not all the generators are fully contributing (only those at the end of the feeder).

Figure 7 shows that for most (95 %) of the voltage-constrained feeders, the effectiveness of the Q(U) is not significantly lower (<4 %) than the effectiveness of the cosφ(P). This means that the difference between both controls in terms of effectiveness is very small and confirms previous work on this [11].

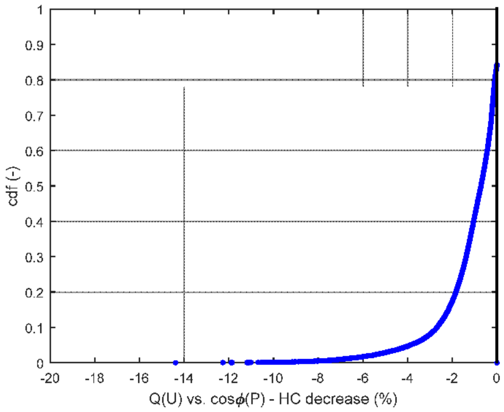


Figure 7 – Hosting capacity increase with reactive power control: Q(U) vs. cosφ(P) – DSO1

4 Conclusions and outlook

Conclusions

The work done in the framework of the project IGREENGrid allowed quantifying the basic deployment potential of smart grids solutions in LV feeders. Of course, another major component which has not been considered here is the actual expected DRES penetration: the actual need to deploy smart grids solutions (or to reinforce the network when cheaper) will be determined by the actual DRES penetration.

The two smart grids solutions considered in this study (voltage band extension through the use of voltage regulated distribution transformer and reactive power-based voltage control) are purely distributed solutions which only control the voltage without any “centralised” observer. For this reason, they should be only implemented in feeders which are “clearly” voltage-constrained. For this reason, the evaluation was done according to criteria:

- identification of the feeders which can actually benefit from these solutions (“clearly” voltage constrained feeders)
- quantification of the benefits in terms of hosting capacity increase.

The very first analysis of the feeder behaviour shows a large dominance of voltage-constrained feeders against current-constrained feeders (ratio 90 %/10 % for DSO1 and 77 % / 23 % for DSO2). On this basis, the general deployment potential of smart grids solutions aiming at controlling the voltage to increase the hosting capacity can be expected to be high. While the DRES scenario (distribution of the generation along the feeder) has of course strong impact on the hosting capacity (especially for voltage-constrained feeders), it proved to have a rather limited impact on the feeder behaviour (e.g. share of voltage and current-constrained feeders).

The full potential offered by a VRDT (more than doubling of the available voltage band) can be actually used in 43 % of the feeders (which remain voltage-constrained) for DSO1 and 21 % of the feeders for DSO2. The use of a VRDT leads on average to increase of the hosting capacity by about +179 % for DSO1 and DSO2. This replication potential (43 % and 21 % respectively) might appear to be small but it stands for feeders which can benefit of the full potential offered by a VRDT (i.e. an extension of the voltage band by 5 % here). For a smaller voltage band extension, the share of feeders remaining voltage-constrained and therefore benefiting from it increases.

The full potential offered by reactive power control (cosφ(P)) can be actually used in 81 % of the feeders for DSO1 and 61 % for DSO2 (feeder remaining voltage-constrained with reactive power control) and leads to an average increase of the hosting capacity by about +25 % for both DSOs.

Outlook

This study is based on a very large number of scenarios and simulations to evaluate the hosting capacity and the deployment potential of smart grids solutions. It does not consider the DRES potential in each feeder. Even when having data allowing to estimate the DRES potential (e.g. available roof area), numerous assumptions are still needed to convert this potential in DRES penetration. Despite the complexity of this work, it can be highly automated and an additional added value is expected.

This paper only considered the purely technical aspects of the considered smart grids solutions. The final decision on deploying smart grids solutions will be dictated by the economic performance of these solutions against the network reinforcement.

Another major part of the work done on the deployment potential of smart grids solutions in LV networks in the framework of the project IGREENGrid has been the attempt to classify LV feeders on the basis of the indicators mentioned in section 2. For MV networks, an extensive analysis has been conducted on a set of 29 representative networks from 8 European DSOs. The results of this work will be presented in the near future.

Acknowledgment

This work as partly done within the project IGREENGrid which has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 308864.

References

[1] T. Stetz, K. Diwold, M. Kraiczy, D. Geibel, S. Schmidt, and M. Braun, 'Techno-Economic Assessment of Voltage Control Strategies in Low Voltage Grids', *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 2125–2132, Jul. 2014.
[2] M. H. J. Bollen and A. Sannino, 'Voltage Control With Inverter-Based Distributed Generation', *IEEE Trans. Power Deliv.*, vol. 20, no. 1, pp. 519–520, Jan. 2005.
[3] A. Einfalt, F. Zeilinger, R. Schwalbe, B. Bletterie, and S. Kadam, 'Controlling active low voltage distribution grids with minimum efforts on costs and engineering', in *Proc. Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE*, 2013, pp. 7456–7461.
[4] Stetz, 'Autonomous Voltage Control Strategies in Distribution Grids with Photovoltaic Systems: Technical and Economic Assessment', Kassel University press GmbH, 2014.
[5] 'IGREENGrid - Home'. [Online]. Available: http://www.igreengrid-fp7.eu/. [Accessed: 23-Sep-2015].
[6] G. Walker, H. Nägele, F. Kniehl, A. Probst, M. Brunner, and S. Tenbohlen, 'An application of cluster reference grids for an optimized grid simulation', in *Proc. CIRED 23rd International Conference on Electricity DistributionProc. CIRED 23rd International Conference on Electricity Distribution*, Lyon, 2015.
[7] C. Schwaegerl, M. H. J. Bollen, K. Karoui, and A. Yagmur, 'Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources', in *Proc. Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on*, 2005, pp. 1–5.
[8] 'PowerFactory - DIgSILENT Germany'. [Online]. Available: http://www.digsilent.de/index.php/products-powerfactory.html. [Accessed: 06-Nov-2015].
[9] Kerber, 'Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen', 2011.
[10] VDE-FNN, 'VDE-AR-N 4105:2011-08 Power generation systems connected to the low-voltage distribution network'. Aug-2011.
[11] S. Kadam, B. Bletterie, G. Lauss, M. Heidl, C. Winter, D. Hanek, and A. Abart, 'Evaluation of voltage control algorithms in smart grids: results of the project: morePV2grid', in *Proc. 29th European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, 2014.
[12] M. Heidl, 'morePV2grid - More functionalities for increased integration of PV into grid', Dec. 2013.
[13] B. Bletterie, J. Le Baut, S. Kadam, R. Bolgaryn, and A. Abart, 'Hosting capacity of LV networks with extended voltage band', in *Proc. 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*, Vienna, 2015.
[14] E-CONTROL, 'Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen'. 2013.
[15] E-CONTROL, 'Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt2: Richtlinie zur Beurteilung von Netzrückwirkungen'. Sep-2006.
[16] G. Roupioz, X. Robe, and F. Gorgette, 'First use of smart grid data in distribution network planning', in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[17] B. Bletterie, S. Kadam, R. Pitz, and A. Abart, 'Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters', in *Proc. PowerTech 2013 IEEE Grenoble*, 2013, pp. 1–6.
[18] R. D. Lazar and A. Constantin, 'Voltage balancing in LV residential networks by means of three phase PV inverters', in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4068 – 4071.
[19] B. Bletterie, S. Kadam, A. Zegers, and Z. Miletic, 'On the effectiveness of voltage control with PV inverters in unbalanced low voltage networks', in *Proc. Electricity Distribution (CIRED 2015), 23rd International Conference and Exhibition on*, Lyon, 2015.
[20] T. Stetz, F. Marten, and M. Braun, 'Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany', *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 534–542, Apr. 2013.
[21] B. Bletterie, A. Goršek, T. Fawzy, D. Premm, W. Deprez, F. Truyens, A. Woyte, B. Blazič, and B. Uljanič, 'Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks', *Prog. Photovolt. Res. Appl.*, vol. 20, no. 6, pp. 747–759, Sep. 2012.
[22] E. Demirok, P. C. González, K. H. B. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, 'Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids', *IEEE J. Photovolt.*, vol. 1, no. 2, pp. 174–182, Oct. 2011.
[23] E-CONTROL, 'Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen'. Oct-2015.

Publication 4

"On the classification of low voltage feeders for network planning and hosting capacity studies"

B. Bletterie, S. Kadam, and H. Renner, "On the Classification of Low Voltage Feeders for Network Planning and Hosting Capacity Studies," Energies, vol. 11, no. 3, p. 651, Mar. 2018.

Own contribution

This paper presents the results of an attempt to predict the hosting capacity constraint (voltage or current) of low voltage feeders and to classify them.

The results summarised in this article emerged mainly out of the European project IGREENGrid (FP7 - Project ID 308864) in which the applicant was one of the key researcher.

The applicant initiated and coordinated the research with the distribution system operators (data gathering, validation, analysis). Based on the simulations performed under his supervision by the second author, he tested and implemented several machine learning methods and wrote most of the paper.

energies

MDPI

Article

On the Classification of Low Voltage Feeders for Network Planning and Hosting Capacity Studies

Benoît Bletterie [1,*], Serdar Kadam [1] and Herwig Renner [2,*]

1 Electric Energy Systems, Center for Energy, Austrian Institute of Technology, Vienna 1210, Austria; serdar.kadam@ait.ac.at
2 Institute of Electrical Power Systems, Faculty of Electrical and Information Engineering, Graz University of Technology, Graz 8010, Austria
* Correspondence: benoit.bletterie@gmail.com or benoit.bletterie@apg.at (B.B.); herwig.renner@tugraz.at (H.R.); Tel.: +43-664-88342832 (B.B.)

Received: 14 February 2018; Accepted: 12 March 2018; Published: 14 March 2018

Abstract: The integration of large amounts of generation into distribution networks faces some limitations. By deploying reactive power-based voltage control concepts (e.g., volt/var control with distributed generators), the voltage rise caused by generators can be partly mitigated. As a result, the network hosting capacity can be accordingly increased, and costly network reinforcement might be avoided or postponed. This works however only for voltage-constrained feeders (opposed to current-constrained feeders). Due to the low level of monitoring in low voltage networks, it is important to be able to classify feeders according to the expected constraint in order to avoid the overloading risk. The main purpose of this paper is to investigate to which extent it is possible to predict the hosting capacity constraint (voltage or current) of low voltage feeders on the basis of a large network data set. Two machine-learning techniques have been implemented and compared: clustering (unsupervised) and classification (supervised). The results show that the general performance of the classification or clustering algorithms might be considered as rather poor at a first glance, reflecting the diversity of real low voltage feeders. However, a detailed analysis shows that the benefit of the classification is significant.

Keywords: hosting capacity; reactive power; voltage control; low voltage feeders; classification

1. Introduction

In order to meet long-term objectives in terms of CO_2 emissions reduction and supply security, the share of renewable generation in the European electricity mix has been steadily growing in the last 10–15 years and must increase further. In particular, wind and solar photovoltaic (PV) power have established themselves as ones of the most promising renewable energy resources, providing a non-negligible share of the overall generation in some regions. This renewable generation has been integrated at the transmission level for the largest wind parks or at distribution level, for most of wind and PV generation. This evolution of the power system results for example in reverse power flows and new power infeed present down to the low voltage level.

However, the integration of large amounts of generation into distribution networks faces some limitations and in some networks the hosting capacity is exhausted [1]. The main two constraints that usually limit the amount of generation that can be hosted by distribution feeders are the maximum admissible voltage and currents. In particular, the voltage rise caused by the power infeed from distributed generators is often considered as one of the most limiting constraints [2]. Having recognised this problem, connection standards or guidelines have been published in most European countries (e.g., [3–5] in Germany and Austria). Besides specifying clear and transparent rules to assess the connection of generation to the distribution network, these guidelines have introduced new possibilities

Energies **2018**, *11*, 651; doi:10.3390/en11030651 www.mdpi.com/journal/energies

or new requirements. These new possibilities (smart grid solutions) allow using new functionalities of modern generators for a more cost-effective network integration of the generation. In particular, several voltage control options based on reactive power (volt/var control), have been proposed in different standards. By implementing voltage control with e.g., distributed generators, the voltage rise caused by the power infeed can be partly mitigated, and the network hosting capacity can be increased accordingly. As a result, costly network reinforcement might be avoided or postponed.

Almost 10 years after the introduction of new requirements for generators in the connection guidelines or standards, the added value of these new features offered by modern generators are only used to a limited extent. One of the reasons for this limited deployment is probably the fact that, despite the large number of research works on e.g., voltage control and reactive power control, clear practical deployment recommendations are missing.

In particular, the actual potential of some smart grid solutions has not been analyzed on a systematic way. Many research efforts have been devoted to develop new control concepts which are more or less complex [6–8], and to investigate their performance, often on the basis of a case-study. In order to be able to conclude regarding the general performance (e.g., achievable hosting capacity increase) and potential (e.g., share of feeders with a substantial benefit) of a specific control, "representative" (wording see Table 1) networks are necessary.

In this context, the search for "representative" networks has been addressed in several works in the last years. Table 1 provides an overview of the main characteristics of the previous works in this field: the scope, the objective, the data set used, the statistical method, the number of parameters and the number of clusters.

A close look at the relevant studies around the topic of feeder classification shows a rather inhomogeneous picture, as visible with the wording which is used (see "target" in Table 1, e.g., "generic", "typical", "reference", "representative", "prototypal", "common" or "benchmark"). Despite this diversity in the wording, most of these studies have the same basic objective: to identify a set of "typical/representative" feeders to perform "generic" network studies.

Moreover, the vast majority of these studies use a clustering analysis to identify these "representative" feeders despite the inaccurate wording (e.g., confusion between clustering and classification—see Section 2.2). In all the studies using clustering, the popular k-means algorithm has been used. While about half of the studies mentioned in Table 1 were dedicated to LV voltage and half to MV voltage, a fundamental difference between these studies is the system boundary. Most of the studies (eight) considered feeders while the others (four) considered networks as observations. Due to the potential large inhomogeneity of feeders belonging to a same network (a primary substation can for example supply purely urban feeders and purely rural feeders at the same time), a classification at feeder level appears to be more pertinent. This approach has been, as previously mentioned, followed by most of the studies analyzed.

Another important difference between the studies on feeder classification is the size of the data set used as input (from less than 200 [9] to about 88,000 [10], see Table 1). As presented in Section 2.1, about 24,000 feeders have been used in this study, which corresponds to the upper range of the previous studies.

One of the most important parameters of clustering is the number of clusters, which needs to be set for k-means clustering at the beginning. In the considered studies, different metrics have been used to quantify the clustering performance and select the "optimal" or "appropriate" number of clusters. More information is presented in Section 2.2.2. The number of clusters specified in the considered studies varies from three to 35, with a median of five clusters. In this study, similar criteria have been used to try to select a suitable number of clusters, and the best trade-off has been obtained for less than 10 clusters. However, a difference between this and the other studies was the main classification objective: to identify with the highest possible confidence the constraint limiting the hosting capacity of LV feeders (voltage or current constraint). For this reason, the clusters (disregarding their numbers) have been mapped into the two categories. The detailed methodology used for the clustering is presented in Sections 2.2.2 and 3.4.

Table 1. Main characteristics of existing studies on distribution feeder/network classification.

Study	Scope	Target	Data Set	Statistical Method [1]	# of Param.	# of Clusters
Willis et al., 1985 [11] (US)	MV feeders	"representative feeders"	1350	k-means	11	10
Schneider et al., 2008 [12] (US)	MV feeders	"prototypal feeders"	575	hierarchical	35	24
Nijhuis et al., 2015 [10] (NL)	LV feeders	"most common types of feeders"	88,000	fuzzy k-medians	945→8 [2]	8
Kerber, 2011 [13]/ Lindner et al., 2016 [14] (DE)	LV networks	"reference networks"	86/358	"qualitative and statistical analysis"	3	7/5
dena, 2012 [15] (DE)	LV and MV networks	"network area classes"	LV: 177 MV [3]: 20	k-means	4	11 [4]
Dickert et al., 2013 [16] (DE)	LV feeders	"benchmark feeders"	n/a	k-means	6	18
Broderick und Williams, 2013 [17] (US)	MV feeders	"representative feeders	3 000	k-means	12 [5]	22
Gust, 2014 [18] (DE)	LV networks	"reference networks"	203	k-medoids	4	20
Cale et al., 2014 [19] (US)	MV feeders	"representative feeders"	1295	k-medoids/random forest	16	12
Li und Wolfs, 2014 [20] (AU)	LV and MV feeders	"representative feeders"	LV: 8858 MV: 204	hierarchical	LV: 7 MV: 6	LV: 8 MV: 9
Walker et al., 2015 [21] (DE)	LV networks	"cluster reference grids"	>20,000	k-means	5 [5]	10
Dehghani et al., 2015 [9] (IR)	MV feeders	"representative feeders"	195	self-organized maps	7 [5]	9

[1] Further methods are additionally used in some cases (e.g., principal component analysis in [17,19] for visualization purpose); [2] A large number of clusters has been selected (94). Feeder properties have been only provided for the 8 largest clusters (representing only about one third of the whole population of feeders); [3] HV networks have also been considered (out of scope here); [4] The clusters are further grouped within five load density areas; [5] after parameter reduction (based on e.g., correlation analysis).

Regarding the input data, the previous studies differed significantly in terms of feeder parameters (variables) used for the clustering. However, a common group of parameters used in several studies has been identified:

- average distance between nodes
- average impedance at the point of connection
- total cable length
- feeder length
- cable or line rating

These parameters, together with many others have been used in this study. The whole set of parameters as well as a correlation analysis are presented in Sections 2.1 and 3.1. Finally, the vast majority of the previous studies did not perform a full validation of the clustering results. Even if the clustering results themselves are good, it is of prime importance to ensure that the clustering results are relevant for the considered question, in our case the distinction between voltage and current-constrained feeders. In this study, the feeder category (in our case voltage and current-constrained feeders) is known since the hosting capacity has been determined (see Section 2.1). This information has been used as an input for the classification (see Sections 2.2.3 and 3.3) or as external validation for the clustering (see Sections 2.2.2 and 3.4).

The main purpose of this paper is to investigate to which extent it is possible to predict the behavior of LV feeders in terms of hosting capacity constraint (voltage or current constraint) on the basis of a large set of real LV feeders. The main motivation behind this work is to allow DSOs to easily discriminate between LV feeders in which reactive power-based voltage control can help in increasing the hosting capacity, and LV feeders for which reactive power control would be counterproductive.

Two machine-learning techniques are implemented and compared: clustering (used in most of the previous studies) and classification. The results show that the general performance of the classification or clustering algorithms is limited and might even be considered as rather poor at a first glance. All the data exploration attempts showed that the feeder population exhibit continuous distributions and that no natural cluster structure has been observed.

However, even with a rather poor general performance, the added value of the feeder classification can be considered to be significant. By reliably identifying a sub-group of the feeders (voltage-constrained feeders) with a high confidence level (sensitivity close to 100%), voltage control concepts can be deployed by DSOs in the target networks, without the need for additional studies.

2. Method and Data Set

The method followed in this study is mainly used on data analysis and statistical methods. The basic research design is based on explanatory research following the objective to formulate a posteriori hypotheses by analyzing the data with different data exploration techniques.

The data used in this study consists in a large dataset of real low voltage networks as explained in Section 2.1. Before performing the main part of the analysis (classification and clustering), several data processing-steps have been necessary. An overview of all these steps is provided in Section 2.2. This subsection presents in particular the core of the analysis based on the two machine learning techniques (classification and clustering) with more details (Sections 2.2.2 and 2.2.3).

2.1. Available Data Set

The analyses presented in this paper have been performed on a set of about 7300 low voltage networks from a DSO supplying a geographical area in Austria which is dominantly rural. The data has been collected and pre-validated in the frame of the IGREENGrid project [22,23].

The network data have been exported from the geographical information systems (GIS) of the DSO and imported into the simulation software DIgSILENT PowerFactory [24] with the exchange format DGS. The automation of the data import and pre-validation has been implemented in the DIgSILENT Programming Language (DPL) and in Python [25]. In addition, load-related data (e.g., annual elecctricity consumption) has been obtained from other data sources such as metering databases.

As a first step after the data import, feeders have been defined for each LV network and a set of automated scripts has been executed to validate the data. Feeders with unexpected properties (non-radial feeders, special purpose feeders) have been eliminated from the analysis, leading to a set of more than 24,000 LV feeders.

In a second step, two types of parameters have been computed for every single feeder:

- descriptive indicators or explanatory variables
- hosting capacity related indicators.

The purpose of the first type of indicators (descriptive indicators) is to provide variables to be used for the statistical analyses that are in the focus of this paper: clustering and classification. All these parameters can be computed with tools generally available for DSOs (e.g., GIS). The purpose of the second type of indicators is to provide some valuable quantitative information on the capacity of the investigated supply area to host distributed generation while fulfilling the planning criteria (see Section 1). A detailed analysis of the networks considering different scenarios in terms of e.g., generation distribution has been presented in [23] and is not in the scope of this paper.

In this paper, the focus is laid on classifying LV feeders. For this purpose, hosting capacity-related indicators have been used. The calculation of these hosting capacity-related parameters is more complex than the first type of parameters. For this, an adapted Newton-Raphson algorithm has been implemented in the simulation environment [26]. This tool increases the generation connected to the considered feeder until one of the planning limits (voltage or current constraint) is reached. The amount of generation obtained to reach this limit is considered as the feeder hosting capacity. For this hosting capacity computation, different scenarios have been considered. In this paper, only three scenarios that are related to the distribution of the generation along the feeders are considered: "uniform", "weighted" and "end of feeder—eof"). The scenario "uniform" assumes a uniform distribution of the generation long the feeder, the scenario "weighted" assumes that the size of the generator is proportional to the annual electricity consumption of the LV-customers (motivated by e.g., self-consumption) and the scenario "end of feeder" assumes that the generation is located at the end of the feeder, which represents a worst-case. For all these scenarios, load an generation are assumed to be balanced (equally distributed over the three phases) Further scenarios have been defined and analyzed in [23]—a complete overview of these scenarios is provided in [26].

The initial set of more than 80 parameters has been reduced to a subset of 12 parameters, which are considered to be relevant to characterize feeders in terms of hosting capacity, and in particular in terms of being prone to voltage or current constraints. This parameter set has been selected by reviewing the relevant literature (Table 1, [9–21]). These parameters are given in Table 2 and in the explanatory text below (Equations (1) to (3)).

Table 2. Feeder parameters (variables) to be used for the clustering analysis and the classification.

Feeder Parameter (Variable)	Description
ADTN	Average Distance To Neighbors (m)
ANON	Average Number of Neighbors (-)
LastBusDist.	Last Bus Distance: path length between secondary substation and the bus with the lowest voltage (last bus [1]) under the considered scenario [2] (m)
FeederLength	Feeder length: largest distance between the secondary substation and any of the busses (m)
TotLineLength	Algebraic sum of the cable or overhead line length in the whole feeder (m)
km/load	Quotient between TotLineLength and the number of loads in the feeder (km)
Rsc	short-circuit resistance at the last bus [2] (Ω)
Rsum	Equivalent sum resistance (real part of the impedeance): see explanation below and Equation (1) (Ω)
kWm	see Equation (2) (kWm)
kWΩ	see Equation (3) (kWΩ)
In_avg	Average rated current for all the cable or lines of the feeder (A)
In_max	Maximum rated current for all the cable or lines of the feeder (A)

[1] the "last bus" is the bus with the lowest voltage in the feeder under the considered scenario; [2] the three considered scenarios are: "uniform", "weighted", and "eof (end of feeder)".

The concept of equivalent sum-impedance *Rsum* which can be computed on the basis of the feeder topology and the impedance of each line segment, captures the combined information about the feeder impedance and the load distribution along the feeder [27]. For a simple case consisting of one radial feeder with a uniform distribution of N loads without laterals, the equivalent sum impedance can be computed by (1):

$$Rsum = \frac{1}{N}\sum_{k=1}^{k=N}\left(R'_k \cdot l_k \cdot (N-k+1)\right), \tag{1}$$

where R'_k and l_k are the specific resistance and length of segment k.

The parameters kWm and kWΩ can be computed by Equations (2) and (3) respectively [26]:

$$\text{kWm} = \sum_{k=1}^{k=N}(P_k \cdot d_k), \tag{2}$$

$$\mathrm{kW\Omega} = \sum_{k=1}^{k=N} (P_k \cdot R_k), \tag{3}$$

where P_k is the power of the load connected to node k, d_k the distance between node k and the secondary substation and R_k the short-circuit resistance at node k.

2.2. *Presentation of the Concept Used for the Feeder Clustering and Classification*

As stated in the introduction, one of the main purpose of the analyses is to implement a feeder classification and to investigate to which extent the feeder behavior can be predicted on the basis of statistical parameters which are usually available for DSOs. In this study, the feeder behavior means whether feeders tend to experience over-voltage or over-current when increasing the generation along the feeders to reach the hosting capacity.

In addition to the feeder classification (supervised learning), clustering (unsupervised learning) has also been implemented since it has been used in almost all the previous work analyzed in Section 1. The results of both analyses (classification and clustering) are compared and discussed (Sections 3.3 and 3.4).

Before explaining the general concept, the basic principles of clustering and classification are recalled here:

- Clustering consists in grouping a set of observations into clusters, on the unique basis of some observed variables, and without knowing a priori the number of clusters. Observations within a cluster should have at the same time a high similarity between each other and a high dissimilarity with observations in other clusters.
- Classification consists in finding a way to identify to which sub-set of observations (category or class) a new observation belongs. This is done on the basis of an algorithm trained on a set of data containing observations whose category or class is known.

2.2.1. General Concept

The analysis presented in this paper has been performed on the basis of the concept shown on Figure 1 and explained below:

I. Data import

In a first step, the data (network data, load data) is imported from different databases (see [23,28]. After a successful import of the network data into the simulation environment (PowerFactory), feeders are automatically defined in order to perform the analysis at feeder level. These feeders are considered as the observations to be clustered or classified.

II. Computation of feeder parameters (variables)

In this second step, all the feeder parameters which have been previously defined (see Section 2.1) are computed through automated scripts [26]. These variables can be divided into two families of variables:

- Descriptive variables (predictors)
- Hosting capacity-related variables (categories or classes)

III. Data validation (plausibilisation)

In this step, the data feeder parameters are carefully analyzed and feeders (observations) having erroneous or unrealistic values are eliminated. In this work, extensive efforts have been devoted to the data validation in order to ensure that only erroneous feeders (bad data) are eliminated. Classical outlier removal methods such as those based on boxplots (using percentiles or other statistical indicators to measure the dispersion from the median) cannot simply be used on multi-dimensional data sets. In some previous works, special outlier removal methods have been used (e.g., error ellipse method [19]). However, fixing a confidence interval (or removing the 1% "more extreme" feeders) results in removing observations which are not usual but are not erroneous. By doing so, the population of feeders is distorted, which can lead to a better classification or clustering performance, and finally to wrong interpretations. For these reasons, only erroneous data has been eliminated from the original data set.

IV. Data preparation

For some of the methods used in this paper (e.g., correlation analysis, see Section 3.1), a scaling of the data is necessary. When necessary, the data have been normalized (subtracting the average value and dividing by the standard deviation).

A further way to prepare data is transforming them to enhance differences between observations (using e.g., logarithm or square root transformation). As in several previous works [17,19] the principal component analysis (PCA) has been used for different purposes: for visualization purpose or to limit redundancy in the data.

V. Data exploration

After the data preparation, the data has been analyzed with classical data exploration techniques such as variable correlation, predictor importance, and variable (feature) selection. One of the objectives of this analysis is to analyze the dependencies between variables and select a limited subset of variables, which best reflects or explains the data structure. Data reduction was not strictly required in this work and has only been applied when a benefit could be obtained.

The detailed statistical analysis of the feeders has been presented in [23] and is therefore not in the scope of this paper. A few results are however provided in Section 3.1.

The next step consists of the analysis itself, which is based either on clustering or on classification. They are described in dedicated sections (Sections 2.2.2 and 2.2.3).

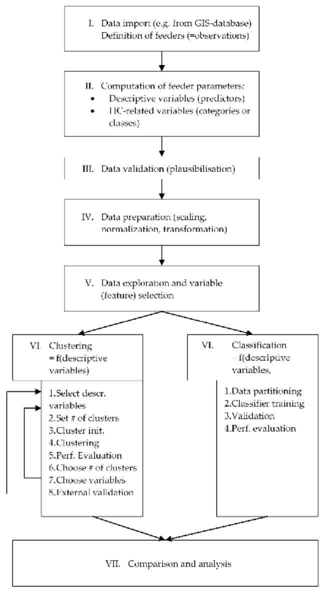


Figure 1. General concept used to perform the clustering and classification.

2.2.2. Feeder Clustering (Non-Supervised Learning)

Clustering is a non-supervised classification (labels or classes are not known) and can be considered as an exploratory data analysis tool. The most popular clustering algorithms are hierarchical clustering and algorithms from the k-means family. From all the relevant papers presented in Table 1, 11 from 12 use clustering: only two are based on hierarchical clustering and nine are based on the family of k-means algorithms (with some variations such as k-medoids or fuzzy k-median).

Hierarchical clustering consists in grouping observations into clusters with an agglomerative or divisive algorithm, based on their proximity. Besides the distance used to evaluate the proximity between observations, the linkage criterion, which defines how to compute the distance between clusters, plays an even more important role. One advantage of hierarchical clustering is that the number of clusters does not need to be a priori set. The partitioning can be directly analyzed by varying the level of resolution (on a so-called dendrogram).

K-means clustering is a heuristic that converges to a local optimum (e.g., minimization of the total distance between observations and their respective cluster centers) for a given number of clusters. One advantage of k-means clustering over hierarchical clustering is that it can be used for large data sets. The main disadvantages are that the number of clusters must be a priory specified, and that the result might be sensitive to the initialization (initial cluster centers which are usually chosen randomly).

There is no consensus whether hierarchical or k-means clustering is better- The decision is usually taken on the basis of the size of the data set. In fact, evaluating whether the clusters identified by a given clustering algorithm are good or not for the considered purpose requires analyzing the data and the results in detail, with domain experts.

Although hierarchical clustering would be feasible for the data set size (24,000 observations) from a computation point of view, k-means clustering has been used in this study to allow a comparison of the results with previous research works. In fact, an extension of k-means clustering called fuzzy c-means (FCM) clustering has been implemented. Fuzzy c-means clustering is a clustering concept introduced in 1981, which uses membership grades instead of hard assignments to cluster observations. With this concept, data points close to the center of a cluster will have a high membership value to that cluster, and low membership values to other clusters.

A variation of k-means clustering is the k-medoids clustering algorithm, which has been used in [18,19]. One of the main differences between these two partitioning clustering algorithms is that the center of the clusters are real observations (instead of a calculated center (centroid) for k-means).

In [28], the authors propose a clustering procedure based on four major steps (see Section 2.2.1):

- Feature selection or extraction
- Clustering algorithm design or selection
- Cluster validation
- Result interpretation

Most of the studies on feeder/network classification presented in the introduction follow to some extend this procedure. However, the validation usually only consists in a comparison between the results of different clustering variables or different number of clusters. None of the considered studies has evaluated to which extent the result of the clustering fulfills the expectations, due to the missing "prior information". In this study, this information is available and has been used for validation.

The results of the clustering analysis are summarized in Section 3.4. In particular, an external validation of the clustering is presented.

2.2.3. Feeder Classification (Supervised Learning)

Classification is a supervised machine-learning technique, which significantly differs from clustering (which is, as previously mentioned, unsupervised). It consists in building an algorithm, which is able to identify to which category or class, observations belong. This algorithm is tuned during a learning process with a training dataset, and then used to predict the category of another set of observations.

Among the different techniques usually used (e.g., discriminant analysis, decision tree learning, support vector machine or neural networks), decision tree has been selected based on several criteria for this study. One of the advantages of decision trees (or classification trees) is that the results (trees) are easy to interpret. An important step of classification is to evaluate the classifier performance. The most straightforward method is to compare the predicted class to the true class by building a so-called confusion matrix, from which several statistical indicators such as accuracy, specificity, etc. can be derived. However, this method has the great disadvantage that overfitting cannot be detected, since the validation and the training are done on the same dataset. Alternatively, cross-validation provides a way to test the classifier on a test dataset, whose observations were not used for the training. In this study, the k-fold validation has been used. With the k-fold cross-validation, the original data set is randomly partitioned into k subsets of equal size, from which one is kept for the validation, and k-1 are used for the training. The cross-validation process is then repeated k times and then, an average performance is computed. In this study, k has been set to 10 (10-fold cross-validation). The detailed concept of the classification used in this study is explained in Section 3.4.

3. Results

The results of the analyses are summarized in this section. The first subsection provides a few examples of statistical characterization (descriptive statistics) of the feeder population. The second sub-section provides some insights into the approach used to select the parameters used for classifying and clustering the feeders. The results of the classification and of the clustering are summarized in the last two subsections.

3.1. Statistical Analysis of the Feeders

Before starting the analyses on classification and clustering, the population of feeders has been explored and analyzed with different statistical methods. In this section, only a few examples are provided. A more detailed analysis has been presented in [23].

Since the R/X ratio of distribution feeders significantly affects the potential of reactive power-based voltage control, a closer look at the R/X distribution has been taken. Figure 2 shows the distribution of the feeder R/X ratio at the end node for the scenario "uniform" (see Section 2.1). For each bar of the histogram (length class), the share of voltage-constrained feeders is show in blue, the share of voltage and current-constrained feeders in magenta and the share of current-constrained feeders in red (for the scenario "uniform"—see Section 2.1).

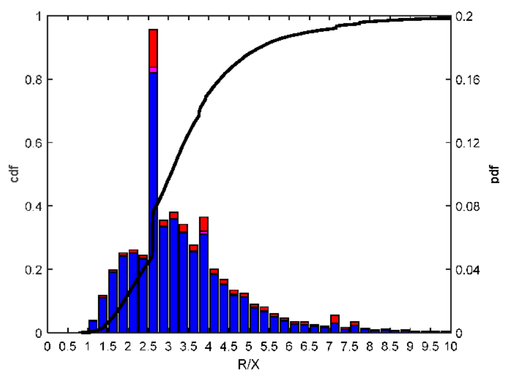


Figure 2. Distribution of the R/X ratio at the end node for the uniform generation distribution.

This R/X ratio plays an important role in the effectiveness of reactive power control for limiting the voltage rise as shown in Equation (4) [29] (for one generator connected at the end of the feeder):

$$\Delta U \approx \frac{R \cdot P}{U_N^2} \cdot \left(1 - \frac{\tan\varphi}{R/X}\right), \tag{4}$$

where ΔU is the voltage rise caused by the power infeed, U_N the nominal voltage, R and X the feeder resistance and reactance, P the injected active power, and φ the displacement angle. By consuming reactive power (increasing $\tan\varphi$), the voltage rise can be partly compensated: the lower the R/X ratio, the more effective the control.

This figure shows that the R/X ratio is almost always above 1, which is in accordance with the usual assumption that LV feeders have a "large" R/X ratio. Only about 21% of the feeder have a R/X ratio below 2.4, which allows a compensation of the voltage rise by 20% with $\cos\phi = 0.90$. The large peak for a R/X ratio of 2.6 corresponds to the most common cable type Al 150 mm^2. Another aspect to consider in this context, is that the reactive power consumption leads to an increase of the current, which might bring originally voltage-constrained (without reactive power-based voltage control) to be current-constrained (with control).

The increase of current due to the reactive power flows caused by the voltage control, can be estimated with Equations (5) and (6) ((5) is obtained by neglecting the voltage drop which is in quadrature with the voltage [30], and (6) is derived from a first order approximation of the current, considering small voltage variations):

$$\Delta U_{max} \approx \frac{R \cdot P_{HC}^{noQ}}{U_N^2} \approx \frac{R \cdot P_{HC}^{Q}}{U_N^2} \cdot \left(1 - \frac{\tan\varphi}{R/X}\right), \tag{5}$$

$$\frac{I_{max}^{Q}}{I_{max}^{noQ}} \approx \frac{1}{\left(1 - \frac{\tan\varphi}{R/X}\right) \cdot \cos\varphi}, \tag{6}$$

where ΔU_{max} is the maximum allowed voltage rise (3% for LV feeders according to [5]), defining the hosting capacity for voltage-constrained feeders, R and X are the feeder resistance and reactance, P_{HC}^{noQ} and P_{HC}^{Q} the hosting capacity without and with reactive power control and U_N the nominal voltage. Putting this simple equation in relation with the R/X statistics shown on Figure 2 lead to the following conclusion: about 50% of the feeders have a R/X ratio below 3, which results in an increase of the current by a factor 1.33 (+33%). This means that these feeders could only fully benefit from a reactive power-based voltage control, if the maximum loading (without control) is below $1/1.33 = 0.75$ p.u.

The remaining of this section is devoted to the main objective of this study: perform and analyze feeder classification and clustering methods.

3.2. Parameter Selection and Data Reduction

Before performing the clustering analysis and classification (see Section 2.1), several data exploration techniques have been used to get a better understanding about the relation between the parameters intended to be used for clustering and classification. Although the number of variables (feeder parameters) available for the analysis does not require the selection of a subset (i.e., the use of data reduction/feature selection techniques), the proximity between these variables has been analyzed in a first step. For this, three methods have been used:

- Correlation analysis
- Variable clustering (details not shown here)
- Principal Component Analysis (PCA)

In order to investigate the correlation between parameters, the Spearman correlation has been computed for the whole data set (for all the feeders) and a threshold of 0.70 has been used to identify significantly correlated variables.

Figure 3 shows the correlation between parameters (only the lower triangle is shown). Red crosses indicate a high correlation (>0.70), and blue crosses a low correlation (≤0.70). The set of parameters with a correlation lower than the considered threshold of 0.70 is indicated with blue squares: three "poorly correlated parameters" and two more which can be taken out of the group of correlated parameters.

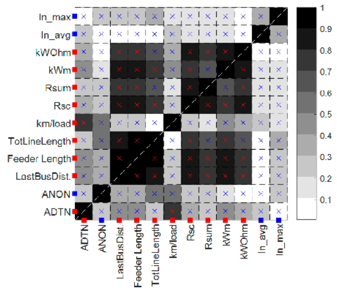


Figure 3. Correlation map (Spearman correlation). Red and blue crosses show a correlation higher or lower than the threshold of 0.70.

Finally, a principal component analysis has been performed in order to validate the variable selection and allow a graphical representation of the clustering result.

Principal component analysis consists in an orthonormal transformation into components which are a linear combination of variables. The components are selected in a way to maximize the variance explained by the first components. In this case, the first two principal components lead to a ratio of explained variance of about 66%. These two first components have the following main parameters (see Figure 4): component 1 is dominated by the parameter Rsum (and its correlated parameters such as the three distance metrics) while component 2 is dominated by the parameter *km*/*load*, *ANON* (and *ADTN*). The first component therefore mainly relates to the feeder length and impedance, and the second component to the structural properties (different metrics related to load density).

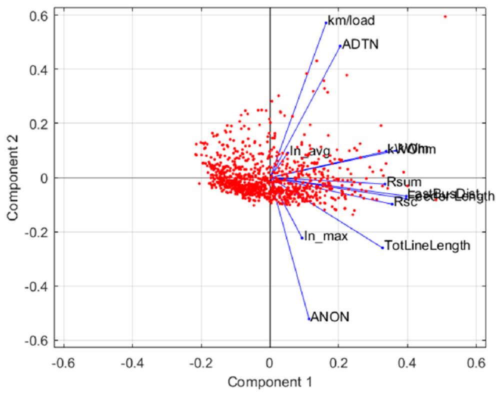


Figure 4. Projection of the parameters on the first two components obtained from a principal component analysis, including a random subset (1000) of the feeder data set (red points).

The results from all these analyses are coherent and confirmed the parameter selection. The final set of "poorly correlated variables" has been determined by selecting the parameters with the highest variance within a cluster (within a group of correlated parameters). These parameters are:

- *In_max*
- *In_avg*
- *km/load*
- *ANON*
- *Rsum*

3.3. Classification of LV Feeders

As explained in Section 2.2, the data set of about 24,000 LV feeders has been classified, using as explanatory variables the feeder parameters mentioned un Section 2.1 (Table 2) and as category the following characteristics:

- voltage-constrained feeders
- current-constrained feeders

Among all the different supervised machine-learning techniques such as neural networks or discriminant analysis, classification trees have been used for their simplicity and interpretability. The software package Matlab has been used for this purpose.

In a first step, a fully-grown classification tree (without restriction on the tree depth, i.e., a deep tree) has been built. It uses all the 12 parameters (or predictors) available. Before looking at the tree properties, the predictor importance can be evaluated. It quantifies the contribution of each variable (predictor) to split the tree. Figure 5 shows the predictor importance for the fully-grown tree: the most important variable is the *kWm*, followed by the parameters *kWOhm*, *FeederLength*, *In_avg* and *LastBusDist* (about 10 times less important).

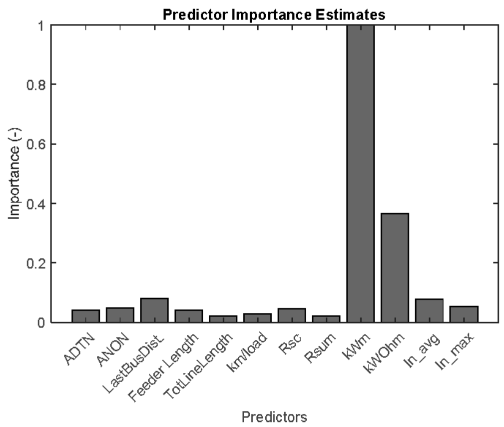


Figure 5. Estimation of the importance of each predictor (variable) for the fully-grown tree.

Deep classification trees (such as the one obtained from this first attempt (fully-grown tree)) are known to be prone to overfitting, which means that the good fitting obtained on a training set cannot be reproduced with a different set (testing set). In such cases, the tree has memorized a learning set instead of learning the general data structure.

Several alternatives are possible in order to avoid overfitting. One possibility is to constrain the tree building process by specifying a maximum number of splits or a minimum leaf size. The drawback of this method is that the constraints must be set from the beginning, i.e., before having some good understanding of the data. Another widely used possibility is to prune the tree (merge leaves) in order to reduce its complexity [31]: this is known as cost-complexity pruning. In order to evaluate the performance of a classifier, two generic indicators are widely used: the resubstitution error and the cross-validation error. The first one is simply evaluated by counting the misclassified observations on the whole data set while the second one requires to separate the data set into a training set and a testing set (usually with the proportion 90%/10%). The advantage of using the cross-validation error is that over-fitting can be detected.

Figure 6 shows the misclassification errors (resubstitution and cross-validation) as a function of the pruning-level: a low number of splits (only two) is enough to obtain the best achievable classification performance (any increase of the number of splitting does not reduce the cross-validation error and might lead to over-fitting).

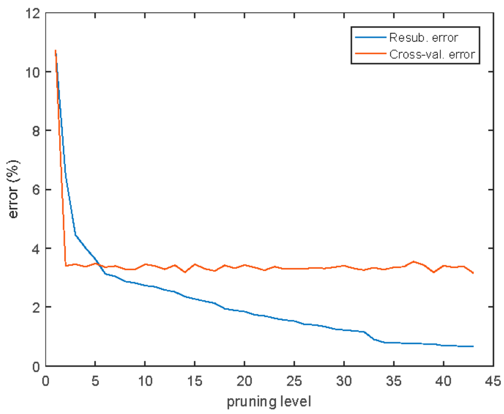


Figure 6. Evaluation of the optimal pruning on the basis of the cross-validation error.

This figure also shows that a low classification error (cross-validation error) can be achieved (about 3.4%). This result should however be carefully interpreted. Indeed, the data set is rather heavily unbalanced (skewed) with about 90% of the observations falling in one category (voltage-constrained feeders), and about 10% falling in the other category (current-constrained feeders)—see Section 3.1 [23]. This means that a random guess would already lead to a rather low misclassification error (10%). In order to consider this, several options are possible. The first one is to partition the data set (training and testing sets) in order to have a balanced proportion of both classes. The second one is to adjust misclassification costs and force the classification to be "equally good" for both categories. In this work, the second option has been selected and some cost weights have been used with the ratio between voltage-constrained and current-constrained feeders (about 90/10). When doing so, the corrected cross-validation error increases to 15.3%.

The final classification tree which is obtained from this analysis (specifying misclassification costs to "balanced" the data set, and pruning to obtain the best compromise between complexity and accuracy) is shown on Figure 7.

In the considered application (classification of LV feeders into voltage-constrained and current-constrained feeders for network planning purpose), misclassification does not have the same impact for both categories (voltage- and current-constrained feeders).

Indeed, one of the options to extend the hosting capacity is to implement a reactive power-based voltage control. As explained in the introduction, this type of control allows reducing the voltage rise caused by the infeed from distributed energy resources, at the cost of an increase of the current resulting from the additional reactive power flow. Since the current is not observed with the considered voltage control concepts, the deployment of such solutions should be limited to feeders which are actually voltage-constrained and not current-constrained. For this reason, a heavily unsymmetrical cost function has been introduced to force the classifier to avoid misclassification of current-constrained feeders. With this cost function, none of the current-constrained feeder is classified as voltage-constrained feeder: there is no misclassified feeder I→U (true class = I, and predicted class = U). This is reached at the cost of a significantly higher misclassification, as seen in Table 3. In order to look into this, the confusion matrix can be used (Table 3): the left part of this table shows the confusion matrix of the pruned tree with "balanced" misclassification costs (i.e., reflecting the ratio between classes). The ratio of problematic misclassified feeders (I→U) is 3.3%. In order to bring this ratio down to 0, high (I→U) "selective" misclassification costs are specified. As a side effect, the ratio of (U→I) misclassified feeders increases strongly from 11.4% to 53.8% (right part of the table).

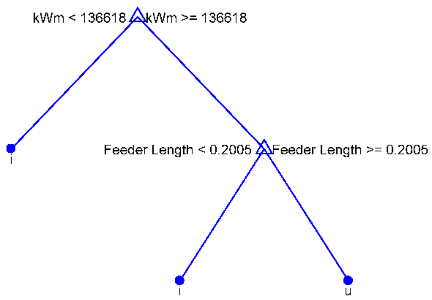


Figure 7. Graphical representation of the pruned tree (FeederLengh in km).

Table 3. Confusion matrix for a pruned classification tree with "balanced" (reflecting the data structure) and "unbalanced" (to avoid misclassification I→U misclassification costs).

Class	**"Legend"**		**"Balanced" Misclassification Costs**		**"Selective" Misclassification Costs**	
True→ Predicted ↓	**U**	**I**	**U**	**I**	**U**	**I**
U	TU [1]	FI [2]	88.6	11.4	46.2	53.8
I	FU [3]	TI [4]	3.3	96.7	0	100

[1] TU: true U-constrained feeders (normalized here to the actual number of U-constrained feeders); [2] FI: false I-constrained feeders (normalized here to the actual number of U-constrained feeders); [3] TI: true I-constrained feeders (normalized here to the actual number of I-constrained feeders); [4] FI: false U-constrained feeders (normalized here to the actual number of I-constrained feeders).

To further analyze the classifier performance, different indicators have been computed:

- Accuracy: probability of a correct classification among the data set (Equation (7))
- Sensitivity: the ability to classify correctly I-constrained feeders among the I-constrained feeders (Equation (8))
- Specificity: the ability to classify correctly U-constrained feeders among the U-constrained feeders (Equation (9))

- False positive rate (false alarm rate): the rate of U-constrained feeders which have been classified as I-constrained feeders (Equation (10)):

$$accuracy = 1 - Error = \frac{\#TU + \#TI}{\#U + \#I}, \tag{7}$$

$$sensitivity = \frac{\#TI}{\#I}, \tag{8}$$

$$specificity = \frac{\#TU}{\#U}, \tag{9}$$

$$false\ alarm\ rate = \frac{\#FI}{\#U}, \tag{10}$$

where # stands for number of elements in the corresponding subset.

Besides the indicators which are commonly derived from the confusion matrix (first three indicators), the fourth one plays an important role in this study as previously explained (reactive power-based voltage control should not be implemented in I-constrained feeders).

Table 3 shows that using high costs for the misclassification of I-constrained feeders allows reaching 100% sensitivity at the expenses of a rather high false alarm rate (53.8%), which represents a strong loss of potential. In fact, a trade-off between selectivity and false alarm rate must be found. In order to visualize this, Receiver Operating Characteristics (ROC) graphs can be used [32]. A ROC curve is a technique to visualize the performance of classifiers, and in particular, the trade-off between sensitivity (y-axis) and false alarm rate (x-axis). A random classifier would have a diagonal (0, 0)-(1, 1) as ROC-curve while a perfect classifier would follow the y and then the x-axes: (0, 0)-(0, 1)-(1, 1).

Figure 8 shows the ROC-curves obtained by varying the ratio of the misclassification costs between FI and FU between 10^{-4} and 10^{4}. For each misclassification cost, a classification tree has been grown and pruned as previously explained, and the ROC curve has been built. This figure shows that a sensitivity rate above 90% can be reached with a rather low false alarm rate (about 5%). However, in order to reach a sensitivity rate of 100%, the false alarm rate increases to about 54%. In fact, these ROC-curves are suitable for a decision-making process implemented in the frame of a probabilistic network planning by specifying a risk level.

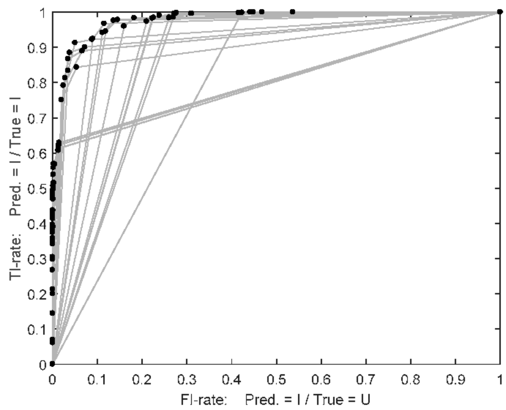


Figure 8. ROC curves (x: false alarm rate (FI)/y: sensitivity (TI)) obtained for different misclassification costs (cost ratio between 1:10^{-4} and 1:10^{4} for the FI and FU costs).

These results might be interpreted as a poor performance of the classifier (high false alarm rate). In fact, using very unsymmetrical misclassification costs (very high costs for FU) forces the classifier to exclude many U-constrained feeders due to only few I-constrained feeders, which are in a region of the variable space dominated by U-constrained feeders. This effect has been indeed observed for the feeder data set. Figure 9 shows the scatter plot for the whole data set, projected on the first two principal components obtained by a principal component analysis (PCA), which are dominated by the equivalent sum impedance *Rsum* (first component) and the parameters *km*/*load* or *ANON* (second component)—see Section 3.2.

In this figure, the observations (feeders) are colored according to the constraint (blue for voltage-constrained feeders and red for current-constrained feeders). This figure shows that current-constrained feeders seem to be located close to the lower left corner (small *Rsum* and small *km*/*load* or *ANON*) while voltage-constrained-feeders are found further from the origin. However, a careful look at the partial distributions (left and lower part of the figure) shows that there is a strong overlap in the region close to the origin, in which most of the feeders are found. This figure confirms the difficulty to discriminate between both classes (here on the sole basis of the two first principal components). In fact, the decision tree allows identifying those I-constrained feeders, which force to exclude numerous U-constrained feeders. Excluding them from the data set is however not a valid approach since these feeders are not outliers.

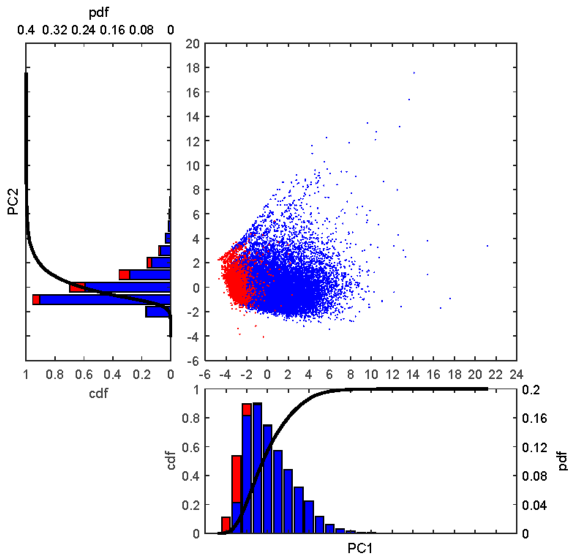


Figure 9. Scatter-plot of the two first principal components—coloring according to the constraint: blue: U-constrained feeders/red: I-constrained feeders.

Finally, a careful look at the misclassified feeders U→I, which necessarily lead to a loss of potential, shows that a great share of these feeders (70%) have a loading greater than 70%, as visible on Figure 10. On this figure, the right axis is for the probability density function (pdf—bars) and the left axis for the cumulative density function (cdf—curve).

These feeders are voltage-constrained but have a rather high loading, which means that they would probably turn to be current-constrained when reactive power-based voltage control is implemented due to the increased active and reactive power flows (see Section 3.1). This is, in fact, confirmed by analyzing the hosting capacity values obtained from the scenario with reactive power-based voltage control (see Section 2.1). As a result, only about one third of the misclassified feeders U→I remain voltage-constrained when implementing a reactive power-based voltage control. This means that the actual reduction of the potential due to the U→I misclassification ("false alarm") is reduced from 53.8% to about 18%.

As a conclusion, a decision tree classifier has been trained with the data set in a way to avoid over-fitting. Besides its generic performance which can be evaluated by the cross-validation for example, unsymmetrical misclassification costs have been introduce to avoid problematic errors (false U-constrained feeders). The side-effect of reaching a high sensitivity (close to 100%), is a rather high false alarm rate, which represents in fact a loss of potential in terms of feeders potentially benefiting from voltage control (the main application here). However, this loss of potential is limited since most of the affected feeders are in fact close to experience over-loading when implementing reactive power control to increase the hosting capacity.

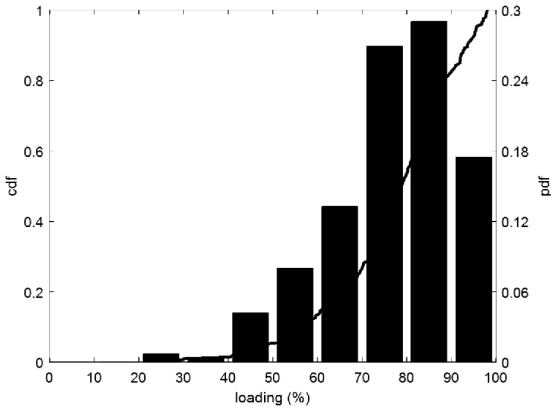


Figure 10. Evaluation of the lost potential with the distribution of the maximum loading for misclassified feeders (true class = U and predicted class = I).

3.4. Clustering of LV Feeders

As explained in Sections 1 and 2.2.2, all the studies mentioned in Section 1 are based on clustering analysis (i.e., process of grouping a set of observations into clusters). In these studies, the results of the clustering analysis have been analyzed and validated through an internal validation, whose purpose was in most cases to support the decision on the number of clusters to be used. In this paper, a clustering analysis has been conducted in a similar way as in most of the considered studies (see Table 1). The results of this analysis are analyzed through an external validation since the information of the class membership (voltage or current-constrained feeders) was available.

The feeders have been clustered with the k-means clustering (using the squared Euclidean distance), which is, as mentioned in Section 1 (Table 1), the most widely used clustering method.

The most important parameters of the clustering analysis which can have a significant impact on the results are:

- Variables used
- Number of clusters used

As in the previous studies, the variables used in the clustering analysis have been selected based on several analyses (e.g., correlation analysis, PCA). However, this variable selection is still subject, to some extent, to subjective decisions and is hard to fully justify. For this reason, the number of variables and the variables themselves have been varied. Regarding the number of clusters, there is no universal method to determine the "optimal" or "appropriate" number of clusters. Instead, there is a number of established methods supporting to some extent the decision.

In the studies reviewed in Section 1, different metrics have been used to quantify the clustering performance and select the "optimal" or "appropriate" number of clusters (R^2 (coefficient of determination) [16], sum of squared errors [10,12,33], silhouette value [10], cubic clustering [17] and Calinski-Harabasz [19] criterions).

In this study, the following two metrics have been evaluated: the silhouette value and the normalized sum of squared errors ($nSSE$).

The silhouette coefficient for each observation (here for each feeder i) is a measure of how similar that observation is to observations in its own cluster, compared to observations in other clusters:

$$s_i = \frac{b_i - a_i}{\max(a_i, b_i)}, \tag{11}$$

where a_i is the average distance to all other objects in the cluster to which feeder i belongs to, and b_i is the minimum over all the clusters not containing feeder i, of the average distance between all the feeders in the considered clusters (not containing feeder i), and feeder i. The silhouette value lies between −1 and +1. A high silhouette value indicates that the observation i is well-matched to its own cluster, and poorly-matched to neighboring clusters.

The normalized sum squared error is the sum of the squared errors (here distance between observations and centroids (cluster centers)), normalized to the error obtained for a single cluster.

Figure 11 shows the clusters obtained by specifying the number of clusters to 3, 4 or 5. The left part shows the clusters on a scatter plot, using the first two principal components to allow an easy visualization (as in [17,19]). The obtained normalized sum squared error ($nSSE$) is given on the top of each scatter plot. The right part of the figure shows the corresponding silhouette plots: the silhouette value is computed for each single observation and shown in a sorted way for each cluster (the average value over all the clusters is given above the silhouette plots).

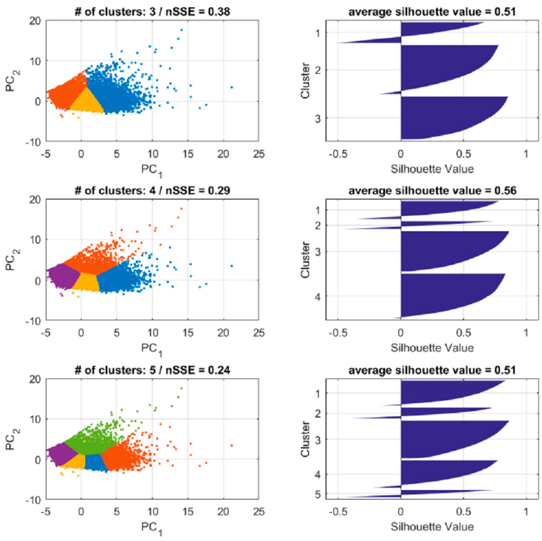


Figure 11. Scatter-plots for the first two principal components (PC_1 and PC_2) and silhouette plots for 3, 4 or 5 clusters.

This figure shows that, as expected, the normalized sum squared error decreases when the number of clusters increases (0.38 for three clusters and 0.24 for five clusters). However, the silhouette value does not show such a monotonic behavior: the best (highest) silhouette value among these three cases is obtained for four clusters (0.56). This means that, in this case and for this metric (silhouette), increasing the number of clusters does not necessarily lead to a better clustering result (in terms of how close observations are within a cluster and how far they are from other cluster).

The cluster plots also show that most of the observations are very close to each other (continuous distribution of feeders) and that there does not seem to have any "natural" cluster structure in the feeder population. The result of the clustering seems to divide the areas with a high density of observations into sectors or roughly equal size.

Figure 12 shows the impact of varying the number of clusters (between 1 and 20) on the two metrics used to quantify the clustering performance (note that the silhouette value is only defined for at least two clusters).

This figure shows that, as expected and previously observed, the normalized sum squared error (*nSSE*) decreases monotonously when increasing the number of clusters. A usual way of selecting the "optimal" number of clusters is to use the elbow criterion. In this case, the *nSSE*-curve does not exhibit a clear elbow shape and a visual selection of the "optimal" number of clusters is questionable (this has also been observed in previous studies with sufficient large data sets). A number of clusters between six and 16 (for the cluster number ranges of most previous studies, see Table 1) could be somehow justified. However, the silhouette curve does not exhibit a monotonic behavior and even shows that the highest clustering performance according to this metric is reached for only two clusters. These analyses confirm the known difficulty to interpret the clustering results and select the "optimal" or "appropriate" number of clusters.

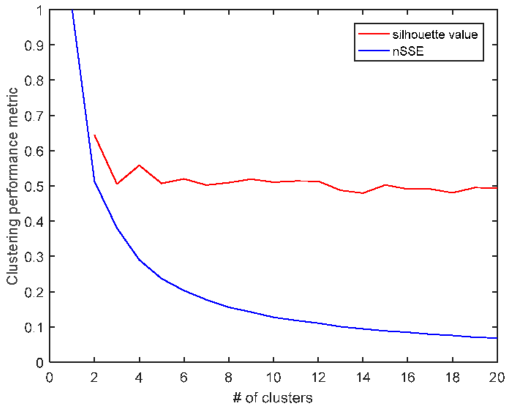


Figure 12. Impact of the number of clusters (between 1 and 20) on the used metrics (average silhouette value and normalized sum squared error).

Finally, the results of the clustering and their suitability for the considered problem (reflect the behavior of feeders in terms of hosting capacity) have been analyzed through an external validation. For this, the classes, which had also been used in the classification, are used to measure how close the clustering is to the predetermined classes (voltage or current-constrained feeder). The results of this external validation for a clustering with four clusters is shown on Figure 13 (projection on the first two principal components).

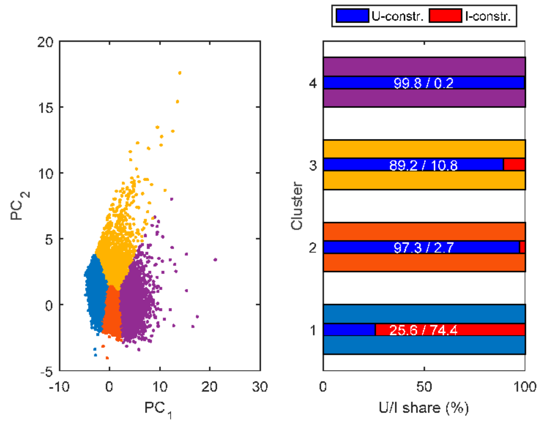


Figure 13. External validation of the clusters—cluster vs. classes.

The left part shows the scatter plot (similar to Figure 11 with different coloring) and the right part shows for each cluster (the wide bars are colored as the clusters) the share of voltage (blue) and current (red)-constrained feeders. This share between both classes is in addition indicated as a numerical value, which allows to evaluate the performance of the clustering for the considered problem (to identify feeders according to their class (voltage or current-constrained)). Indeed, this share can be interpreted as a "partial purity" measurement. A common metric used to quantify the clustering performance with an external validation is the (global) purity, given by Equation (12):

$$purity(\mathrm{CLU}, \mathrm{CLA}) = \frac{1}{\mathrm{N}} \cdot \sum_{clu \in CLU} \max_{cla \in CLA} |clu \cap cla|, \tag{12}$$

where $purity(\mathrm{CLU}, \mathrm{CLA})$ is the (global) purity of the clusters (against the classes), *cla* are the classes belonging to the set of classes CLA (here voltage or constrained-feeders), *clu* the clusters belonging to the set of clusters CLU and N the number of observations (feeders). In our case, the "partial purity" values (for each cluster) have been considered.

The more dissymmetric the ratio (the purest), the more the clustering is able to discriminate between both classes. For example, the fourth cluster (purple) almost only contains voltage-constrained feeders (99.8% of the feeders in this cluster are voltage-constrained). On the opposite, the cluster 1 (blue) mostly contains only current-constrained feeders, with however a significantly lower level of purity. The reader should note that these two clusters (with the highest purity levels for both classes) do not have any border.

Following the same reasoning as for the classification (considering that current-constrained feeders should be identified with the highest possible confidence), the most interesting cluster is the fourth cluster which has the highest purity level (only cluster with a purity level greater than 99%). This cluster contains however only about 16% of the whole feeder population (or about 18% of the population of voltage-constrained feeders). This means that this clustering leads to a rather poor result: its ability to discriminate between the two classes (voltage and current-constrained feeders) is low, even when accepting a "risk" (here 0.2% due to the "impurity").

By following the same conservative approach as for the classification (considering only feeders which are (almost) surely voltage constrained), the deployment potential of reactive power-based voltage control would be significantly lower than for the classification. The share of voltage-constrained feeders which would be safely identified as such, is about 46% for the decision tree-based classification (see Section 3.3), and only about 18% for the clustering (loss of potential or 54% and 82% respectively).

4. Discussion and Conclusions

In this study, two main concepts for identifying “typical” or “representative” feeders have been analyzed, on the basis of a large set of real LV feeders in Austria (24,000 LV feeders). The main motivation behind this work is to be able to clearly identity the constraint limiting the feeders hosting capacity (voltage or current). Indeed, reactive power based voltage control concepts have been developed and successfully validated in the past years. By consuming reactive power, the amount of generation that can be integrated into the network (maintaining an acceptable voltage level), can be increased. This increase of the hosting capacity through voltage control can, of course, only be implemented in feeders which are voltage-constrained (and not current-constrained). Due to the low (or almost inexistent) level of monitoring in LV networks, it is of prime importance to be able to classify feeders (i.e., identify the constraint: voltage or current) with a high level of confidence in order to avoid deploying controls which would in fact worsen the situation.

The first concept implemented to identify voltage-constrained feeders, k-means clustering, is an unsupervised machine-learning technique, which has been used in most of the previous studies. The result of this clustering consists in a set of clusters, which intend to reflect the data structure, based on the parameters used to characterize the observations (the feeders).

The second concept implemented to identify voltage-constrained feeders, classification, is a supervised machine-learning technique, which uses prior information (the belonging to the class voltage or current-constrained feeders) on a data set to train a classifier (decision tree here). In opposite to previous works, the hosting capacity and the associated constraint have been determined for a large data set, which allowed implementing a classification and validating the clustering results.

The analyses performed in this study showed that a perfect classification cannot be reached, which means that some feeders are misclassified. Misclassification does not have the same impact for both categories (voltage- and current-constrained feeders). Current-constrained feeders should be identified with a high confidence level (in a conservative way) to avoid implementing a control which would be counterproductive.

The results shown in this paper might be interpreted as rather poor, but they reflect in fact the diversity of the feeders within the data set. All the attempts to identify a clear structure in the data (data exploration and visualization) showed continuous distributions of feeders whatever the variables considered.

The lowest achieved misclassification to ensure that (almost) no current-constrained feeders are wrongly classified as voltage-constrained feeders is rather high: 54% for the decision tree and 82% for the k-means clustering. This can be considered as a significant loss of potential. As expected, the supervised learning based on a decision tree classifier leads to significantly better results than the k-means clustering. With 82% loss of potential, the benefits of using clustering are even questionable.

This performance, which might be considered to be poor, is the costs of reaching a very high sensitivity (close to 100%), which results in a high false alarm rate (loss of potential to implement reactive power control for hosting capacity increase of voltage-constrained feeders). However, a detailed analysis showed that this loss of potential is in fact limited, since most of the affected feeders are close to experience over-loading when implementing reactive power control. When considering this, the loss of potential drops from 54% to about 18%.

As a conclusion, even with a modest performance from a generic point of view, the benefit of the feeder classification can be considered as significant. The concept developed allows predicting the behavior of LV feeders in terms of hosting capacity constraint with a limited number of variables. By identifying a sub-group of the feeders (voltage-constrained feeders) with a very high confidence level (sensitivity close to 100%), the control concepts can be deployed by DSOs in the target networks without the need for additional studies. As a result, more detailed planning studies can be prioritized to those feeders for which the classification results are unsure.

As future research direction, the investigated concepts could be used for further data sets to validate the results. In particular, the classification results might be significantly better for less skewed (unbalanced) data sets. A further research direction could be a formalization of the probabilistic character of the classification and of the clustering to reflect the probabilistic nature of distribution network planning.

Acknowledgments: This work has been partly supported by the project IGREENGrid which has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 308864.

Author Contributions: Benoît Bletterie performed the hosting capacity evaluation and the feeder classification. Serdar Kadam supported this work by writing scripts for simulation automation. Herwig Renner contributed to the analysis and discussion of the results.

Conflicts of Interest: The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Bollen, M.; Rönnberg, S. Hosting Capacity of the Power Grid for Renewable Electricity Production and New Large Consumption Equipment. *Energies* **2017**, *10*, 1325.
2. Bletterie, B.; Goršek, A.; Uljanić, B.; Jahn, J. Enhancement of the network hosting capacity—Clearing space for/with PV. In Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition, Valencia, Spain, 6–10 September 2010; pp. 4828–4834.
3. VDE. *VDE-AR-N 4105 Generators Connected to the Low-Voltage Distribution Network—Technical Requirements for the Connection to and Parallel Operation with Low-Voltage Distribution Networks*; VDE: Frankfurt am Main, Germany, 2017.
4. Ministère de L'écologie, de L'énergie, du Développement Durable et de L'aménagement du Territoire. *Arrêté du 23 Avril 2008 Relatif aux Prescriptions Techniques de Conception et de Fonctionnement Pour le Raccordement à un Réseau Public de Distribution D'électricité en Basse Tension ou en Moyenne Tension D'une installation de Production D'énergie Électrique*; Ministère de L'écologie, de L'énergie, du Développement Durable et de L'aménagement du Territoire: Paris, France, 2008.
5. E-Control. *Technische und Organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere Technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen*; E-Control: Vienna, Austria, 2016.
6. Bletterie, B.; Gorsek, A.; Fawzy, T.; Premm, D.; Deprez, W.; Truyens, F.; Woyte, A.; Blazic, B.; Uljanic, B. Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks. *Prog. Photovolt. Res. Appl.* **2012**, *20*, 747–759. [CrossRef]
7. Kadam, S.; Bletterie, B.; Lauss, G.; Heidl, M.; Winter, C.; Hanek, D.; Abart, A. Evaluation of voltage control algorithms in smart grids: Results of the project: MorePV2grid. In Proceedings of the 29th European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands, 22–26 September 2014.
8. Stetz, T.; Marten, F.; Braun, M. Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany. *IEEE Trans. Sustain. Energy* **2013**, *4*, 534–542. [CrossRef]
9. Dehghani, F.; Nezami, H.; Dehghani, M.; Saremi, M. Distribution feeder classification based on self organized maps (case study: Lorestan province, Iran). In Proceedings of the 20th Conference on Electrical Power Distribution Networks Conference (EPDC), Zahedan, Iran, 28–29 April 2015; pp. 27–31.
10. Nijhuis, M.; Gibescu, M.; Cobben, S. Clustering of low voltage feeders from a network planning perspective. In Proceedings of the CIRED 23rd International Conference on Electricity Distribution, Lyon, France, 15–18 June 2015.
11. Willis, H.L.; Tram, H.N.; Powell, R.W. A Computerized, cluster based method of building representative models of distribution systems. *IEEE Trans. Power Appar. Syst.* **1985**, *12*, 3469–3474. [CrossRef]
12. Schneider, K.P.; Chen, Y.; Chassin, D.P.; Pratt, R.G.; Engel, D.W.; Thompson, S. *Modern Grid Initiative: Distribution Taxonomy Final Report*; Pacific Northwest National Laboratory: Richland, WA, USA, 2008.
13. Kerber, G. *Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen*; Technical University of Munich: Munich, Germany, 2011.
14. Lindner, M.; Aigner, C.; Witzmann, R.; Frings, R. Aktuelle Musternetze zur Untersuchung von Spannungsproblemen in der Niederspannung. In Proceedings of the 14 Symposium Energieinnovation, Graz, Austria, 10–12 February 2016.

15. DeNA. *DeNA-Verteilernetzstudie. Ausbau-und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030*; DeNA: Tokyo, Japan, 2012.
16. Dickert, J.; Domagk, M.; Schegner, P. Benchmark low voltage distribution networks based on cluster analysis of actual grid properties. In Proceedings of the 2013 IEEE Grenoble Conference on PowerTech (POWERTECH), Grenoble, France, 16–20 June 2013; pp. 1–6.
17. Broderick, R.J.; Williams, J.R. Clustering methodology for classifying distribution feeders. In Proceedings of the 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), Tampa, FL, USA, 16–21 June 2013; pp. 1706–1710.
18. Gust, G. *Analyse von Niederspannungsnetzen und Entwicklung von Referenznetzen*; KIT: Cornwall, UK, 2014.
19. Cale, J.; Palmintier, B.; Narang, D.; Carroll, K. Clustering distribution feeders in the Arizona Public Service territory. In Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), Denver, Colorado, 8–13 June 2014; pp. 2076–2081.
20. Li, Y.; Wolfs, P.J. Taxonomic description for western Australian distribution medium-voltage and low-voltage feeders. *IET Gener. Transm. Distrib.* **2014**, *8*, 104–113. [CrossRef]
21. Walker, G.; Nägele, H.; Kniehl, F.; Probst, A.; Brunner, M.; Tenbohlen, S. An application of cluster reference grids for an optimized grid simulation. In Proceedings of the CIRED 23rd International Conference on Electricity Distribution, Lyon, France, 15–18 June 2015.
22. Varela, J.; Hatziargyriou, N.; Puglisi, L.J.; Rossi, M.; Abart, A.; Bletterie, B. The IGREENGrid Project: Increasing Hosting Capacity in Distribution Grids. *IEEE Power Energy Mag.* **2017**, *15*, 30–40. [CrossRef]
23. Bletterie, B.; Kadam, S.; Abart, A.; Priewasser, R. Statistical analysis of the deployment potential of Smart Grids solutions to enhance the hosting capacity of LV networks. In Proceedings of the 14 Symposium Energieinnovation, Graz, Austria, 10–12 February 2016.
24. PowerFactory—DIgSILENT Germany. 2017. Available online: http://www.digsilent.de/index.php/products-powerfactory.html (accessed on 6 November 2015).
25. Python. 2017. Available online: https://www.python.org/ (accessed on 21 March 2016).
26. Kadam, S.; Bletterie, B.; Gawlik, W. A Large Scale Grid Data Analysis Platform for DSOs. *Energies* **2017**, *10*, 1099. [CrossRef]
27. Bletterie, B.; Abart, A.; Kadam, S.; Burnier, D.; Stifter, M.; Brunner, H. Characterising LV networks on the basis of smart meter data and accurate network models. In Proceedings of the Integration of Renewables into the Distribution Grid (CIRED 2012 Workshop), Lisbon, Portugal, 29–30 May 2012; pp. 1–4.
28. Xu, R.; Wunsch, D. Survey of Clustering Algorithms. *IEEE Trans. Neural Netw.* **2005**, *16*, 645–678. [CrossRef] [PubMed]
29. Bletterie, B.; Gorsek, A.; Abart, A.; Heidl, M. Understanding the effects of unsymmetrical infeed on the voltage rise for the design of suitable voltage control algorithms with PV inverters. In Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 5–9 September 2011; pp. 4469–4478.
30. Jenkins, N.; Allan, R.; Crossley, P.; Kirschen, D.; Strbac, G. *Embedded Generation*; The Institution of Engineering and Technology: London, UK, 2000.
31. Sutton, C.D. Classification and Regression Trees, Bagging, and Boosting. In *Handbook of Statistics*; Elsevier: Amsterdam, The Netherlands, 2005; Volume 24, pp. 303–329.
32. Bradley, A.P. The use of the area under the ROC curve in the evaluation of machine learning algorithms. *Pattern Recognit.* **1997**, *30*, 1145–1159. [CrossRef]
33. Walker, G.; Krauss, A.-K.; Eilenberger, S.; Schweinfort, W.; Tenbohlen, S. Entwicklung eines standardisierten Ansatzes zur Klassifizierung von Verteilnetzen. In *VDE-Kongress 2014*; VDE Verlag: Berlin, Germany, 2014.

Publication 5

"Voltage control with PV inverters in low voltage networks – In depth analysis of different concepts and parameterization criteria"

B. Bletterie, S. Kadam, R. Bolgaryn, and A. Zegers, "Voltage control with PV inverters in low voltage networks – In depth analysis of different concepts and parameterization criteria," IEEE Trans. Power Syst., pp. 1–1, 2016.

Own contribution

This paper presents the results of a detailed analysis of different volt/var control concepts based on a sensitivity analysis. In this study, several evaluation criteria have been used: besides the effectiveness (ability of a control to mitigate the voltage rise caused by the generation), the impact of the control on the reactive power balance and on the losses have been analysed.

The applicant initiated and coordinated the research. He designed the scope and details of the parametric study and supervised the second and third authors who performed the simulations. He introduced the concept of Volt/var Index (VVI) and wrote most of the paper.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

Voltage control with PV inverters in low voltage networks – In depth analysis of different concepts and parameterization criteria

B. Bletterie, *Member, IEEE*, S. Kadam, R. Bolgaryn and A. Zegers

***Abstract* — In some rural and sub-urban areas, the hosting capacity of low voltage networks is restricted by voltage limits. With local voltage control, photovoltaic generators can mitigate the voltage rise partly and therefore increase the hosting capacity. This paper investigates the effectiveness and general performance of different reactive and active power control concepts. It presents the findings of an extensive simulation-based investigation into the effectiveness of voltage rise mitigation, additional reactive power flows, network losses and power curtailment. The two most common implementations of reactive power control have a similar effectiveness. The voltage rise can be compensated for by up to 25 % and more than 60 % for typical cable and overhead feeders respectively. By additionally using active power curtailment of up to 3 % of the annual yield, the hosting capacity can be increased by about 50 % and 90 % for the considered cable and overhead feeder respectively (purely rural feeders).**

***Index Terms*—Inverters, Photovoltaic power systems, Power distribution, Reactive power control, Voltage control**

I. Introduction

SOLAR photovoltaic (PV) power is considered in most scenarios as an important energy resource for meeting the medium and long term renewable energy targets. Authors in [1] report growth of around 6 GW per year between 2011 and 2013 in Europe, and with five countries exceeding 1 GW despite the clear market decline in Europe, mainly in Germany and Italy.

A very specific property of PV generation is its highly decentralized nature: according to [2], more than 70 % of the installed PV capacity (more than 38 GW in 2014) is embedded in the low voltage (LV) network. In some areas, the local PV penetration reaches very high values (200 kWp/km^2 [3]) and the hosting capacity (HC) of LV networks is locally exhausted triggering expensive network reinforcement measures [4].

One of the main limitations towards the hosting capacity is the voltage rise caused by the PV infeed. Currently, the voltage at remote nodes of feeders with a high penetration of PV generation, might exceed the planning limits of distribution system operators (DSO) which are set to allow them to comply with the +10 % limit specified in the voltage quality standard [5]. An alternative to the network reinforcement is local voltage control with PV inverters. Alongside the emergence of different local control concepts, the grid codes, standards and connection guidelines have been modified to allow DSOs to make use of them [6]. However, the requirements of the current connection rules usually consist of "must have" requirements for distributed energy resources (DER) and do not provide any guidance on how to adjust the settings of the voltage control algorithms.

Despite the positive conclusions of many field tests, the roll-out of the proposed concepts has still not occurred, probably due to the lack of investigations on when to use them and how to adjust them. This study aims to fill in this gap. This is achieved by using a generic approach with a synthetic European test feeder following [7] and a parametric study.

This paper is structured as follows: Section II provides a short review of existing local voltage control concepts, including requirements according to current connection rules. Section III illustrates the concept of hosting capacity and quantifies it for the considered networks. Section IV provides a quantitative comparison of the considered control concepts with different settings. The paper concludes with a discussion of the results (Section V).

B. Bletterie, S. Kadam, A. Zegers are with AIT - Austrian Institute of Technology (e-mail: {benoit.bletterie, serdar.kadam, antony.zegers}@ait.ac.at).

R. Bolgaryn is with University of Applied Sciences FH Technikum Wien (e-mail: ee13m013@technikum-wien.at).

II. Review of Existing Voltage Control Concepts

A. State of the art

In the recent years, exhaustive research results have been published on how to mitigate the voltage rise caused by PV generation, with voltage rise being one of the most important limitations towards hosting capacity.

While several local control concepts have been proposed, the most covered control modes are those currently required in grid codes [8],[9],[10] and [11]: cosφ(P) (power factor as a function of the injected power) and Q(U) (reactive power as a function of the voltage at point of connection).

In [12], the impacts of the parameterization of local reactive power control (*Q(U)*) on its performance have been investigated for a MV network located in Belgium. In [13], several local reactive power control methods for overvoltage prevention are investigated. In that paper, a new concept is proposed: a *cosφ(P,U)* control. Authors in [4] propose a concept for ensuring a more homogenous contribution of PV inverters connected along a LV feeder. It consists of parameterizing the dead band of the *Q(U)* controller, depending on the network impedance at the point of connection. In [14], a concept for curtailing the active power in an equitable manner via centralized control or consensus control is proposed. In [15], a concept of offline coordination is proposed for sharing the active power curtailment between generators connected to the same feeder. It uses a similar approach to [4].

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

Some studies have been dedicated to investigating the voltage control under unbalanced conditions. The voltage rise effect is significantly higher for unbalanced PV infeed conditions than for balanced conditions. The voltage rise caused by a single-phase PV generator is, for example, approximately six times higher than the voltage rise caused by a three-phase generator of the same power [16]. In [17], the impact on the effectiveness of the voltage control *Q(U),* due to asymmetrical power infeed is investigated. In [18], the impact on the control due to neutral point shifting is analysed. Several methods have been proposed in order to reduce or actively compensate the possible asymmetry introduced by single-phase PV installations. In [17], a concept for determining the optimal phase connection with smart meters has been proposed. One of the most important conclusions of [16], [17], [19] is that distributing the PV power over the three phases should be the first measure to counteract voltage unbalance. The study presented here considers high PV penetration scenarios for which a nearly symmetrical distribution of the PV power can be assumed.

While most of the literature related to *Q(U)* control focuses on steady-state considerations, recently some research has been devoted to studying the stability of *Q(U)* control [20][21]. For this control type, it has been observed that stability problems are not expected, even at high PV penetration levels. Some of the publications also cover laboratory tests and field tests [22][23], and in general confirm the proper operation of the inverters even under real conditions.

Finally, some papers propose the use of coordinated control, thereby combining central assets and controllers with PV inverters.

In [24], various strategies are proposed for increasing the hosting capacity of low voltage networks. In addition to active and reactive power control by PV inverters, distribution transformers with On-Load-Tap-Changing are considered.

In [25], different architectures for voltage control, which include local, centralized and model-based control, are compared. Coordinated control with adaptive zoning is proposed. In this concept, generators are grouped within zones in order to limit the complexity and communication needs.

In [26] and [27], a step model with increasing complexity is proposed to control the voltage in LV networks. The proposed concepts include coordinated control in which settings are sent to an on-load-tap-changer and to the PV inverters, depending on the voltage measurements provided by smart meters.

B. Contribution

A study of the literature in this field clearly shows the lack of general findings due to the diversity and complexity of the network setups. Most existing studies are hard to generalise, due to their being case-studies with findings that are specific to that particular set of conditions, albeit having realistic results. In light of this, this paper investigates the effectiveness and performance of different local voltage control concepts on a general basis. For this purpose, two generic feeders are used (cable and overhead line) which allows general conclusions to be drawn, with all due precautions. The performance is evaluated on the basis of a comprehensive set of parameters: voltage level, feeder losses, reactive power consumption from the upstream network and power curtailment.

III. Hosting Capacity Of Distribution Networks

A. Hosting capacity definition

The concept of hosting capacity as introduced in [28] and further developed in [29] quantifies *the acceptable degree of DER penetration under given circumstances.* From the network planning perspective, the first requirements that must be fulfilled are the voltage quality (e.g. compliance with the applicable limits [5]) and the loading constraint. Considering that high PV penetration levels are mostly expected in rural and semi-rural areas, only voltage-constrained networks are considered. Although a perfectly homogenous distribution is a purely theoretical case, networks with high PV penetration are expected to tend to this case and it offers the possibility to better understand and compare different control concepts.

B. Considered networks

This study considers two types of LV feeders:

- a cable feeder (Cab.) with a cable type frequently used in Central Europe: 150 mm^2 Aluminium with R'=0.208 Ω/km and X'=0.08 Ω/km
- an overhead line feeder (OH) with an overhead line type frequently used in Central Europe: 70 mm^2 Aluminium with R'=0.436 Ω/km and X'=0.31 Ω/km

The length of the feeders (identical for both types of feeders) has been arbitrarily chosen since it has no influence, as long as the feeder is voltage-constrained. The distribution transformer has been omitted for the sake of simplicity. Depending on its rated power and short-circuit voltage, the results would only be marginally different.

In [7], a continuous feeder (infinite number of infinitely small PV installations) of length L and per length impedance $Z'=R'+jX'$ is considered. According to this approach (see Fig. 1), the following four scenarios for the PV distributions are considered here:

- Scenario 1: uniformly distributed generation
- Scenario 2: linearly increasing generation
- Scenario 3: linearly decreasing generation
- Scenario 4: punctual generation (end of the feeder)

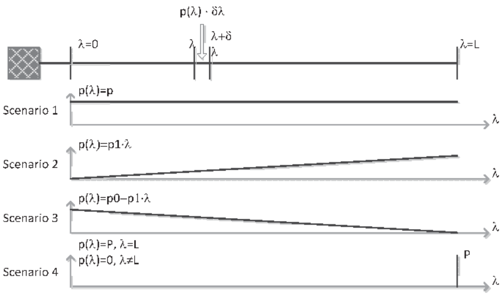


Fig. 1. Test feeders with the four considered scenarios.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

In Fig. 1, λ is the relative position along the feeder, L is the total feeder length, $p(\lambda)$ is the power density (the power injected between λ and λ+δλ is $p(\lambda).\delta\lambda$), with $p0$ and $p1$ as linear coefficients. Modelling LV feeders with a continuous PV power density, allows for the comparison of different controllers and generalised parameterization, in order to avoid results specific to a particular network or consumption situation, which occur within a given real network. Furthermore, feeders with a limited number of roughly uniformly distributed installations (e.g. 10) behave like a continuous feeder.

C. Hosting capacity determination

For each of the scenarios introduced in the previous Section, the hosting capacity has been calculated considering a maximal voltage rise of 8 % which is significantly higher than the planning limit of 3 % specified in current connection rules (e.g. [8] in Germany and few other European countries). The reason being that the current planning rules will be revised and become less conservative when the system observability increases or when medium voltage and low voltage levels become decoupled with the use of on-load-tap-changing distribution transformers. The maximum admissible loading has been considered to be 100 % and has never been reached due to the chosen feeder length.

Fig. 2 shows the result of the hosting capacity evaluation for the four considered PV distribution scenarios, expressed as power density (W/m), with the length of the feeder being arbitrary. As expected, Scenario 3 ("decreasing") leads to the highest hosting capacity and Scenario 4 ("punctual") leads to the lowest hosting capacity.

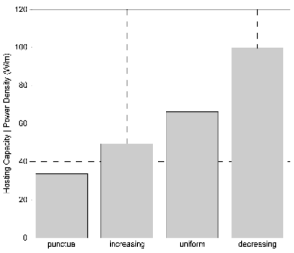


Fig. 2. Hosting capacity (expressed here as power density) for the four PV distribution scenarios (overhead line).

IV. Comparison Of Different Local Control Concepts – Parametric Study

A. Method and modelling assumptions

The proposed network is a continuous feeder (overhead line or cable) with an infinite number of PV generators. A simple computation showed that using 100 nodes (or generators) is sufficient to approximate the theoretical case. The hosting capacity is considered to be limited by the maximum admissible voltage. It was confirmed by verifying that the loading of the cable or the overhead line always stays below 100 % at full reactive power consumption. The PV generation is considered to be symmetrical, homogenously and continuously distributed along the feeder (Scenario 1). Low voltage consumers are not explicitly considered in this study as they would, impact some of the results (lower voltages, losses, curtailment or greater hosting capacity). Additionally, using specific consumption profiles would lead to specific results due to the stochastic character of consumers in LV networks. On the other hand, using a uniform consumption density would result in a reduced generation density and, by de facto, not affect the results.

The amount of PV generation connected along the feeder has been investigated for the three basic types of control:

- without control
- reactive power-based voltage control (*Q(U) / cosφ(P)*)
- reactive and active power-based voltage control *Q&P(U) / cosφ(P)&P(U)*

While the reactive power control helps to reduce the voltage rise caused by the PV infeed, the violation of voltage limits cannot be fully excluded in the case of wrong planning. For this reason, an active power curtailment (*P(U)*) has been considered.

For the reactive power-based controls, the amount of PV generation has been chosen so that the maximal voltage (at the end of the feeder) can be kept to 1.09 p.u., leaving 1 % of the nominal voltage as reserve. This reserve has been considered due to the fact that the reactive power control does not a priori guarantee that the voltage remains below the limit, unlike active power control for which the limit has been set to 1.10 p.u.. TABLE I summarises the power density considered for the three scenarios (three types of control).

TABLE I
MAXIMUM POWER DENSITY FOR THE DIFFERENT TYPES OF CONTROL

Control	Max. power density (W/m)	
	Cab. (150 mm²)	OH (70 mm²)
w/o control	117	57
reactive power control only	148	93
reactive and active power control	185	116

This table shows that the hosting capacity can be increased by 26 % for the cable network and 63 % for the over-head line network with reactive power control. For reactive and active power-based controls, the amount of generation has been increased by 25 % compared to the reactive power-based controls.

The minimal power factor is considered to be 0.90, the *PQ*-diagram of the inverter is considered to be triangular (see Fig. 3) and the PV inverters are considered to be sufficiently rated, so that they can operate with a power factor of 0.90 at full active power output (oversizing by about 11 %).

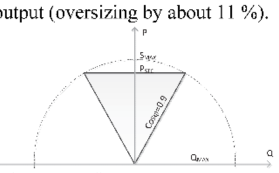


Fig. 3. Considered inverter *PQ*-diagram.

The control modes listed in TABLE II have been considered.

TABLE II
CONTROL MODES SETTINGS

Control	
Q(U)	*Q(U)* with all possible settings
cosφ(P)	*cosφ(P)* according to [8]
P&Q(U)	*P(U)* according to Fig. 4
cosφ(P)&P(U)	*cosφ(P)* according to [8] and *P(U)* as previously
P(U)	as previously
Optimal Power Flow	Maximise the net PV power subject to: • U_{max}=1.10 p.u. • max. loading A_{max}=100 % (not limiting)

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

The *Q(U)*-settings have been varied between 1.02 p.u. and 1.09 p.u. (the start of the *P(U)*-control, if activated). In this study, control parameters are always chosen symmetrically (for under- and over-voltage settings around the nominal voltage). In total, 28 different settings have been considered for the *Q(U)* control.

In order to sort out all these cases, an index is proposed to quantify a priori the effectiveness of the *Q(U)*-control. The Volt-Var-index (*VVI*) is defined as the ratio between the dashed area and dotted area in Fig. 4 (size of the area with control (Q>0) in relation to the whole voltage band). In Fig. 4, *UQdb* and *UQmax* are the dead-band voltage and the voltage above which Q is at maximum for *Q(U)* while *UPdb* and *UPmax* are the dead-band voltage and the voltage above which P is reduced to zero for *P(U)*.

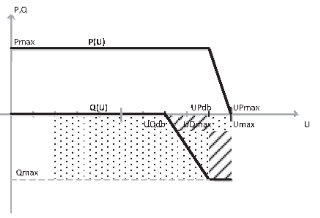


Fig. 4. Exemplary *Q(U)* and *P(U)* (here limited to $U \geq U_N$).

In addition, an optimal power flow (OPF) has been implemented for benchmarking purposes. Although the implementation of an OPF is not realistic in LV networks due to high requirements in terms of control and communication, it allows for the comparison of the results to a reference. Among all the possible OPF formulations [30], a simple implementation has been chosen for the purpose of this study: the objective has been set to maximise the net PV production (export to the upstream network P_{net}, see (1)). The equality constraints are, as usual, the power flow equations ((2)-(3)) and the inequality constraints are the operational constraints of the network (voltage limits (4) and current limits (5)) and from the PV generators ((6)-(7)). The operational constraints of the PV generators, in reality, do not exactly follow (6)-(7) but fully reflect the *PQ*-diagram of the inverters.

$$max\ P_{net} \quad (1)$$

$$0 = -P_i + \sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right), \mathrm{i} = 1..\mathrm{N} \quad (2)$$

$$0 = -Q_i + \sum_{j=1}^{N} V_i V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}\right), \mathrm{i} = 1..\mathrm{N} \quad (3)$$

$$U_{min} \leq u_i \leq U_{max}, \mathrm{i} = 1..\mathrm{N} \quad (4)$$

$$I_{ij} \leq I_{max,ij}, \mathrm{i}, \mathrm{j} = 1..\mathrm{N} \quad (5)$$

$$P_i \leq P_{max\,i}, \mathrm{i} = 1..\mathrm{N} \quad (6)$$

$$Q_{min} \leq Q_i \leq Q_{max}, \mathrm{i} = 1..\mathrm{N} \quad (7)$$

In equations (1) to (7), i and j are node indices, N is the number of nodes. P_i and Q_i, are the net active and reactive power respectively, injected at node i. G_{ij} and B_{ij} are the real and imaginary parts of the corresponding element of the admittance matrix. θ_{ij} is the difference in voltage angle between nodes i and j. u_i is the voltage at node i and I_{ij} is the current flowing between nodes i and j. U_{min} and U_{max} are the planning voltage limits and $I_{max,ij}$ is the rated current of the line between nodes i and j. $P_{max,i}$, $Q_{min,i}$ and $Q_{max,i}$ represent the operational limits of generator i.

The evaluation of "integral figures" (e.g. yearly network losses, reactive power balance over the year, curtailed energy) has been carried out using typical measured PV profiles, which capture the stochastic nature of PV generation. These profiles for sunny/cloudy/variable days of summer and winter, are weighted with their respective their respective occurrence, as per the approach and PV profiles used in [31]. The software DIgSILENT© PowerFactory has been used for all the simulations.

B. *Effectiveness of the considered local controls*

Fig. 5 shows the voltage profile, along with the injected active and reactive power along the overhead line feeder for a high PV infeed scenario, and also utilising *Q&P(U)* control. Four representative *VVI* values (Reference=without control and *VVI* = 0.25/0.5/0.75) have been considered. As expected, it can be seen that for smaller *VVI* values (e.g. *VVI*=0.25), only the generators located at the end of the feeder consume the maximum reactive power and reduce the voltage (only generators situated in the last 40 % of the feeder length). For a *VVI* value of about 0.5, generators at the end of the feeder have to curtail their output power by about 50 % at full PV infeed.

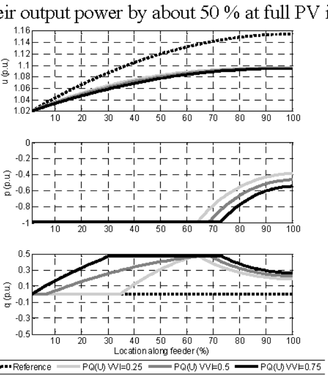


Fig. 5. Voltage profile, active and reactive power injection along the feeder for three different *Q&P(U)* control parameterizations - OH.

Fig. 6 shows the impact of the control mode and parameterization (*cosφ(P)* and *Q(U)*) on the maximum voltage for the overhead line feeder. Since the voltage curve as a function of the *VVI* (and later all the other curves) is globally monotone (there is only a very small variation for identical *VVI* values), the *VVI* is a suitable index to prequantify the performance of the *Q(U)* control. Fig. 6 further shows a limited difference between lowest and highest *VVI*, which means that the effectiveness of the different types of control and parametrization are rather comparable (about 1.3 % of the nominal voltage or approximately 10 % of the voltage rise caused by the considered PV infeed without control (11.1 %)). The voltage maximum can be reduced from about 1.13 p.u. to about 1.09 p.u. for the *cosφ(P)* control (-4.2 percentage points / voltage rise compensation of almost 40 %).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

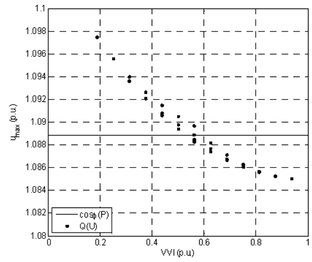


Fig. 6. Impact of parameterization on maximal voltage - OH.

C. *Impact on reactive power, losses and curtailment*

Since reactive power consumption has some implications for the distribution network operator (possible charges by the transmission network operator), the reactive energy has been evaluated. Fig. 7 shows the impact of the parameterization on the yearly reactive power balance. For the overhead line feeder, the ratio between the integral of the reactive energy and the integral of the active energy ("*tanφ*"), summed up for all generators, lies between 0.47 for the most effective *Q(U)* control (high *VVI* and lowest maximal voltage) and 0.07 for the least effective *Q(U)* control (low *VVI* and highest maximal voltage). The overall amount of reactive power consumed to control the voltage is six times greater for the highest *VVI* than for the lowest *VVI*.

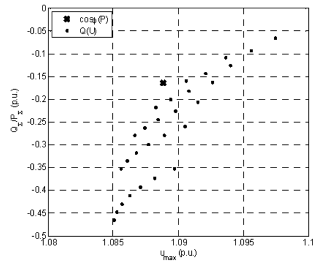


Fig. 7. Reactive energy (*Q*/*P* ratio) consumed for *cosφ(P)* and *Q(U)* against the maximal voltage - OH.

Fig. 8 shows a comparison between the reactive power balance for the *Q(U)*-control and the *cosφ(P)* by using the *cosφ(P)* as reference. It shows that below a *VVI* of about 0.40, the *Q(U)* control leads to a smaller integral reactive power consumption than the *cosφ(P)* control. The most effective *Q(U)* control (highest *VVI*) leads to almost 200 % more reactive energy consumption. Indeed, high *VVI* values are reached by moving the *Q(U)* characteristic to the left (close to the nominal voltage) which forces all the inverters to consume reactive power even for low infeed values.

Fig. 9 shows the impact of the different reactive power control modes and parameterization on the feeder losses. It shows that the most effective *Q(U)* parameterization (highest *VVI*) leads to a relative increase of losses of about 28 % compared to the reference case without control. In comparison, the *cosφ(P)* control leads to an increase of about 10 %. These relative values may seem high, but they correspond to very high PV penetration scenarios and do not consider the effect of consumers.

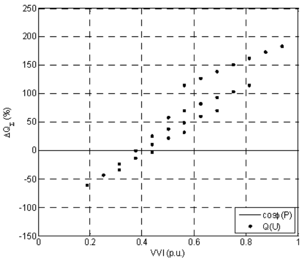


Fig. 8. Reactive energy (*Q*/*P* ratio) consumed for *cosφ(P)* and *Q(U)* - OH.

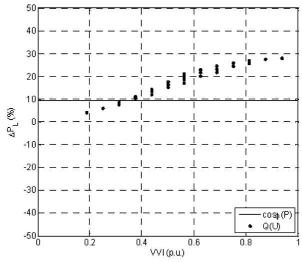


Fig. 9. Impact of parameterization on network losses - OH (relative increase).

Fig. 10 and Fig. 11 show the impact of the control mode and parameterization on the energy curtailment and the feeder losses (overhead line / cable). Both magnitudes are calculated for a year.

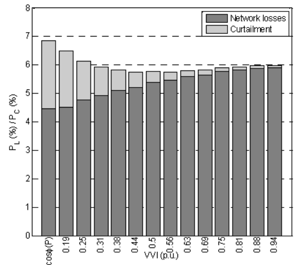


Fig. 10. Impact of control parameters on network losses and curtailment - OH.

For the overhead line feeder, Fig. 10 shows the existence of a minimum of the sum of losses and curtailment for *VVI* between 0.44 and 0.63 (trade-off for sum of energy curtailment and network losses (losses of 5.2 % and curtailment of 0.55 %=5.75 % of the annual yield)). However, the curve is very flat and any *VVI* value above 0.3 leads to almost the same value. Therefore, the exact parameterization of the *Q(U)* control does not play a major role in this regard, however the *Q(U)* control always leads to smaller network losses and active energy curtailment (almost 20 %) than for *cosφ(P)*.

For the cable feeder (Fig. 11), the sum of active energy curtailment and network losses is higher for high VVI values, but the curve is even flatter than for the overhead line feeder. There is no significant difference between the *cosφ(P)* and *Q(U)* control for such feeders.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

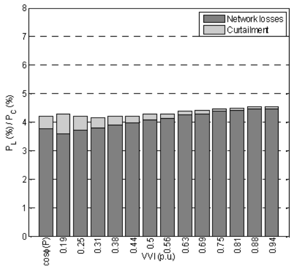


Fig. 11. Impact control parameters on network losses and curtailment - Cab.

D. Benchmark with optimal power flow

Finally, the hosting capacity has been evaluated for two different types of control:

- *Q&P(U)* control (*VVI*=0.5)
- Optimal Power Flow for benchmark purpose

For both control types, the base scenario is defined as the maximal PV power density leading to a maximal voltage of 1.10 p.u. without control. This maximum PV power density is given in TABLE III for the cable and the overhead line feeder. In the following, the power density (quantifying here the PV penetration) is always normalised to these p_0 values.

TABLE III
REFERENCE POWER FOR THE CABLE AND THE OVERHEAD LINE FEEDER

Feeder	Cable	Overhead line
Power density *p0* (W/m)	135.6	65.3

To begin with, the impact of the installed power on the energy curtailment has been quantified for the cable feeder (Fig. 12) and the overhead line feeder (Fig. 13) on the same basis as in [32].

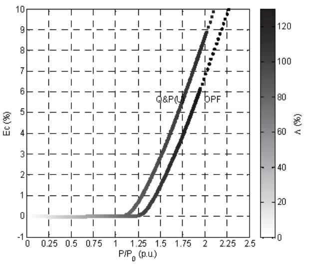


Fig. 12. Curtailed energy (Ec) as a function of the PV penetration - Cab.

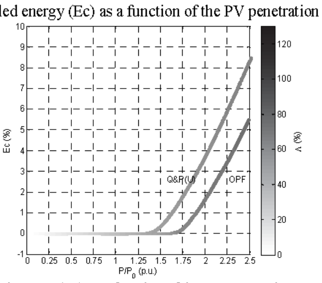


Fig. 13. Curtailed energy (Ec) as a function of the PV penetration - OH.

In these figures, the grey scale is used to represent the maximum loading Λ and the dotted part of the curves represent penetration levels that lead to overloading. The flat-shape of the curves in Fig. 12 (cable feeder) shows that a limited curtailment can already significantly increase the hosting capacity, as observed in [32]. With the *Q&P(U)* control, the hosting capacity can be increased by about 50 % or 70 % if accepting a curtailment of 3 % or 5 %. For comparison, the OPF would lead to a hosting capacity increase of 66 % or 84 % for 3 % and 5 % curtailment, respectively. With the penetration levels considered here (+84 % for the OPF corresponding to a curtailment of 5 % of the annual yield), the loading constraint is not reached and the cable feeder remains voltage-constrained.

Fig. 13 (overhead line feeder) shows that with the *Q&P(U)* control, the hosting capacity can be increased by about 91 % or 115 % when accepting a 3 % or 5 % curtailment. For comparison, the OPF would lead to a hosting capacity increase of 119 % and 143 % for 3 % and 5 % curtailment. The overhead line feeder is voltage-constrained and is not overloaded. These figures are summarised in TABLE IV.

TABLE IV
HOSTING CAPACITY INCREASE FOR DIFFERENT CURTAILMENT (Q&P(U) CONTROL)

Curtailment	3 %	5 %
Cable feeder	+50 %	+70 %
Overhead line feeder	+91 %	+115 %

In the next step, the hosting capacity has been calculated for the two selected controls (*Q&P(U)* and OPF) and visualised in the *UI*-plane. Fig. 14 shows for the cable feeder the impact of increasing the PV penetration (measured as the power density) on the feeder loading and maximum voltage. Three different curves are shown for: the reference scenario - without control, *Q&P(U)* control and OPF. The colour represents the power density normalised to the reference (hosting capacity without control) and the doted part of the curves represents penetration levels resulting in energy curtailment.

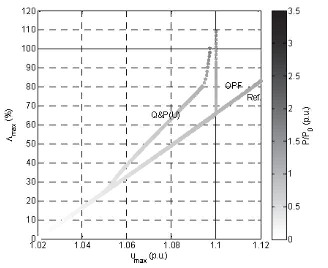


Fig. 14. Hosting capacity in the *UI*-plane - Cab.

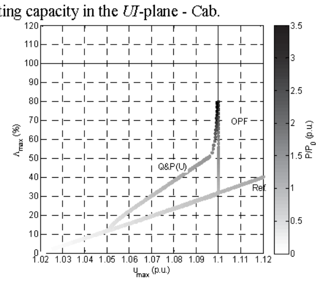


Fig. 15. Hosting capacity in the *UI*-plane - OH.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

As observed previously, the hosting capacity can be enhanced to a greater extent for the overhead line feeder (Fig. 15) than for the cable feeder (Fig. 14) due to the lower *R/X* ratio.

The loading constraint is reached only for the cable feeder in the considered range (up to +250 % hosting capacity). For the overhead line feeder, the asymptotic behaviour is visible: any further increase of the PV penetration largely leads to a high increase of the loading and curtailment, while keeping the maximal voltage below the limit. Shorter feeders change from loading-constrained to being voltage constrained when using *Q&P(U)* control. Ultimately, these figures show that *Q&P(U)* control is 30 % less effective (hosting capacity is 30 % lower) than the optimal power flow for a given maximal curtailment of, as an example, 3 %.

E. Impact of feeder properties on the control effectiveness

For all the investigations shown previously, only one type of cable and one type of overhead line has been considered (standard types). In this subsection, a sensitivity analysis is done to evaluate the impact of different types of cables and overhead lines on the effectiveness of the reactive power-based voltage control. The R/X ratio has been varied between 0.5 and 3. A 120 mm^2 overhead line has, for example, a R/X ratio of about 0.8 and a 120 mm^2 cable a R/X ratio of about 3.2 For a given R/X ratio and a given power factor, the compensation of the voltage rise can be estimated by (8), where P is the injected active power, R and X are the network resistance and reactance respectively and φ is the phase angle between the voltage and current.

$$\Delta U \approx \frac{R \cdot P}{U_N^2} \cdot \left(1 - tan(\varphi) \cdot \frac{1}{R/X}\right) \quad (8)$$

Fig. 16 (upper-left part) shows the impact of both the R/X ratio and the power factor of the PV inverter that is achievable from the compensation of the voltage rise, according to (8). The upper-right part shows the section for different R/X ratios, with the power factor maintained at 0.90 and the lower-left part shows the section for different power factors keeping the R/X ratio to at 1.41 (corresponding to the chosen overhead line of 70 mm^2).

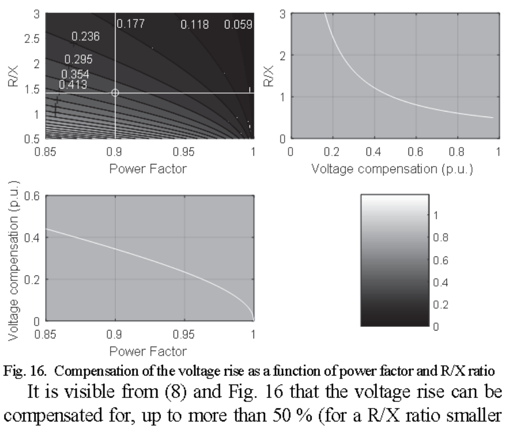


Fig. 16. Compensation of the voltage rise as a function of power factor and R/X ratio

It is visible from (8) and Fig. 16 that the voltage rise can be compensated for, up to more than 50 % (for a R/X ratio smaller than 1 (e.g. 120 mm^2 overhead line) and power factor of 0.90). For the chosen standard cable and the overhead line, the compensation factor reaches about 19 % and 34 % respectively. In practise, the reactance of the distribution transformer decreases the R/X factor (especially small transformers with a large short-circuit voltage) and slightly higher compensation grades are possible. Following on from this simple sensitivity analysis, the hosting capacity increase can be estimated for other types of cables or overhead lines.

V. Discussion and Conclusion

This paper presented the results of comprehensive investigations on the performance and effectiveness of common reactive power-based controls with optional active power curtailment. These investigations tend to show a slightly better performance of the *Q(U)* control, as summarised below.

The proposed Volt-Var Index (*VVI*) proved to be a suitable indicator for the comparison of different potential settings of the *Q(U)*-control (i.e. dead-band, droop value). These settings have a large impact on the consumed reactive energy (factor six between the least effective and the most effective *Q(U)* control) and on the effectiveness of the control (ability to compensate the voltage rise caused by the infeed).

A comparison between the *cosφ(P)* and *Q(U)* controls shows that their general performance is comparable for an average parametrization (*VVI* close to 5 – dead band until 1.05 p.u. and maximum reactive power consumption beyond 1.07 p.u.).

On the one hand, their effectiveness is very similar: with a *VVI*-value of about 0.5, both controls lead to a reduction of the initial voltage rise of 11.1 % by more than 4 percent (voltage rise compensation by about 40 % for the overhead line feeder).

The consumed reactive energy is also similar for both types of control with a *VVI*-value around 0.5.

In terms of network losses, the Q(U) control parametrized at a *VVI*-value of around 0.5 leads to slightly higher losses than the cosφ(P) control (increase of 15 % vs. 10 %).

In practice, a *Q(U)* control will however generally lead to a lower reactive energy consumption and to lower network losses since it reacts on the actual voltage which is influenced by loads connected to the different voltage levels.

Active power curtailment (*P(U)*) has been implemented and integrated in addition to the reactive power-based voltage control, showing an interesting potential of increasing the hosting capacity by +50 % for the cable feeder (and 90 % for the overhead line feeder) at the cost of a small reduction in the annual yield.

This parametric study tends to show that the impact of the settings of voltage controllers is limited, however, with a generally better performance of the *Q(U)* control, especially for very high penetration or for networks not yet needing this controls (low PV penetration). According to these investigations, the *Q(U)* curve should be parametrized to lie in the middle between the no-load voltage and the maximum allowed voltage (*VVI*=0.5), to ensure maximal effectiveness at minimal reactive energy consumption, network losses and curtailment.

For further work, more detailed investigations considering different voltage levels should be performed for deeper

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

investigation into the actual reactive energy consumption for a whole DSO supply area and evaluate the potential financial implications depending on the charging system between transmission and distribution networks. In addition, promising features of modern PV inverters such as the provision of reactive power during night time should be considered and monetized.

VI. References

[1] G. Masson, S. Orlandi, and M. Rekinger, "Global market outlook for Photovoltaics 2014-2018." 2014.

[2] "EnergyMap - Auf dem Weg zu 100% EE," 04-Feb-2015. [Online]. Available: http://www.energymap.info/. [Accessed: 04-Feb-2015].

[3] Stetz, "Autonomous Voltage Control Strategies in Distribution Grids with Photovoltaic Systems: Technical and Economic Assessment," Kassel University press GmbH, 2014.

[4] G. Kerber, R. Witzmann, and H. Sappl, "Voltage limitation by autonomous reactive power control of grid connected photovoltaic inverters," in *Proc. Compatibility and Power Electronics, 2009. CPE'09.*, 2009, pp. 129–133.

[5] CENELEC, "Voltage characteristics of electricity supplied by public electricity networks." 01-Mar-2011.

[6] M. Braun, T. Stetz, R. Bründlinger, C. Mayr, K. Ogimoto, H. Hatta, H. Kobayashi, B. Kroposki, B. Mather, M. Coddington, K. Lynn, G. Graditi, A. Woyte, and I. MacGill, "Is the distribution grid ready to accept large-scale photovoltaic deployment? State of the art, progress, and future prospects," *Prog. Photovolt. Res. Appl.*, vol. 20, no. 6, pp. 681–697, Sep. 2012.

[7] M. H. J. Bollen and A. Sannino, "Voltage Control With Inverter-Based Distributed Generation," *IEEE Trans. Power Deliv.*, vol. 20, no. 1, pp. 519–520, Jan. 2005.

[8] VDE-FNN, "VDE-AR-N 4105:2011-08 Power generation systems connected to the low-voltage distribution network." Aug-2011.

[9] "Generating Plants Connected to the Medium-Voltage Network," Jun. 2008.

[10] CEI, "CEI 0-21 - Reference technical rules for the connection of active and passive users to the LV electrical Utilities." Dec-2013.

[11] E-CONTROL, "Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen." 2013.

[12] B. Bletterie, A. Goršek, T. Fawzy, D. Premm, W. Deprez, F. Truyens, A. Woyte, B. Blazič, and B. Uljanič, "Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks," *Prog. Photovolt. Res. Appl.*, vol. 20, no. 6, pp. 747–759, Sep. 2012.

[13] E. Demirok, P. C. González, K. H. B. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, "Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids," *IEEE J. Photovolt.*, vol. 1, no. 2, pp. 174–182, Oct. 2011.

[14] S. Alyami, Y. Wang, C. Wang, J. Zhao, and B. Zhao, "Adaptive Real Power Capping Method for Fair Overvoltage Regulation of Distribution Networks With High Penetration of PV Systems," *IEEE Trans. Smart Grid*, vol. 5, no. 6, pp. 2729–2738, Nov. 2014.

[15] R. Tonkoski, L. A. C. Lopes, and T. H. M. EL-Fouly, "Coordinated Active Power Curtailment of Grid Connected PV Inverters for Overvoltage Prevention," *IEEE Trans. Sustain. Energy*, vol. 2, no. 2, pp. 139–147, Apr. 2011.

[16] B. Bletterie, A. Gorsek, A. Abart, and M. Heidl, "Understanding the effects of unsymmetrical infeed on the voltage rise for the design of suitable voltage control algorithms with PV inverters," in *Proc. 26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, 2011, pp. 4469 – 4478.

[17] B. Bletterie, S. Kadam, R. Pitz, and A. Abart, "Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters," in *Proc. PowerTech 2013 IEEE Grenoble*, 2013, pp. 1–6.

[18] L. Degroote, B. Renders, B. Meersman, and L. Vandevelde, "Neutral-point shifting and voltage unbalance due to single-phase DG units in low voltage distribution networks," in *Proc. PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1–8.

[19] S. Weckx, C. GonzalezDeMiguel, P. Vingerhoets, and J. Driesen, "Phase switching and phase balancing to cope with a massive photovoltaic penetration," in *Proc. Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[20] F. Andren, B. Bletterie, S. Kadam, P. Kotsampopoulos, and C. Bucher, "On the Stability of local Voltage Control in Distribution Networks with a High Penetration of Inverter-Based Generation," *IEEE Trans. Ind. Electron.*, pp. 1–1, 2014.

[21] A. Constantin and R. D. Lazar, "Open Loop Q(U) Stability Investigation in Case of PV Power Plants," in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 3745 – 3749.

[22] B. Bletterie, A. Stojanovic, S. Kadam, G. Lauss, M. Heidl, C. Winter, D. Hanek, A. Pamer, and A. Abart, "Local voltage control by PV inverters first operating experience from simulation, laboratory tests and field tests," in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4574–4581.

[23] H. Wang, T. Stetz, M. Kraiczy, C. Töbermann, and M. Braun, "Parallel operation of photovoltaic inverters with autonomous voltage control strategies – comparison of Q(V)/P(V) and automatic voltage limitation," in *Proc. 29th European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, 2014, pp. 2921 – 2926.

[24] T. Stetz, F. Marten, and M. Braun, "Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 534–542, Apr. 2013.

[25] J. Barr and R. Majumder, "Integration of Distributed Generation in the Volt/VAR Management System for Active Distribution Networks," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 576–586, Mar. 2015.

[26] A. Einfalt, F. Zeilinger, R. Schwalbe, B. Bletterie, and S. Kadam, "Controlling active low voltage distribution grids with minimum efforts on costs and engineering," in *Proc. Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE*, 2013, pp. 7456–7461.

[27] A. Einfalt, F. Kupzog, H. Brunner, and A. Lugmaier, "Control strategies for smart low voltage grids — The project DG DemoNet — Smart LV Grid," in *Proc. CIRED Workshop*, Lisbon, 2012, pp. 1–4.

[28] C. Schwaegerl, M. H. J. Bollen, K. Karoui, and A. Yagmur, "Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources," in *Proc. Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on*, 2005, pp. 1–5.

[29] M. H. Bollen and H. Fainan, *Integration of Distributed Generation in the Power System*. John Wiley & Sons, 2011.

[30] J. A. Momoh, M. E. El-Hawary, and R. Adapa, "A review of selected optimal power flow literature to 1993. I. Nonlinear and quadratic programming approaches," *IEEE Transation Power Syst.*, vol. 14, no. 1, pp. 96–104, Feb. 1999.

[31] B. Bletterie, S. Kadam, M. Heidl, C. Winter, D. Hanek, and A. Abart, "Techno-Economic Evaluation of Voltage Control in LV Networks: A Smart Grid Case Study," in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Paris, 2013, pp. 4210 – 4216.

[32] N. Etherden and M. H. J. Bollen, "Overload and overvoltage in low-voltage and medium-voltage networks due to renewable energy – some illustrative case studies," *Electr. Power Syst. Res.*, vol. 114, pp. 39–48, Sep. 2014.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2016.2554099, IEEE Transactions on Power Systems

VII. Biographies

Benoît Bletterie, (M'07) born in 1978 in Vichy, France, studied electrical engineering at Supélec and Universidad Politécnica de Madrid (2001). He is working as senior engineer at the Austrian Institute of Technology (AIT) in the field of smart grids, network integration, network planning, voltage control. He has worked in several national and European research projects (DG DemoNetz, morePV2grid, MetaPV, EcoGrid EU, IGREENGrid). He published more than 70 papers in this area and is an active member of several standardization working groups.

Serdar Kadam holds an Electrical Engineering master degree from the University of Technology Vienna. His master thesis "Systematical analysis of low voltage-networks for smart grid studies" and was awarded by Austrian Society for Power Engineering. Since 2012 he is working at the Austrian Institute of Technology on several national and European research projects in the field of Smart Grids. His main interests are network simulation and modelling of Smart Grid functionalities. Currently he is pursuing a PhD degree on the topic of reference feeders and network classification.

Roman Bolgaryn, born in 1992 in Dnipropetrowsk, Ukraine, has studied Renewable energy systems at UAS Technikum Wien. He has written his Master thesis at the Austrian Institute of Technology on the topic "Compensation of voltage unbalance in LV networks to increase hosting capacity". His main interests are smart grids and renewable energy.

Antony Zegers, born 25th of March 1986, Belgium, studied Electro-Mechanical Engineering at Ghent University in Belgium. He gained experience in the utility sector working as an R&D engineer Smart Grids at Eandis, Belgium´s largest distribution network operator. In 2013, he joined the Austrian Institute of Technology, and is responsible for R&D projects for System Operators and Service Providers. His main experience areas are the integration of renewable energy sources in distribution grids and the implementation of ancillary services.

Publication 6

“On the stability of local voltage control in distribution networks with a high penetration of inverter-based generation”

F. Andren, B. Bletterie, S. Kadam, P. Kotsampopoulos, and C. Bucher, “On the Stability of local Voltage Control in Distribution Networks with a High Penetration of Inverter-Based Generation,” IEEE Trans. Ind. Electron., pp. 1–1, 2014.

Own contribution

This paper presents the results of a detailed investigation of possible stability problems in distribution networks with several generators operating in Volt/var control mode.

The applicant initiated and coordinated the research activities summarised in this paper. With the help of the third author, he developed an average model of the inverter operating in Volat/var control mode, which is suitable for stability analysis. He performed the first investigations with the modal analysis in PowerFactory and implemented with the help of the first author the simulation model in Matlab for verification and generalisation purpose. With the help of the second author, he automated the simulations to perform a parametric study and established a clear stability criterion. He also performed the lab used for validation purpose and initiated a follow-up work using power hardware-in-the-loop together with the fourth author.

IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 62, NO. 4, APRIL 2015 2519

On the Stability of Local Voltage Control in Distribution Networks With a High Penetration of Inverter-Based Generation

Filip Andrén, *Member, IEEE*, Benoit Bletterie, *Member, IEEE*, Serdar Kadam, Panos Kotsampopoulos, *Member, IEEE*, and Christof Bucher

***Abstract*—A stability study of distribution networks with a high penetration of distributed generators (DGs) actively supporting the network is presented in this paper. A possible way of mitigating the voltage rise caused by DGs is the local control of reactive power. Among the different possible options, the Q(U) control (reactive power as a function of the voltage) is one of the commonly suggested solutions. However, the Q(U) control can, under certain conditions, lead to instability. This paper summarizes the results of a stability study conducted on a single-inverter system and on a multiinverter system. It shows that the requirements for reaching a stable operation can easily be met for integrated systems but could be a significant constraint for systems relying on communication.**

***Index Terms*—Inverters, power distribution, power system stability, voltage control.**

I. Introduction

SOLAR photovoltaic (PV) power is considered in most scenarios as an important energy resource to meet the medium- and long-term renewable energy targets [1]. It is also one of the most distributed energy resources. In some rural areas, the hosting capacity of distribution networks has been exhausted [2]. To avoid or postpone network reinforcement, generators are required to contribute to the system operation by providing ancillary services [3]. One of the main problems in rural areas is the voltage rise caused by power infeed from distributed generators (DGs). Among the two most discussed control options for mitigating the voltage rise (power factor as a function of the injected power, i.e., $\cos\varphi(\mathrm{P})$, and reactive power as a function of the voltage, i.e., Q(U)) [3], the Q(U) control exhibits a feedback loop and can potentially lead to instability.

Even if the general idea of the local voltage control is not to react on each very fast voltage variation (caused by, e.g., sudden load changes) but rather to compensate part of the voltage rise caused by the own PV infeed, the stability of a large system with hundreds of generators controlling the voltage must be guaranteed [2]. Given the minimum performance that controllers must meet according to current requirements, a sufficient stability reserve or damping must be ensured. Until now, the stability issue of the Q(U) control has been insufficiently addressed, which might explain the rather low deployment of this control in practice. The purpose of this paper is to establish a clear stability criterion for networks with a high share of DGs.

This paper is organized as follows. Section II provides an introduction to the problem of voltage rise through distributed generation and an overview of related work. Section III gives a general description of the problem studied in this paper. Section IV provides the stability study of a system with a single inverter, and Section V generalizes this to a multiple-inverter system. In Section VI, results from a laboratory experiment are discussed, and Section VII concludes this paper.

II. Voltage Rise Through Distributed Generation

A. Related Work

In recent years, the increase of renewable energies and DGs has led to new problems and challenges for network operators [4], [5]. As a consequence, ancillary services for medium- and low-voltage networks have received a higher focus in projects and grid-interconnection codes [3], [6].

One example where ancillary services have become necessary is the so-called "50.2-Hz problem" in Germany, which is caused by the automatic disconnection of PV systems in case of nonsevere overfrequency. With a PV generation capacity exceeding 30 GW, the system security is not guaranteed anymore, and corrective actions must be taken [7].

Since the PV generation is almost exclusively connected at distribution level, and most of it at low voltage level, local problems and, in particular, voltage rise problems are increasingly experienced in rural areas of several countries [8]–[11]. Ancillary services can help increasing the network hosting capacity while maintaining the quality of supply through local voltage control [8]–[11].

The issue of voltage control with PV inverters is particularly relevant in microgrids and has been investigated for such systems [12], [13]. In microgrids, inverter-connected systems (e.g., PV and wind generators) play an important role and must be controlled to ensure the system stability and maintain frequency

Manuscript received February 18, 2014; revised June 13, 2014; accepted July 14, 2014. Date of publication August 1, 2014; date of current version March 6, 2015.

F. Andrén, B. Bletterie, and S. Kadam are with the Energy Department, AIT Austrian Institute of Technology, 1210 Vienna, Austria (e-mail: filip.andren@ait.ac.at; benoit.bletterie@ait.ac.at; serdar.kadam@ait.ac.at).

P. Kotsampopoulos is with the National Technical University of Athens, 10682 Athens, Greece (e-mail: kotsa@power.ece.ntua.gr).

C. Bucher is with Basler and Hofmann AG, 8032 Zürich, Switzerland (e-mail: christof.bucher@baslerhofmann.ch).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIE.2014.2345347

and voltage within acceptable limits. For this, droop control for frequency and voltage control is a common technique for controlling inverters in microgrids [13], [14].

In normal grid-connected systems, local voltage control through DGs also becomes more and more common [15]–[18]. Since DGs are usually operated to feed as much active power as possible into the network, these solutions usually concentrate on reactive power. In order to mitigate unwanted voltage changes, the DGs consume or produce reactive power [15]–[17]. This paper focuses on a concept consisting in controlling the reactive power exchanged with the network depending on the voltage at the generator's point of connection (Q(U) control).

In order to limit the possible drawbacks from the generator or the network point of view, new and effective methods need to be implemented into inverters, which can then offer voltage control as an ancillary service [18].

In addition to purely local concepts such as the Q(U) control [10], many solutions in the literature focus on distributed voltage control solutions. These are often characterized by some central coordinator combined with local Q(U) controllers implemented in DGs. The coordinator is responsible for calculating optimal voltage set points for the local controllers, and the DGs provide reactive power based on this voltage set point [18]–[22]. The presence of local controllers in almost all the concepts (purely local/distributed) stresses the importance of ensuring the stability of inverters with voltage control features.

In addition to the use case of voltage control, there are also a number of examples in the literature where reactive power provided by DGs is used to improve the power quality or reduce power losses [10], [23].

Even if there already exist a lot of work on voltage control through reactive power management by inverters, very few have studied the actual stability of networks with a significant amount of local generation featuring these ancillary services. There are examples in the literature where the stability of the local controller has been investigated [24]. However, so far, very few investigations consider the stability of a power system with multiple inverters using Q(U) controllers. A first study of this was done in [25], where the stability of a PV plant with multiple inverters with Q(U) control was investigated through simulations. This paper generalizes the approach from [25] through an analytic study and further investigates how a stability criterion can be formulated for one or for several inverters.

B. Grid Connection Rules

Many existing grid codes already require DGs to be able to provide reactive power for voltage control purposes. However, even if the main general types of control are generally specified, many connection rules still do not specify any particular requirement on the dynamic response of these controls, e.g., Belgium [26] and Austria [27] are among the countries specifying a Q(U) control in their connection rules.

The German guideline for connecting generators to the MV network [6] and the Italian standard [28] have both rather general requirements. The Italian standard [28] requires the maximal response time to be smaller than 10 s, and the German guideline [6] states the following: "If a characteristic is specified by the network operator, any reactive power value resulting from the characteristic must automatically adapt as follows:

- within 10 s for the $\cos\varphi(\mathrm{P})$-characteristic and
- adjustable between 10 seconds and 1 minute for the Q(U) characteristic (specified by the network operator)."

The absence of requirement on the dynamic response of Q(U) controllers reflects the lack of investigations in this field. In this paper, the stability of the Q(U) control is investigated through generic simulations.

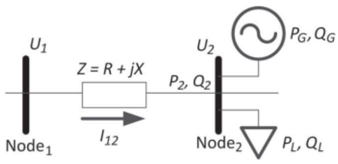


Fig. 1. Simplified view of a feeder in distribution grid.

III. General Problem Description

This section provides an overview of the main problem studied in this paper, i.e., voltage rise caused by DG and how to mitigate this by the supply of reactive power.

A. Problem Formulation

To get a more general view of the voltage rise problem in distribution networks and how this can be mitigated, a simple power system is considered (equivalent network at the point of connection; see Fig. 1). Based on this description, the following simplification can be formulated [29], [30]:

$$U_2 \approx U_1 + \frac{RP_2 + XQ_2}{U_2}. \tag{1}$$

Thus, the difference in voltage $\Delta U = U_2 - U_1$ between node 2 and node 1 (i.e., the voltage rise/drop) depends on the line parameters, i.e., R and X, and the active and reactive power injected at node 2, i.e., P_2 and Q_2. As can be seen in (1), the ratio between R and X determines the effectiveness of the reactive power Q_2 against the active power P_2 [29], [30].

In this paper, the main focus is on voltage rise caused by DG connected to low-voltage grids. The main idea is to partly mitigate the voltage rise with reactive power consumption by DGs. With a Q(U) controller, the reactive power of the DG is controlled depending on the current value of the local voltage, i.e., Q_G in Fig. 1 directly depends on the current voltage U_2.

B. Voltage Control Through Reactive Power

The Q(U) control is a nonlinear P-controller, with varying gain depending on the controller settings. Thus, the reactive power value is directly determined by the measured voltage. The whole system is of course a closed-loop system since the voltage at the terminals depends on the inverter reactive power output. Depending on the implementation of the controller, some instability may appear.

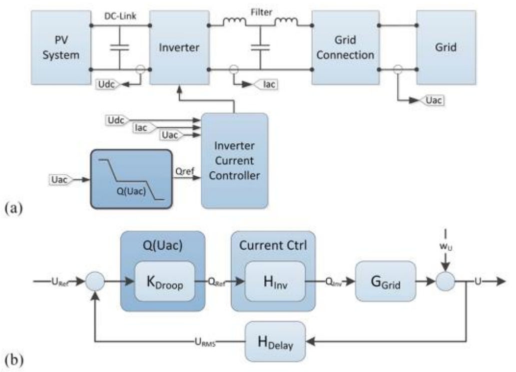


Fig. 2. (a) Overview of the investigated inverter system. (b) Simplified block representation of the studied control system.

A simplified representation of the inverter system is shown in Fig. 2(a). For the purpose of this study, the system is described by considering only the part of the inverter current controller related to the voltage control. Since the impact of the output filters on the reactive power output is usually compensated by the current controller within a very short time (a few cycles), these have not been considered here.

Fig. 2(b) shows a simplified version where only the most important components are shown. These components are as follows.

- K_{Droop}: This block represents the computation of the reactive power set point according to the parameterized characteristic. The relation between Q and U (droop) is not necessarily linear and generally consists of several areas (dead band, proportional part, limitation).
- H_{Inv}: This block represents the inverter dynamic, with focus on the reactive current controller represented by either of the following:
  - — first-order transfer function for which the time constant can be adjusted to the desired value;
  - — rate limiter for which the maximal reactive power gradient can be adjusted to the desired value.
- G_{Grid}: This block represents the network (modeled as an ideal voltage source behind the network impedance (R, X)).
- H_{Delay}: This block represents the delay after the voltage measurement, including all the signal processing (e.g., computation of the RMS, filtering, and averaging), as well as communication delays if any.
- w_U: This is the noise acting on the output voltage U. It can correspond, for example, to a voltage step caused by the sudden disconnection of a large load or by a sudden irradiance increase.

In theory, considering an ideal signal processing (e.g., voltage measurement) and no communication delays, such a system is always stable since the only pole of the system comes from the inverter dynamics (here, reactive current control), which is usually a first-order function (or a rate limiter). In practice, the signal processing introduces some delays, which influence the system stability. These delays can come from the following:

- delay due to the voltage RMS computation (at least half a cycle: 10 ms);
- delay introduced by filters to smoothen the voltage (e.g., signal processing and moving average);
- delay in the communication (e.g., communication between controllers within the inverter or between external controller and inverter).

For this study, the delays aforementioned were summarized into one delay, which is depicted as the measurement delay in Fig. 2(b).

The stability of the single- and multiinverter problems is investigated in Sections IV and V, respectively.

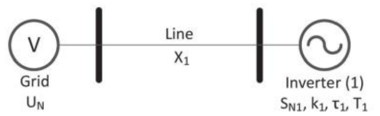


Fig. 3. Network model with a single inverter.

IV. Stability Study of the Single-Inverter Problem

This section shows the results of the investigations performed to study the stability of a network with a single inverter, as shown in Fig. 3.

A. Problem Linearization

The considered control system shown in Fig. 2(b) is a nonlinear system due to the following:

- the nonlinearity of the power flow (weak nonlinearity);
- the nonlinearity introduced by the controllers (e.g., rate limiter and delays);
- the nonlinearity of the droop control (Q(U)).

In order to investigate the stability with classical methods, the system will be linearized. By assuming that the system only operates in the droop part of the Q(U) characteristic, the system can be linearized around the operation point, and the stability can be studied by classical methods. In practice, the operation point can be anywhere on the Q(U) curve (block K_{Droop}). However, operation points within the dead-band ($Q = 0$) area and the limitation part ($Q = \pm Q_{\max}$) are always stable since the reactive power output is maintained at zero, disregarding the actual voltage. For this reason, this study has been limited to the linear part (droop).

In this paper, the inverter is considered to be sufficiently dimensioned to be able to provide the full reactive power at full active power output.

Based on Fig. 2(b), the transfer functions for the single-inverter problem can be formulated as follows:

$$K_{\text{Droop}} = k_1 = P_{N1} \cdot \tan\varphi_{\max} / \Delta U_{\text{droop}} \tag{2}$$

$$H_{\text{Inv}} = \frac{1}{1 + \tau_1 s} \tag{3}$$

$$G_{\mathrm{Grid}} = \frac{X_1}{U_N^2} \tag{4}$$

where s is the Laplace variable, k_1 is the droop factor at the point of linearization, P_{N1} is the nominal inverter active power, $\varphi_{\max}$ is the maximal displacement angle to which the inverter can operate, τ_1 is the time constant of the inverter response, X_1 is the network reactance at the point of connection, and U_N is the nominal voltage. From this, the open-loop transfer function can be written as

$$G_{\mathrm{ol}} = \frac{K_{\mathrm{ol}}}{1+\tau_1 s} \tag{5}$$

where K_{ol} is the open-loop gain

$$K_{\mathrm{ol}} = \frac{k_1 \cdot X_1}{U_N^2}. \tag{6}$$

After some simplifications and adaptations, the open-loop gain can be rewritten as

$$K_{\mathrm{ol}} = \frac{\Delta U_{\mathrm{PV}}}{\Delta U_{\mathrm{droop}}} \cdot \frac{\tan \varphi_{\max}}{R/X} \tag{7}$$

where ΔU_{PV} is the voltage rise caused by the power infeed, $\Delta U_{\mathrm{droop}}$ is the voltage range of the droop area, and R/X is the ratio between the resistive and reactive parts of the network impedance.

As previously mentioned, the dynamic response of the reactive power control can be adjusted by either the time constant of a first-order transfer function or by a rate limiter. In order to avoid nonlinearities, the reactive power control has been modeled as a first-order transfer function. Moreover, this implementation is recommended in [31].

The dynamic response of the system is also determined by eventual delays present in the control loop [see Fig. 2(b)]; these delays shall be therefore considered appropriately. In this paper, a Padé equivalent [32] has been used to replace the transfer function of a time delay T by a rational transfer function of order n, i.e.,

$$H_{\mathrm{Padé\_}n} = \frac{1 - k_1 \cdot s + k_2 \cdot s^2 - \cdots \pm k_n \cdot s^n}{1 + k_1 \cdot s + k_2 . s^2 + \cdots + k_n \cdot s^n}. \tag{8}$$

For an order $n = 2$, the coefficients $k1$ and $k2$ are $T/2$ and $T^2/12$, respectively, where T is the desired time delay. After linearizing the system and introducing the Padé approximation for the time delay, the system transfer functions can be formulated. Since the voltage reference U_{Ref} does not change during normal operation, the focus is laid on the transfer function from w_U to U, i.e.,

$$G_{w_U U} = \frac{1}{1 + K_{\mathrm{Droop}} H_{\mathrm{Inv}} G_{\mathrm{Grid}} H_{\mathrm{Delay}}}. \tag{9}$$

This transfer function is of third order with three poles in the complex plane dictating the system stability.

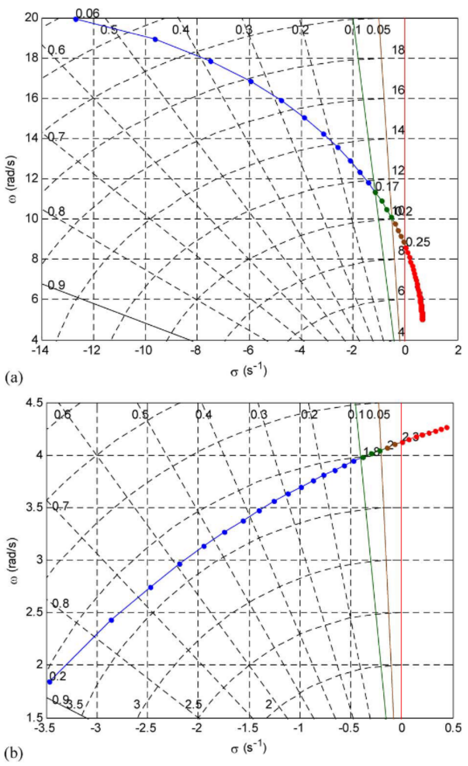


Fig. 4. Stability locus. (a) $\tau = 0.2$ s$|T_D$ variable $|K_{\mathrm{ol}} = 2$. (b) $\tau = 0.5$ s$|T_D = 0.5$ s$|K_{\mathrm{ol}}$ variable.

B. Parametric Study of the System Stability

A parametric study was performed in order to investigate the impact of the following factors on the system stability:

- K_{ol}: open-loop gain as defined in (7);
- τ: time constant of the Q(U) controller, which is used to specify the dynamic behavior;
- T: time delay (sum of the delays in the controller loop (see Section III-B).

For the parametric study, only the open-loop gain has been considered since the individual parameter combinations $(\Delta U_{\mathrm{PV}}, \Delta U_{\mathrm{droop}}, \tan \varphi, R/X)$ are as such not relevant.

The impact of the time delay on the system damping is shown in Fig. 4, which depicts the evolution of the most critical pole (σ and ω being the real and imaginary parts of this pole) for increasing time delay values.

In addition to the stability limit, the damping ratios of 5% and 10% are shown in this diagram. For increasing delay values, the most critical pole is shifted to the right, and the system damping is decreased. In this case, time delays greater than 250 ms lead to instability. In order to reach a 10% damping ratio, the delay shall not be greater than 170 ms (compared with the time constant $\tau = 200$ ms).

TABLE I
SETTINGS OF THE PARAMETRIC STUDY

Parameter	Parameter range	
	min	max
K_{ol} (-)	0.1	3
T (s)	0	0.5
τ (s)	0	10

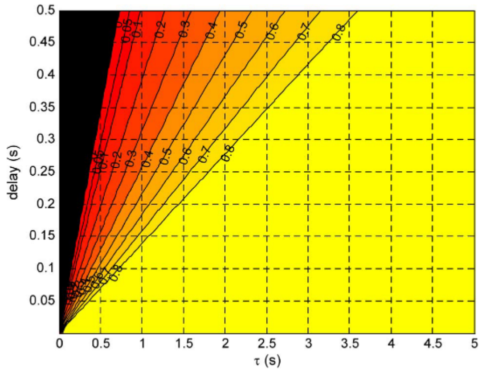


Fig. 5. Stability limits for $K_{\rm ol} = 3$ and varying τ and T.

Fig. 4(b) also shows the result of a similar analysis made for the open-loop gain $K_{\rm ol}$. This figure shows that the system is always stable for open-loop gain values below 2.3.

In order to better understand and quantify the impact of the three influencing factors, i.e., open-loop gain $K_{\rm ol}$, time constant of the Q(U) controller τ, and time delay T, a parametric study has been performed with the settings specified in Table I. With this study, stability criteria have been empirically identified.

The parameters have been varied in the closed-loop system, and the poles of the system have been computed (third-order system). The damping ratio of the most critical pole has been identified and put into relation with the three parameters.

Fig. 5 shows the damping ratio for an open-loop gain $K_{\rm ol} = 3$ and varying τ and T. It shows that stable conditions are obtained when the ratio between the delay and the time constant of the Q controller (T/τ) is below a certain value (linear relation). The black area corresponds to factor combinations resulting in the unstable operation, i.e., the delay T is too large in comparison with the controller time constant τ. The damping ratio can be read from the contour lines.

In a second step, the impact of the open-loop gain $K_{\rm ol}$ has been investigated in order to quantify the general observation that higher gain values have a negative impact on the stability. Fig. 6 presents the result of this investigation, showing clear dependence between the ratio T/τ and the open-loop gain $K_{\rm ol}$. On this figure, in addition to the stability limit (red curve), the condition to reach a damping ratio ζ of 5% or 10% is shown with the green and blue curves, respectively. This figure shows that the system always remains stable for open-loop gain values below one.

Moreover, the frontier for an overdamped response is shown (black curve). While the minimum acceptable damping ratio in classical small-signal stability studies (study of oscillations

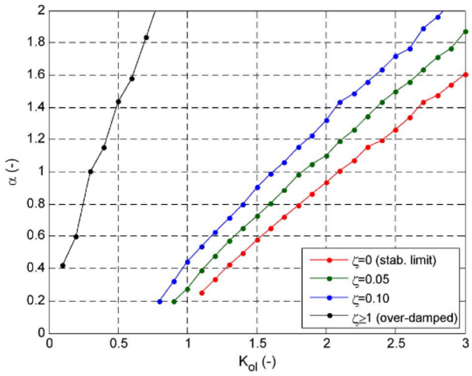


Fig. 6. $\alpha = f(K_{\rm ol})$ leading to different damping ratios ζ.

between rotating generators) is system dependent and is based on operating experience, minimum acceptable ratios in the range of 3%–5% are usually used. In this paper, a damping ratio of 5% is considered to be poor, and a damping ratio of 10% is considered to be sufficient.

These curves show, as expected, that, for increasing open-loop gain values, the factor between the time delay T and the controller time response τ must increase (linear dependence). The stability criterion is expressed with

$$\frac{T}{\tau} \leq \frac{1}{\alpha(K_{\rm ol})} \tag{10}$$

where α is a function of $K_{\rm ol}$, which is defined as

$$\alpha(K_{\rm ol}) = a_\zeta \cdot K_{\rm ol} + b_\zeta. \tag{11}$$

Combining (10) and (7) and using the expression of the open-loop gain, the stability criterion can be rewritten as

$$\frac{T}{\tau} \leq \frac{1}{a_\zeta \cdot \frac{\Delta U_{\rm PV}}{\Delta U_{\rm droop}} \cdot \frac{\tan\varphi}{R/X} + b_\zeta} \tag{12}$$

where a_ζ and b_ζ are linear equation constants.

Equation (12) shows that the "geometric distance" between the delay T and the Q(U) controller time response τ must be greater to ensure stability for the following:

- a system with a large impact on the network, meaning a high $\Delta U_{\rm PV}$, caused by
  - — a weak network and/or
  - — a large PV power;
- a small R/X ratio, i.e., a large network reactance;
- a small droop range $\Delta U_{\rm droop}$;
- a large maximum reactive power, i.e., a small $\cos\varphi$.

The equation coefficients a_ζ b_ζ can be determined on the basis of Fig. 6, and the different types of response limits, namely, unstable, poorly damped (5%), sufficiently damped (10%), and critical/overdamped ($\geq$100%)), are given in Table II.

TABLE II
LINEAR EQUATION COEFFICIENTS

Parameter	Damping ratio / type of response			
	unstable	oscillating		critical/over-damped
ζ(%)	0	5	10	≥100
a_ζ (-)	0.71	0.78	0.85	2.10
b_ζ (-)	-0.49	-0.46	-0.40	0.30

TABLE III
PARAMETERS FOR WORST CASE STABILITY CRITERION

Parameter	Value
ΔU_{PV} (%)	6
ΔU_{droop} (%)	1
R/X (-)	1
$\cos\varphi$ (-)	0.90

TABLE IV
MAXIMUM DELAY T FROM THE WORST CASE SCENARIO

Time response 3τ (s)	Maximum delay T (s)	
	ζ = 0 %	ζ = 10 %
10	2.12	1.61
5	1.06	0.81
1	0.21	0.16

Having identified the stability criteria as a function of the three influencing factors K_{ol}, τ, and t, the stability criterion is determined for the worst case. For this, the parameters given in Table III have been used.

The maximal voltage rise caused by the PV infeed has been considered to be 6%, i.e., the double of the voltage rise allowed in the current connection rules [27], which can be therefore considered as high PV penetration. While the maximum PV penetration ensuring stability depends on the other parameters, for this worst case, the maximum allowable voltage rise caused by the PV infeed $\Delta U_{\mathrm{droop}}$ to ensure stability for any delay and time constant would be about 2% (smaller than the threshold in current connection rules [27]).

In addition, a small droop range (1%) and a small R/X ratio (roughly corresponding to a 95-mm^2 aluminum overhead line) have been considered.

Using these four parameters leads to an open-loop gain $K_{\mathrm{ol}} = 2.91$ and to about $\alpha(K_{\mathrm{ol}}) = 1.57$, which is the stability limit. This means that, under the worst case, the following must apply for the delay $T \leq \tau/\alpha(K_{\mathrm{ol}}) = 0.64\tau$. The standards or grid codes addressing the time response of Q(U) controllers do not require a fast controller response, e.g., steady state reached within 10 s (see Section II-B). In order to reach the steady state within 10 s, the time constant of the controller (considered as a first-order transfer function in this paper) shall be smaller than about 3 s ($3\tau < 10$ s for a 5% tolerance band as usually required (e.g., [33]). In order to ensure stability, the delay T must therefore stay below 1.9 s, and in order to reach a damping ratio of 10%, the delay shall not exceed 1.4 s. If a response time of 1 s is targeted ($3\tau < 1$ s) with a 10% damping ratio, the delay shall not exceed 160 ms. The resulting maximum allowed delay T from the worst case scenario is shown in Table IV.

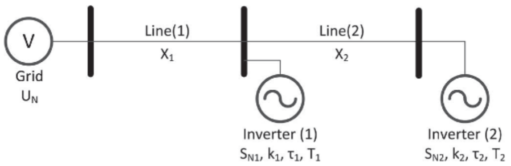


Fig. 7. Grid model for the two-inverter problem.

Studying the results in Table IV, it is clear that all the delays are in hundreds of milliseconds. For integrated systems, i.e., where the measurement and the Q(U) control are both integrated into the inverter, these maximal delays should be easy to reach. However, in a case where the measurement and the Q(U) controller are implemented as independent devices and connected to the inverter with a communication interface, higher time delays may occur. This can be the case in a PV park with multiple inverters and a central plant controller or in more distributed control approaches [10].

V. STABILITY STUDY FOR MULTIINVERTER NETWORKS

In reality, distribution feeders host several PV installations. This section aims at generalizing the findings in Section IV to multiinverter networks. As for the single-inverter problem, the assumption has been made that all the inverters operate in the droop area (not in the dead-band or the limitation part). In practice, depending on the voltage profile along the feeder, some of the inverters are operating in the dead-band or the limitation part. These inverters do not have any impact on the stability since they operate with zero reactive power disregarding the voltage magnitude. Considering that all the inverters are in the droop area is therefore a worst case consideration.

A. Adaptation to Two Inverters

In order to investigate the two-inverter problem, a simple two-bus network has been considered, as shown in Fig. 7.

For the stability analysis, the grid model in Fig. 7 is studied as a multi-input–multi-output system with the block representation in Fig. 2(b) and the following system functions:

$$K_{\mathrm{Droop}} = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \tag{13}$$

$$H_{\mathrm{Inv}} = \begin{bmatrix} \frac{1}{1+\tau_1 s} & 0 \\ 0 & \frac{1}{1+\tau_2 s} \end{bmatrix} \tag{14}$$

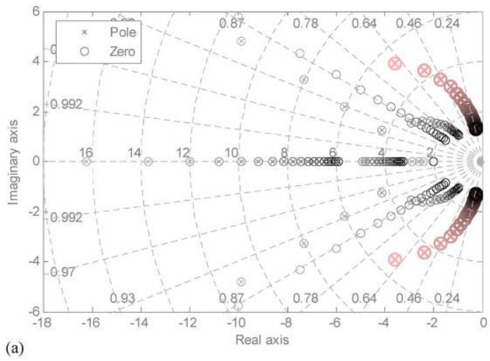
$$G_{\mathrm{Grid}} = \begin{bmatrix} \frac{X_1 P_{N1}}{U_N^2} & \frac{X_1 P_{N2}}{U_N^2} \\ \frac{X_1 P_{N1}}{U_N^2} & \frac{X_T P_{N2}}{U_N^2} \end{bmatrix} \tag{15}$$

$$D_{\mathrm{Delay}} = \begin{bmatrix} \frac{1-\frac{T_1}{2}s+\frac{T_1^2}{12}s^2}{1+\frac{T_1}{2}s+\frac{T_1^2}{12}s^2} & 0 \\ 0 & \frac{1-\frac{T_2}{2}s+\frac{T_2^2}{12}s^2}{1+\frac{T_2}{2}s+\frac{T_2^2}{12}s^2} \end{bmatrix} \tag{16}$$

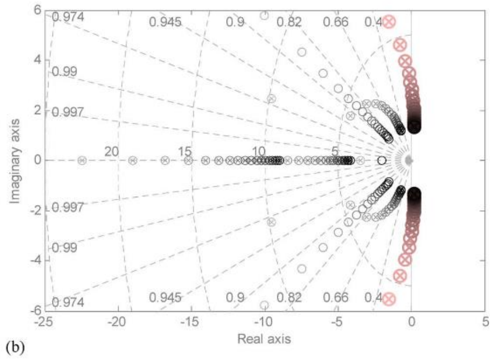
where $X_T = X_1 + X_2$. With two or more inverters, the system function from w_U to the output U is written as

$$G_{w_U U} = (I + D_{\mathrm{Delay}} K_{\mathrm{Droop}} H_{\mathrm{Inv}} G_{\mathrm{Grid}})^{-1} \tag{17}$$

where I is the unity matrix of dimension $N = 2$.



(a)



(b)

Fig. 8. Pole/Zero plot of the two-inverter system with varying delay $T_1 = T_2 \in \{0.3, 0.4, \ldots, 2\}$ s. (a) $\Delta U_1 = \Delta U_2 = 5\%$. (b) $\Delta U_1 = \Delta U_2 = 2\%$.

Considering (13)–(17), $G_{w_U U}$ is a sixth-order transfer function for the two-inverter problem. In order to understand how the two inverters affect the system stability, a parametric study was implemented using MATLAB. In addition, the analysis has been also made with the modal analysis tool of the software DIgSILENT PowerFactory, which computes the eigenvalues of the linearized system in order to verify the results. The results were indeed identical.

In a first step, the impact of increasing delay values (T_1 and T_2 between 0.3 and 2 s) on the poles/zeros for two different droop values (all other parameters being kept constant: $S_{N1} = S_{N2} = 15$ kW, $X_1 = 0.3\,\Omega$, $X_2 = 0.6\,\Omega$, and $\tau_1 = \tau_2 = 0.5$ s) has been investigated.

The results are shown in Fig. 8. In Fig. 8(a), $\Delta U_1 = \Delta U_2 = 5\%$, and in Fig. 8(b), $\Delta U_1 = \Delta U_2 = 2\%$. Both figures show that, when the delay increases, the most critical poles (marked in red) move toward the origin of the complex plane. With $\Delta U_1 = \Delta U_2 = 5\%$, the system remains stable whatever the delay. With $\Delta U_1 = \Delta U_2 = 2\%$, however, the system becomes unstable when the delay is increased too much.

This study shows that, when the open-loop gain increases (in this case, through a decrease in ΔU), the most critical pole is pushed toward the left half-plane, resulting in a possible unstable system.

TABLE V
PARAMETRIC STUDY FOR THE TWO-INVERTER PROBLEM

Parameter	Value / Range
X_1 (Ω)	0.3
X_2 (Ω)	0.6
P_{N1} (kW)	40
P_{N2} (kW)	10
Δ^{-}_{droopi} (s)	0 %-10 %
T_i (s)	0.020-0.400
τ_i (s)	0.050-1.000

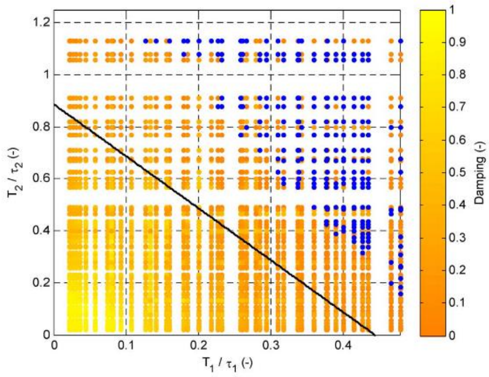


Fig. 9. Damping ratio ζ of the worst pole as a function of T_1/τ_1 and T_2/τ_2.

In a second step, a comprehensive parametric study has been conducted to formulate a generalization of the stability criterion determined for the single-inverter problem. For this purpose, the equivalent open-loop gain $K_{\text{ol\_eq}}$ needs to be introduced. It can be computed according to the following equation:

$$K_{\text{ol\_eq}} = K_{\text{ol}_1} + K_{\text{ol}_2} = \frac{P_{N1} X_1 \tan\varphi_1}{\Delta U_{\text{droop}_1} U_N^2} + \frac{P_{N2} X_T \tan\varphi_2}{\Delta U_{\text{droop}_2} U_N^2}. \tag{18}$$

The stability criterion formulized in (10) for the single-inverter problem can be then altered into

$$\sum_{i=1}^{N} \frac{K_{\text{ol}_i}}{K_{\text{ol\_eq}}} \cdot \frac{T_i}{\tau_i} \leq \frac{1}{\alpha(K_{\text{ol\_eq}})} \tag{19}$$

where N is the number of inverters, and K_{ol_i} is the open-loop gain corresponding to inverter i computed according to (7).

The network reactance and the inverter power have been kept constant, whereas the delay and the time constant of each controller have been varied independently (nonidentical settings of the two inverters) between 20–400 and 50–1000 ms, respectively (see Table V).

On the following two figures, the validity of the proposed stability criterion is investigated by varying the delay T_i, the time constant τ_i (see Fig. 9), and the voltage range of the droop area ΔU_i (see Fig. 10) of the controller.

In Fig. 9, the damping ratio of the most critical pole has been plotted as a function of the ratio between the time delay T_i and the controller time constant τ_i of each inverter i. For this figure,

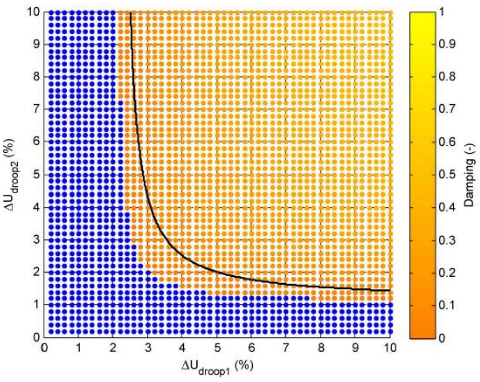


Fig. 10. Damping ratio ζ of the worst pole as a function of $\Delta U_{\text{droop}_1}$ and $\Delta U_{\text{droop}_2}$.

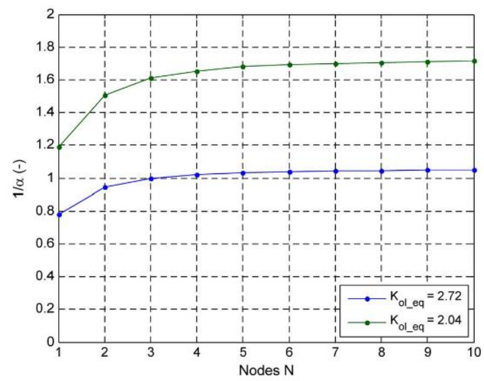


Fig. 11. $1/\alpha$ as a function of the number of nodes N or *inverters*.

the droop factor and the minimum power factor have been kept constant ($\Delta U_i = 1\%$ and $\cos\varphi_i = 0.9, i = 1, 2$). The axes have been limited to $1/\alpha(K_{\text{ol\_1}})$ and $1/\alpha(K_{\text{ol\_2}})$, respectively. In addition, the stability criterion formulated in (19) is shown with the solid black line, and unstable combinations are shown by blue points.

Fig. 9 shows that (19) is a sufficient criterion to ensure stability since no blue points are located below the solid black line. Another interesting observation is that the stability criterion seems to be more conservative than the reality when looking at the distance between the solid black line and the border of the blue points, which was not the case for the single-inverter problem. Further investigations are presented in Section V-B.

In Fig. 10, the damping ratio of the most critical pole has been plotted as a function of the voltage range of the droop area ΔU_i of each inverter i. For this figure, the delay, the time constant, and the minimal power factor have been kept constant ($T_i = 0.8$ s, $\tau_i = 0.53$ s, and $\cos\varphi_i = 0.9, i = 1, 2$).

Fig. 10 confirms that (19) is a sufficient criterion to ensure stability since no blue points are located beyond the solid black line (instability for small ΔU_i or steep droops). Another interesting observation is that the stability criterion seems also to be more conservative than the reality when looking at the distance between the solid black line and the border of the blue points.

In addition, further investigations with different delay and time constant of the controller have been conducted. They all confirmed that (19) is a sufficient stability criterion and showed that, for nonequal settings (different delay and time constant for both controllers), the stability criterion is more conservative. In the case of nonequal settings, the oscillation risk is smaller since the inverters respond differently to the excitation. As a conclusion, (19) seems to be a sufficient criterion to ensure stability for two-inverter systems. Section V-B investigates the generalization to more than two inverters.

B. Generalization to N Inverters

In order investigate the impact of the number of inverters on the validity of the criterion, the following investigation has been conducted: the number of nodes (and therefore inverters) has been varied between 1 and 10 while keeping the equivalent open-loop gain $K_{\text{ol\_eq}}$ equal (i.e., the same PV penetration) and using identical settings for all the inverters.

To ensure a constant equivalent open-loop gain $K_{\text{ol\_eq}}$, the total cable length has been kept constant, and the inverter nominal power has been scaled according to

$$P_N = P_{N-1} \cdot \frac{N}{(N+1)} \tag{20}$$

where P_N is the nominal power per inverter for a feeder with N inverters, and P_{N-1} is the nominal power per inverter for a feeder with $N-1$ inverters. By doing this, the effect of the PV generation on the network (ΔU_{PV}) can be kept constant.

In the following, two cases have been considered: a constant equivalent open-loop gain 1) $K_{\text{ol\_eq}} = 2.72$ and 2) $K_{\text{ol\_eq}} = 2.04$. For both cases, the total impedance is $X = 0.15\ \Omega$, the nominal power for one node is set to $P_1 = 60$ kW or 45 kW (for $K_{\text{ol\_eq}} = 2.72$ and $K_{\text{ol\_eq}} = 2.04$, respectively). The droop has been set with a voltage $\Delta U_{\text{droop}} = 1\%$ and the minimal power factor to $\cos\varphi = 0.9$.

The results of this investigation shown in Fig. 11 confirm that $1/\alpha$ increases with increasing number of inverters and saturates at a value, which depends on $K_{\text{ol\_eq}}$ (about 135% of the basis value achieved for the single-inverter problem for $K_{\text{ol\_eq}} = 2.72$ and 144% for $K_{\text{ol\_eq}} = 2.04$).

This observation means that the more distributed the PV power along the line is, the greater is the damping.

In practice, the PV inverters along a feeder might not all operate in the droop area of the Q(U) characteristic and possibly contribute to instability; this is particularly true for small droop areas (ΔU_{droop}) and high PV penetrations. This criterion is therefore sufficient, considering several inverters with different delay/time constants and different droop factors.

VI. Laboratory Experiment

Here, the results of laboratory measurements implemented in the project morePV2grid [34], [35] are compared with the simulation results. In these laboratory tests, many different

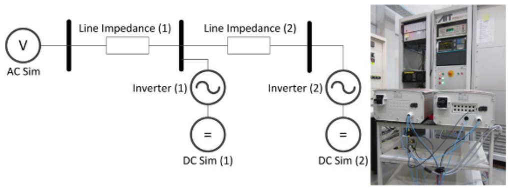


Fig. 12. (Left) Laboratory test setup with two inverters. (Right) Picture of the laboratory test setup.

TABLE VI
SETTINGS FOR THE LABORATORY EXPERIMENT

Equipment	Settings
AC Simulator	Voltage step of 1 %
DC Simulator	$P_{Inv1} = 3$ kW; $P_{Inv2} = 3$ kW
Line Reactance (1)	$X_1 = 0.25\ \Omega$
Line Reactance (2)	$X_2 = 1.57\ \Omega$
Inverter (1&2)	$T_{mova} = 640$ ms; $\Delta Q/\Delta t = 200$ %/s[1] $cos\varphi_{min} = 0.85$, $\Delta U_{droop} = 3$ %

[1] % of $Q_{max} = P_N \cdot \tan\varphi_{max}$

situations have been investigated with the test setup shown in Fig. 12.

First, a test case leading to badly damped oscillations has been considered. In order to reach a badly damped response with a limited inverter power, very large (unrealistic) line reactances have been used.

The two inverters have a nominal power of 4 kVA (single-phase), and the dynamic behavior of the Q(U) controllers is mainly determined by the following.

- The voltage is averaged by a moving average with window size T_{mova} [35].
- The controller response is adjusted with a reactive power slew rate limiter ($\Delta Q/\Delta t$, specified in percent of the maximal reactive power per second).

The test parameters are listed in Table VI.

The model presented in Section V must be adapted due to the moving average and the reactive power rate limiter. In order to model the moving average, the transfer function of the delay H_{Delay} defined in (9) must be replaced by the transfer function H_{mova} according to the following equation:

$$H_{\mathrm{mova}}(s) = \frac{1 - H_{\mathrm{Delay}}}{T_{\mathrm{mova}} \cdot s} \qquad (21)$$

where T_{mova} is the moving average window (to be used also in H_{Delay}). The delay element introduced by the moving average can, as previously mentioned, be approximated by the Padé equivalent.

In order to be able to use the model in Section V, the rate limiter has been approximated with a first-order function [H_{Inv} in (3)] with a time constant τ_{eq} given by the following, considering that the steady-state is reached after three time constants:

$$3 \cdot \tau_{\mathrm{eq}} = \frac{\Delta u_{\mathrm{step}}}{\Delta U_{\mathrm{droop}}} \cdot \frac{1}{\Delta Q/\Delta t}. \qquad (22)$$

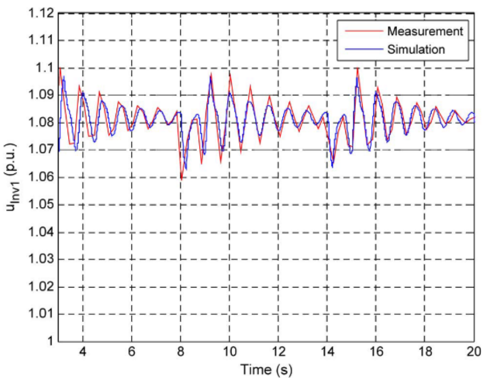


Fig. 13. System response to voltage steps (measurement/simulation).

In this case, the settling time to reach the fully reactive power output is 0.5 s (with a rate limiter of $\Delta Q/\Delta T = 200\%/\mathrm{s}$). The settling time corresponding to a voltage step $\Delta u_{\mathrm{step}} = 1\%$ is one third of the settling time for the whole droop voltage $\Delta U_{\mathrm{droop}} = 2\%$, which leads to $3 \cdot \tau_{\mathrm{eq}} = 167$ ms or $\tau_{\mathrm{eq}} = 56$ ms.

The laboratory measurements have been compared with two simulation models: In a first step, a model with moving average and rate limiter has been implemented into PowerFactory, and in a second step, the model presented in Section V [see (13)–(17)] with the adaptations previously mentioned has been used. Fig. 13 shows the response of the system (measurement and simulation) to voltage steps with a period of 6 s, where it can be seen that both are in good agreement. The very poor damping is, as previously explained, due to the large reactances leading to an equivalent open-loop gain $K_{\mathrm{ol\_eq}} = 7.2$ according to (14) and to the long averaging window compared with the system response ($T_{\mathrm{mova}} = 640$ ms and $\tau_{\mathrm{eq}} = 56$ ms).

The stability assessment with the model presented in (13)–(17) leads to a damping ratio of about 0.5% (for the worst pole), which is indeed small. Due to the rate limiter whose influence on the response is shown in Fig. 13 (linear instead of exponential decrease of the maxima), it is not straightforward to compare the experimental results with the simulation. The experimental damping ratio ζ has, however, been determined the first five maxima (with the logarithmic decrement): It varies between 1.4% and 0.7% and is, as expected, greater than the damping ratio previously determined from the stability assessment (0.5%).

As in Sections IV and V, a parametric study has been performed in order to determine the stability criterion for systems with a moving average. Due to the fact that the effect of the moving average is significantly smaller than a pure delay, the impact on stability is much smaller, and no instability could be observed for the parameter range in Table I. The minimum damping ratio was well above 10%.

VII. CONCLUSION

On the basis of comprehensive simulations on the stability of electrical feeders with one or more PV inverters actively controlling the voltage with a Q(U) controller, a sufficient stability criterion has been proposed and validated. The higher the open-loop gain (e.g., large network reactance, high inverter power, and high droop factor) is, the higher the geometric distance between the delay T and the Q(U) controller time response τ must be. The proposed criterion is sufficient to ensure stability for multiinverter systems with equal or nonequal delays, time constants, and droop factors and is therefore applicable in networks with a high PV generation share.

This stability criterion of the Q(U) control is rather weak, which means that the minimal ratio between the delay T present in the controller loop and the controller time response τ is not very small and easy to comply with. For the considered worst case, the minimum ratio between delay and controller time response is about 0.5. For example, in order to reach a well-damped response (10% damping ratio) with a time response of $3\tau = 5$ s, the delay shall stay below 0.80 s.

In theory, implementing an inverter control with a Q(U) controller with a total delay below 0.80 s is easily manageable. However, the situation might be different for systems with an external controller (e.g., plant controller according to [10]), which might be required (e.g., [27]) to control the voltage at a remote node. In such cases, a careful system design considering the communication delays is necessary.

As a conclusion, achieving a well-damped response is uncritical for local controllers integrated into the inverter even under critical network conditions (e.g., weak network and high PV power). For systems relying on communication, more attention shall be paid to ensure a well-damped response.

References

[1] M. Liserre, T. Sauter, and J. Y. Hung, "Future energy systems: Integrating renewable energy sources into the smart power grid through industrial electronics," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 18–37, Mar. 2010.

[2] J. Pecas Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," *Elect. Power Syst. Res.*, vol. 77, no. 9, pp. 1189–1203, Jul. 2007.

[3] "Power generation systems connected to the low-voltage distribution network—Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks," VDE Assoc. Elect., Electron. Inf. Technol., Frankfurt, Germany, Tech. Rep. VDE-AR-N 4105, 2011.

[4] C. Cecati, C. Citro, A. Piccolo, and P. Siano, "Smart operation of wind turbines and diesel generators according to economic criteria," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4514–4525, Oct. 2011.

[5] G. Spagnuolo *et al.*, "Renewable energy operation and conversion schemes: A summary of discussions during the seminar on renewable energy systems," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 38–51, Mar. 2010.

[6] "Generating plants connected to the medium-voltage network (Guideline for generating plants' connection to and parallel operation with the medium-voltage network)," BDEW, Berlin, Germany, Tech. Rep., 2008.

[7] "General conditions for a temporary arrangement for the frequency-Dependent active power control of PV systems in the LV distribution network," VDE Assoc. Elect., Electron. Inf. Technol., Frankfurt, Germany, Tech. Rep., 2011.

[8] M. Stifter *et al.*, "DG demonet validation: Voltage control from simulation to field test," in *Proc. 2nd IEEE PES Int. Conf. Exhib. ISGT Europe*, Dec. 5–7, 2011, pp. 1–8.

[9] A. Einfalt, F. Zeilinger, R. Schwalbe, B. Bletterie, and S. Kadam, "Controlling active low voltage distribution grids with minimum efforts on costs and engineering," in *Proc. IEEE IECON*, Nov. 10–13, 2013, pp. 7456–7461.

[10] T. Stetz, F. Marten, and M. Braun, "Improved low voltage grid-integration of photovoltaic systems in Germany," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 534–542, Apr. 2013.

[11] A. Cagnano, E. De Tuglie, M. Liserre, and R. A. Mastromauro, "Online optimal reactive power control strategy of PV inverters," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4549–4558, Oct. 2011.

[12] J. C. Vasquez, J. M. Guerrero, J. Miret, M. Castilla, and L. G. de Vicuña, "Hierarchical control of intelligent microgrids," *IEEE Ind. Electron. Mag.*, vol. 4, no. 4, pp. 23–29, Dec. 2010.

[13] H. Bevrani and S. Shokoohi, "An intelligent droop control for simultaneous voltage and frequency regulation in islanded microgrids," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1505–1513, Sep. 2013.

[14] Q.-C. Zhong, "Harmonic droop controller to reduce the voltage harmonics of inverters," *IEEE Trans. Ind. Electron.*, vol. 60, no. 3, pp. 936–945, Mar. 2013.

[15] A. Camacho, M. Castilla, J. Miret, J. C. Vasquez, and E. Alarcon-Gallo, "Flexible voltage support control for three-phase distributed generation inverters under grid fault," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1429–1441, Apr. 2013.

[16] V. Calderaro, G. Conio, V. Galdi, G. Massa, and A. Piccolo, "Optimal decentralized voltage control for distribution systems with inverter-based distributed generators," *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 230–241, Jan. 2014.

[17] M. Castilla, J. Miret, A. Camacho, J. Matas, and L. Garcia de Vicuna, "Voltage support control strategies for static synchronous compensators under unbalanced voltage sags," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 808–820, Feb. 2014.

[18] R. A. Mastromauro, M. Liserre, and A. Dell'Aquila, "Control issues in single-stage photovoltaic systems: MPPT, current and voltage control," *IEEE Trans. Ind. Informat.*, vol. 8, no. 2, pp. 241–254, May 2012.

[19] V. Loia, A. Vaccaro, and K. Vaisakh, "A self-organizing architecture based on cooperative fuzzy agents for smart grid voltage control," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1415–1422, Aug. 2013.

[20] M. Haomin, K. W. Chan, and L. Mingbo, "An intelligent control scheme to support voltage of smart power systems," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1405–1414, Aug. 2013.

[21] M. Brenna *et al.*, "Automatic distributed voltage control algorithm in smart grids applications," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 877–885, Jun. 2013.

[22] A. A. Aquino-Lugo, R. Klump, and T. J. Overbye, "A control framework for the smart grid for voltage support using agent-based technologies," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 173–180, Mar. 2011.

[23] C.-H. Chan, Y.-H. Lin, Y.-M. Chen, and Y.-R. Chang, "Simplified reactive power control for single-phase grid-connected photovoltaic inverters," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, pp. 2286–2296, May 2014.

[24] M. N. Marwali, M. Dai, and A. Keyhani, "Robust stability analysis of voltage and current control for distributed generation systems," *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 516–526, Jun. 2006.

[25] A. Constantin and R. D. Lazar, "Open loop Q(U) stability investigation in case of PV power plants," in *Proc. 27th Eur. Photovoltaic Solar Energy Conf. Exhib.*, Frankfurt, Germany, 2012, pp. 3745–3749.

[26] "Prescriptions techniques spécifiques de raccordement d'installations de production décentralisée fonctionnant en parallèle sur le réseau de distribution," Synergrid, Brussels, Belgium, Tech. Rep. C10/11, 2012.

[27] TOR D4 Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen, e-control, Version 2.1, 2013.

[28] *Reference technical rules for the connection of active and passive users to the LV electrical utilities*, CEI 0-21, 2012, CEI.

[29] K. De Brabandere, "Voltage and frequency droop control in low voltage grids by distributed generators with inverter front-end," Ph.D. dissertation, Dept. Elect. Eng., Katholieke Univ., Leuven, Belgium, 2006.

[30] T. Strasser, F. Andrén, F. Lehfuss, M. Stifter, and P. Palensky, "Online reconfigurable control software for IEDs," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1455–1465, Aug. 2013.

[31] "Communication networks and systems for power utility automation—Part 90-7: Object models for power converters in distributed energy resources DER systems," International Electrotechnical Commission (IEC), Geneva, Switzerland, IEC/TR 61850-90-7 ed1.0, 2013.

[32] G. Liu, A. Zinober, and Y. B. Shtessel, "Second-order SM approach to SISO time-delay system output tracking," *IEEE Trans. Ind. Electron.*, vol. 56, no. 9, pp. 3638–3645, Sep. 2009.

[33] FGW-TG3 Determination of electrical characteristics of power generating units and systems connected to MV, HV and EHV grids, FGW 2013.

[34] B. Bletterie *et al.*, "More functionalities for increased integration of pv into grid," Fronius, Wels, Austria, Final Rep., 2013.

[35] B. Bletterie *et al.*, "Local voltage control by PV inverters: First operating experience from simulation, laboratory tests and field tests," in *Proc. 27th Eur. Photovoltaic Solar Energy Conf. Exhib.*, Frankfurt, Germany, 2012, pp. 4574–4581.

Filip Andrén (M'12) received the M.Sc. degree in applied physics and electrical engineering, with a thematic focus on control and information systems, from Linköping University, Linköping, Sweden, in 2009.

Since 2009, he has been a Scientist with the Energy Department, AIT Austrian Institute of Technology, Vienna, Austria. He specializes in smart grids and power utility automation. His main research interests are automation and control systems; communication and automation standards; and modeling, simulation, and development of intelligent grid components.

Benoit Bletterie (M'01) received the M.Sc. degree in electrical engineering jointly from the École Supérieure d'Électricité, Gif-sur-Yvette, France, and Universidad Politécnica de Madrid, Madrid, Spain, in 2001.

In 2003, he joined, as a Researcher, Arsenal Research (now AIT Austrian Institute of Technology), Vienna, Austria, where he became a Senior Engineer in 2011 after working on power quality, network simulations, and performance of photovoltaic inverters for eight years. His major fields of expertise are smart grids, network integration of distributed energy resources, network planning, voltage control, simulations, and inverter control. He has authored or coauthored over 100 papers in these areas.

Mr. Bletterie is a member of several standardization working groups.

Serdar Kadam received the B.Sc. degree in electrical engineering and the M.Sc. degree in energy engineering from Vienna University of Technology, Vienna, Austria, in 2011 and 2012, respectively. His diploma thesis topic was "Systematical analysis of low voltage networks for smart grid studies," which was awarded by the Society for Power Engineering (OGE).

Since 2012, he has been a Junior Scientist with the AIT Austrian Institute of Technology, Vienna, where his work focus is on network simulations in the smart grid context, including modeling of intelligent and innovative network elements. His main research interests are the integration of renewables in electrical networks and the classification of electrical grids.

Panos Kotsampopoulos (M'12) received the Diploma degree in electrical and computer engineering from the National Technical University of Athens (NTUA), Athens, Greece, in 2010. He is currently working toward the Ph.D. degree, in the area of distributed energy resources, in the Electric Power Division, NTUA.

His research interests include real-time and hardware-in-the-loop simulation, distributed generation, microgrids, ancillary services, and rural electrification.

Mr. Kotsampopoulos is a member of the Technical Chamber of Greece.

Christof Bucher received the M.Sc. degree in information technology and electrical engineering from ETH Zurich, Zurich, Switzerland, in 2008.

Since then, he has been a Planning Engineer for photovoltaic systems with Basler and Hofmann AG (formerly Enecolo AG), Zurich. From 2010 to 2014, he was an external Ph.D. student at ETH and continued his practical work with Basler and Hofmann AG. He investigated the grid connection of photovoltaic systems in his thesis.

Publication 7

“On the effectiveness of voltage control with PV inverters in unbalanced low voltage networks”

B. Bletterie, S. Kadam, A. Zegers, and Z. Miletic, “On the effectiveness of voltage control with PV inverters in unbalanced low voltage networks,” in Proc. Electricity Distribution (CIRED 2015), 23rd International Conference and Exhibition on, Lyon, 2015.

Own contribution

This paper presents the results an analysis of the general performance of different implementations of Volt/var control under unbalanced conditions.

The applicant initiated and coordinated the research activities summarised in this paper. With the help of the second author, he developed a generic and fully configurable average model of single-phase inverters operating in Volt/var control mode. He specified the simulation cases, analysed the results and wrote most of the paper. Moreover, he initiated a follow-up work on active unbalance mitigation with power converters.

CIRED 23rd International Conference on Electricity Distribution Lyon, 15-18 June 2015

Paper 1082

ON THE EFFECTIVENESS OF VOLTAGE CONTROL WITH PV INVERTERS IN UNBALANCED LOW VOLTAGE NETWORKS

Benoît BLETTERIE
AIT – Austria
benoit.bletterie@ait.ac.at

Serdar KADAM
AIT – Austria
serdar.kadam@ait.ac.at

Antony ZEGERS
AIT – Austria
antony.zegers@ait.ac.at

Zoran MILETIC
AIT – Austria
zoran.miletic@ait.ac.at

ABSTRACT

Unsymmetrical loads and PV infeed limits the hosting capacity of LV feeders due to a faster exceeding of the over-voltage limit. While current connection rules require from inverters to control the voltage, they do not address at all the behaviour of three-phase inverters under unbalanced conditions. This paper investigates the impact of different control options on the network performance (voltage levels, voltage unbalance, neutral conductor loading and losses).

INTRODUCTION

Solar power is widely acknowledged as one of the most promising resources to meet sustainability targets. The integration of photovoltaic (PV) generation into distribution networks faces some limitations due to the network constraints. The hosting capacity of low voltage (LV) networks is for some rural and sub-urban feeders exhausted. One of the main limitation is the voltage rise caused by the power infeed which must stay below a certain threshold [1][2] to ensure that the distribution system operator is able to meet the normative requirements ([3]).

Unbalanced PV infeed resulting from e.g. small single-phase generators worsens the problem. Indeed, besides the voltage unbalance itself caused by the unsymmetrical infeed, the voltage rise caused by an unsymmetrical PV infeed is significantly higher (up to 6 times greater [4]) than for a symmetrical infeed. In order to limit the impact of unsymmetrical PV infeed on the network, the maximal power of single-phase generators (or the maximal power imbalance between phases) is usually limited to about 5 kVA (4.6 kVA in Germany and Austria, 5 kVA in Belgium, 6 kVA in France and Italy) to limit voltage unbalance.

Against this background, some requirements appeared in most the grid codes, connection guidelines or national standards of most European countries to allow generators to control the voltage (through reactive power) and partly compensate the voltage rise caused by the PV infeed and therefore enhance the hosting capacity as investigated in several research and demonstration projects [5][6][7].

These requirements usually consist of a reactive power capability (P-Q operation diagram) and several voltage control scheme (e.g. Q(U), cosφ(P), P(U)).

However, under unbalanced conditions (caused by unsymmetrical loads or PV generation), the behaviour of three-phase generators is specified in none of the existing regulation and has been poorly investigated. [8] reported for example two different implementations of a Q(U) control (using as the average or the maximum of the three phases controller input).

This paper tries to answer the question of how existing voltage control concepts behave under unbalanced conditions from the network point of view (implications on inverter designs are briefly mentioned but not in the focus of the paper).

I. VOLTAGE UNBALANCE IN LV NETWORKS

Several definitions of voltage unbalanced can be used depending on the effects considered.

[3] defines voltage unbalance as the condition in a polyphase system in which the r.m.s. (root mean square) values of the line-to-line voltages (fundamental component), or the phase angles between consecutive line voltages, are not all equal. It is quantified by the voltage unbalance factor – VUF defined as the ratio between the negative and the positive sequence and specifies that it should lie below 2 % for 95 % of the time (in specific cases up to 3 % according to [3]).

The IEEE defines the phase voltage unbalance rate (PVUR) as the maximal voltage deviation from the average phase voltage divided by the average phase voltage.

In addition to these definitions, the phase spreading which is computed as the difference between the highest and the lowest voltage among the three phases in p.u. has been proposed in [9].

Voltage unbalance: general causes and consequences

As previously stated, voltage unbalance in normal operation is mainly caused by unsymmetrical loads (e.g. single-phase loads) in LV networks. With the deployment of small single-phase PV generators, PV generation turned to be an additional potential source of voltage unbalance.

The main consequences of voltage unbalance are:

- earlier exceeding of the upper-voltage limit [3][10][11]
- additional losses in the neutral conductor of cables and in transformers [12]
- loss of performance, over-heating of induction motors [13]
- addition uncharacteristic harmonics, unsymmetrical currents flow in the three phases which can even lead to over-heating or even over-load tripping for frequency converters [14]

II. VOLTAGE CONTROL OF SINGLE-PHASE GENERATORS

In [5], the effectiveness of reactive power-based voltage control has been investigated with a three-phase four-wire network model for single-phase generators. For the three cases considered (three PV generators evenly connected to the three phases, two generators connected to two of the three phases and a single PV generators), the effectiveness of a Q(U) control has been investigated. The voltage rise caused by a single-phase infeed can be compensated to an even greater extent than in the three-phase balanced case. This has also been confirmed by field tests in e.g. [5]. However, a side-effect is mentioned in [5]: the voltage in the phase with the PV infeed is decreased but at the same time the voltage decreases in one of the other two phases due to the star point displacement [15]. This might lead to an under-voltage situation in case of additional unfavourable load imbalance.
The rest of the paper considers three-phase inverters and their behaviour under unbalanced conditions.

III. MITIGATION OF VOLTAGE UNBALANCE

As mentioned in the introduction, unsymmetrical PV infeed strongly limits the hosting capacity due to the voltage rise. For this reason, several authors have proposed different concepts to limit the PV generation imbalance at its source. [16] proposed to use smart meters to identify situations requiring a reduction of unbalance and to use monte-carlo simulations to determine a sorted set of switching combinations allowing to reduce the infeed imbalance according to the pareto principle.
A similar approach has been proposed in [17] with however a different purpose, namely to reduce network losses caused by the large neutral currents under heavily unbalanced conditions.
Besides these concepts trying to improve the PV infeed distribution over the three phases, other authors investigated the possibility to actively mitigate voltage unbalance by three-phase PV inverters.
[18] tries for example to reduce the voltage unbalance by injecting imbalanced currents into the network on the basis of a comparison between the phase voltages and the positive sequence component. The authors report about a reduction of the voltage unbalance, a decrease of the neutral current and the line losses.
[19] considered the use of a storage system to try to inject or consume a symmetrical current. The benefits on terms of voltage profiles, star point displacement and neutral current.
[20] proposes the use of a DSTATCOM to control the phase voltages individually with a droop factor. This paper proposed to place the DSTATCOM at 2/3 of the feeder length to reach an optimal reduction of the voltage unbalance factor.
[21] proposes the control of reactive power only (reactive power management method) to reduce voltage unbalance with plug-in hybrid electric vehicle chargers. As in [19], the controller tries to symmetrise the line currents, which leads as a side effect to a reduction of the voltage unbalance.
Using PV inverters to actively compensate the voltage unbalance has some implications in terms of inverter design. Some considerations are given in the conclusions.

IV. VOLTAGE CONTROL OF THREE-PHASE GENERATORS UNDER UNBALANCED CONDITIONS

In this section, the behaviour of current control schemes under unbalanced conditions is analysed through extensive simulations.

Considered controls

In this paper, the considered voltage control schemes have been limited to the most investigated schemes which are currently mentioned in some connection guidelines [2][22], namely cosφ(P) and Q(U). The following implementations have been considered (some of them being reported in [8]):

- symmetrical cosφ(P)
- Q(U)
  - unsymmetrical Q-control (“$Q(U_{ind})$”) ($Q_i=(U_{LiN})$, i=1..3)
  - symmetrical Q-control:
    - based on the maximal voltage (“$Q(U_{max})$”): ($Q_1=Q_2=Q_3=Q(\max\{U_{LiN}, i=1..3\})$)
    - based on the average voltage (“$Q(U_{mean})$”) ($Q_1=Q_2=Q_3=Q(\text{mean}\{U_{LiN}, i=1..3\})$)
    - based on the pos. seq. (“$Q(U_+)$”) ($Q_1=Q_2=Q_3=Q(U_+)$)

In addition, a P(U) control as proposed in [23] has also been considered in some scenarios.

Models, assumptions

For the investigations, a simple network consisting of a standard 400 kVA distribution transformer and a single overhead feeder (600 m – 4x70 Al) modelled as three-phase four-wire systems has been used. A long overhead line has been used to ensure a high impact of the reactive power control.

At the end of the feeder, a three-phase PV inverter rated 5 kWp per phase is connected and different voltage unbalance situations are created by an imbalanced load/generator object. The three-phase generator causes at the end of this long feeder a voltage rise of about 2.3 %.
For the imbalanced and uncontrolled load/generator object, an active power flow between -5 kW and +5 kW (with steps of 1 kW) per phase is used. The corresponding single-phase power infeed of 5 kW causes a voltage rise of about 4.5 %. With this model, the behaviour of the three-phase inverter under all the possible unbalance conditions can be investigated (more than 3.000 cases for 19 different control schemes).
The inverter has been modelled as a controlled power source for which the reactive power can be adjusted to follow each of the control options previously mentioned.
The inverters are considered to be oversized in order to be able to operate at power factor 0.9 (Q_{max}=0.44) at full power and to not exhibit any minimal power factor.
The controller settings used in this study are shown in Figure 1 for the Q(U) (and P(U)) control. For the cosφ(P) control, the standard settings from [2] have been used.

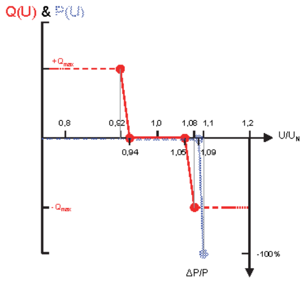


Figure 1 – Considered settings for the Q(U) and optional P(U) controls. Qmax=0.44 p.u.

Results

The results of the simulations have been processed automatically and a distribution function has been derived for all the relevant magnitudes (voltages, VUF, PVUR, voltage spreading, neutral current, losses, …).
These distribution functions show for which percentage of the possible combinations a magnitude would exceed a threshold (without considering the real distribution of input parameters (solar irradiance and load)).
Figure 2 shows the cumulated distribution function of the maximal voltage (over the three phases) for the five considered control schemes, the most relevant part being of course on the upper right part of the curve corresponding to large voltage rise values (due to a high generation/load imbalance). It shows that the most effective control is the (unsymmetrical) individual control ($Q(U_{ind})$). Considering the 99 % most unfavourable combination, the maximal voltage rise can be reduced by about 12 % with the $Q(U_{max})$ control and 19 % with the $Q(U_{ind})$ control representing about 1.3 % of the nominal voltage. These values might appear to be small, but it corresponds to more than half of the voltage rise caused by the three-phase generator.
From all the symmetrical controls $Q(U_{mean})$ and $Q(U_{+})$ are as expected the least effective controls.

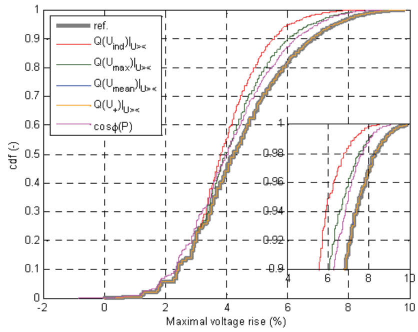


Figure 2 – Maximal voltage rise for all load/generation combinations

Figure 3 shows the cumulated distribution function for the voltage unbalance factor, clearly showing that the better effectiveness of the $Q(U_{ind})$ control is reached at the cost of a higher negative sequence component. For the worst unbalance combination, the normative value of 2 % [3] is even slightly exceeded.

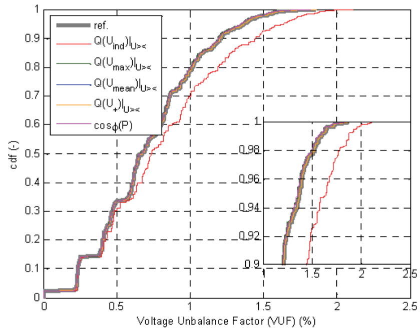


Figure 3 – Maximal VUF for all load/generation combinations

Figure 4 shows the vector diagram for three different control schemes (without control, with $Q(U_{ind})$ and with $Q(U_{max})$) and for the unbalance combination leading to the highest voltage unbalance factor (i.e. negative sequence component). The operation point for the $Q(U_{ind})$ control is shown in Figure 5.
The origin of the diagrams represents the earth potential and the star point displacement is shown with the purple arrow (Earth-Neutral voltage, multiplied with a factor 100 compared to the phase voltages to allow a proper visualisation). To allow a proper visualisation, the three phase-neutral L_X-N phasors are shown with an offset in

magnitude. Although this transformation is not fully correct (phase to phase voltages cannot be constructed), it allows visualising the magnitude and angle of each phase.

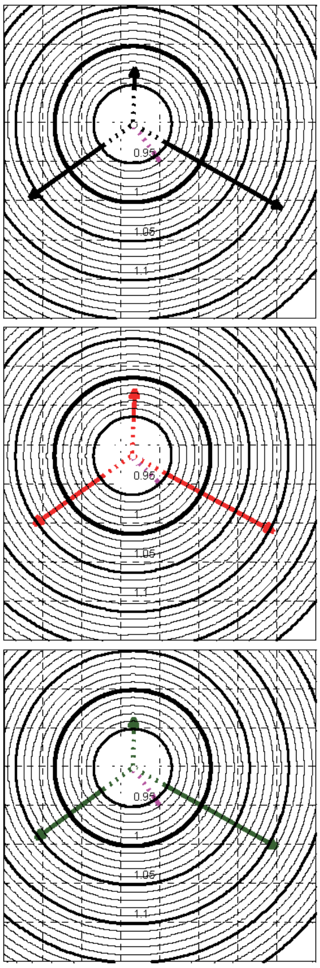


Figure 4 – Phasor diagram. Top: without control / Middle: with Q(U_{ind}) / Bottom: with Q(U_{max})

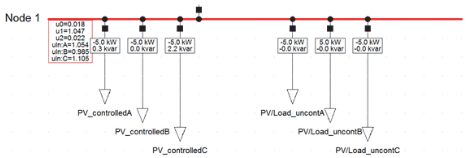


Figure 5 – Operation point for the considered combination leading to the highest VUF (for Q(U_{ind}))

This diagram confirms that the Q(U_{ind}) control allows a larger decrease of the highest voltage while at the same time increasing of the lowest voltage. The Q(U_{max}) control leads to a smaller decrease of the highest voltage and at the same time a further decrease of the lowest voltage. The angle between the two phases with the highest voltage deviates more from 120° for the Q(U_{ind}) control than for the Q(U_{max}) control: 116.2 instead of 117.5° compared to 117.3° without control. This leads to an increase of the negative sequence component which directly impacts the voltage unbalance factor VUF as already shown in Figure 3.

For highly unbalanced situations (99 % percentile), the Q(U_{ind}) control leads to approximately 6 % less losses than the reference case (without control) while the Q(U_{max}) and cosφ(P) lead to approximately 7 % more losses (relative increase / decrease).

V. CONCLUSION

The investigations shown in this paper demonstrate that under unbalanced conditions, the maximal voltage can be reduced to a greater extent with the unsymmetrical control using the individual phase voltages than with the symmetrical controls. In addition, the phase spreading and the phase voltage unbalance factor can also be more reduced with this control. However, this control intends to control the phasor magnitude without controlling the angle between phasors which results in a higher voltage unbalance factor (negative sequence) under heavily unbalanced conditions. In some cases, the normative 2 %-limit can even be exceeded.

From the network point of view, the unsymmetrical control using the individual phase voltages provides the highest benefits except for the negative sequence component. In theory, the control could evaluate the negative sequence component and limit the reactive power control to avoid exceeding the limit.

The inverter design point of view has been left out of this paper but designing and operating a three-phase inverter under unbalanced voltage conditions and injecting unbalanced currents has many implications, mostly in terms of:

- higher rating needed to exploit most of the benefits
- need to oversize the DC-link in order to mitigate voltage and current ripple caused by instantaneous active power oscillation
- limited MPPT-window and reduced MPP tracking efficiency due to the voltage ripple on the DC-link
- impact on harmonic distortion of phase currents which can lead to additional magnetics core losses.

This paper only considers the unbalanced operation of three-phase inverters operated with existing control schemes (“passive compensation” of voltage unbalance). Other concepts for actively compensating the voltage unbalance within the inverter capabilities are feasible and a cost/benefit analysis should be conducted accordingly.

REFERENCES

[1] E-CONTROL, "Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt2: Richtlinie zur Beurteilung von Netzrückwirkungen." Sep-2006.

[2] VDE-FNN, "VDE-AR-N 4105:2011-08 Power generation systems connected to the low-voltage distribution network." Aug-2011.

[3] CENELEC, "Voltage characteristics of electricity supplied by public electricity networks." 01-Mar-2011.

[4] B. Bletterie, A. Gorsek, A. Abart, and M. Heidl, "Understanding the effects of unsymmetrical infeed on the voltage rise for the design of suitable voltage control algorithms with PV inverters," in *Proc. 26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, 2011, pp. 4469 – 4478.

[5] B. Bletterie, A. Stojanovic, S. Kadam, G. Lauss, M. Heidl, C. Winter, D. Hanek, A. Pamer, and A. Abart, "Local voltage control by PV inverters first operating experience from simulation, laboratory tests and field tests," in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4574–4581.

[6] E. Demirok, P. C. González, K. H. B. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, "Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids," *IEEE J. Photovolt.*, vol. 1, no. 2, pp. 174–182, Oct. 2011.

[7] T. Stetz, M. Kraiczy, M. Braun, and S. Schmidt, "Technical and economical assessment of voltage control strategies in distribution grids," *Prog. Photovolt. Res. Appl.*, vol. 21, no. 6, pp. 1292–1307, Sep. 2013.

[8] P. Esslinger, "Studie Q(U)," Munich, Aug. 2012.

[9] B. Bletterie, A. Abart, S. Kadam, D. Burnier, M. Stifter, and H. Brunner, "Characterising LV networks on the basis of smart meter data and accurate network models," in *Proc. Integration of Renewables into the Distribution Grid, CIRED 2012 Workshop*, 2012, pp. 1–4.

[10] D. Habijan, M. Cavlović, and D. Jakšić, "The issue of asymmetry in low voltage network with distributed generation," in *Proc. 22nd International Conference on Electricity Distribution CIRED*, Stockholm, 2013.

[11] E. De Jaeger, A. DU BOIS, and B. Martin, "Hosting capacity of LV distribution grids for small distributed generation units, referring to voltage level and unbalance," in *Proc. Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[12] R. Salustiano, E. Neto, and M. Martinez, "The unbalanced load cost on transformer losses at a distribution system," in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–3.

[13] A. Siddique, G. S. Yadava, and B. Singh, "Effects of voltage unbalance on induction motors," in *Proc. Electrical Insulation, 2004. Conference Record of the 2004 IEEE International Symposium on*, 2004, pp. 26–29.

[14] A. Von Jouanne and B. Banerjee, "Assessment of voltage unbalance," *Power Deliv. IEEE Trans. On*, vol. 16, no. 4, pp. 782–790, 2001.

[15] L. Degroote, B. Renders, B. Meersman, and L. Vandevelde, "Neutral-point shifting and voltage unbalance due to single-phase DG units in low voltage distribution networks," in *Proc. PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1–8.

[16] B. Bletterie, S. Kadam, R. Pitz, and A. Abart, "Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters," in *Proc. PowerTech 2013 IEEE Grenoble*, 2013, pp. 1–6.

[17] G. Roupioz, X. Robe, and F. Gorgette, "First use of smart grid data in distribution network planning," in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[18] R. D. Lazar and A. Constantin, "Voltage balancing in LV residential networks by means of three phase PV inverters," in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4068 – 4071.

[19] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "Effectiveness of traditional mitigation strategies for neutral current and voltage problems under high penetration of rooftop PV," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, 2013, pp. 1–5.

[20] F. Shahnia, A. Ghosh, G. Ledwich, and F. Zare, "Voltage Unbalance reduction in low voltage distribution networks with rooftop PVs," in *Proc. 20th Australasian Universities Power Engineering Conference (AUPEC)*, Christchurch, 2010.

[21] J. Fernandez, S. Bacha, D. Riu, H. Turker, and M. Paupert, "Current unbalance reduction in three-phase systems using single phase PHEV chargers," in *Industrial Technology (ICIT), 2013 IEEE International Conference on*, 2013, pp. 1940–1945.

[22] E-CONTROL, "Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen." 2013.

[23] S. Kadam, B. Bletterie, G. Lauss, M. Heidl, C. Winter, D. Hanek, and A. Abart, "Evaluation of voltage control algorithms in smart grids: results of the project: morePV2grid," in *Proc. 29th European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, 2014.

Publication 8

"Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters"

B. Bletterie, S. Kadam, R. Pitz, and A. Abart, "Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters," in Proc. PowerTech 2013 IEEE Grenoble, 2013, pp. 1–6.

Own contribution

This paper presents a concept for reducing unbalance in low voltage networks with a high share of single-phase generators by switching phases.

The results summarised in this article partly emerged from the Austrian research project DG DemoNet-Smart LV Grid of the Austrian Climate and Energy Fund (FFG - Project ID 829867) in which the applicant was one of the key researcher.

The applicant initiated and coordinated the research activities summarised in this paper. With the help of the second author, he automated the monte-carlo simulations. He introduced a pareto-optimal approach to identify the best trade-off between efforts and benefits.

He wrote most of the paper and applied successfully together with the second author for a patent building an extension of this work.

Optimisation of LV networks with high photovoltaic penetration – balancing the grid with smart meters

Benoît Bletterie, Serdar Kadam, Matthias Stifter
Austrian Institute of Technology, Vienna, Austria
benoit.bletterie@ait.ac.at

Richard Pitz
Energy Automation Development
Siemens AG Österreich
Vienna, Austria
richard.pitz@siemens.com

Andreas Abart
Asset management-PowerQuality
Energie AG Oberösterreich Netz
Gmunden, Austria
andreas.abart@netzgmbh.at

***Abstract*—This paper presents the latest results of several research activities in the field of low voltage network optimization in regard to unsymmetrical power infeed from distributed generators. A method for balancing networks with a high number of single-phase generators is proposed. By applying the method, the voltage unbalance can be reduced, the available voltage band can be better utilized and the hosting capacity for distributed energy resources extended.**

***Index Terms*—Distributed power generation, Power quality, Smart grids, Power system measurement, Solar power generation**

I. Introduction: Voltage Unbalance In LV Networks

Although a significant part of installed photovoltaic capacity is connected in low voltage (LV) networks (e.g. about 70 % of more than 29 GW_p in Germany by mid-2012 [1]), the actual impact of these installations on the network is still not well known. Especially, unsymmetrical generation (e.g. small photovoltaic (PV) generators) lead to voltage unbalance. Voltage unbalance is not only a concern as such (e.g. degradation of the performance of three-phase machines due to torque pulsations, overheating due to the negative sequence) but also a concern for complying with the voltage limits as stated in the standard EN 50160 [2]. Indeed, the unsymmetrical infeed leads to a disproportionate increase of the voltage in one phase which might exceed the limit. Besides the voltage effects which are in the focus of this paper, unsymmetrical infeed causes an increased loading of the neutral conductor and an increase of losses. In this paper, the focus is laid on reducing the unsymmetrical infeed in order to improve voltage profiles in LV networks since voltage rise is widely considered to be one of the most severe limitations of the hosting capacity of distribution networks [4].

Currently, distribution network planning and voltage band management are necessarily conservative due to the lack of detailed information [5] (e.g. simultaneity factor, connection phase of single-phase generators). One common assumption is to consider that single-phase generators are connected to the same phase due to the lack of information (worst-case). Without a profound knowledge of the actual network situation, these assumptions can however not be relieved. Any improvement in this field shall enable to better use the existing infrastructure.

II. Understanding The Impact Of Unsymmetrical Power Infeed

The effect of unsymmetrical power infeed in LV networks has been investigated in [2] on the basis of simulations. The effect of neutral point displacement was shown on the basis of simulations with real network, load and generation data. While the voltage unbalance factor as defined in [3] was not exceeded in the considered case, a very high difference between the phase voltages at the end of the longest feeder was observed (about 10 %). Figure 1 shows as example the voltage profile on a real network with 47 PV installations (network from the demonstration project presented in [6]).

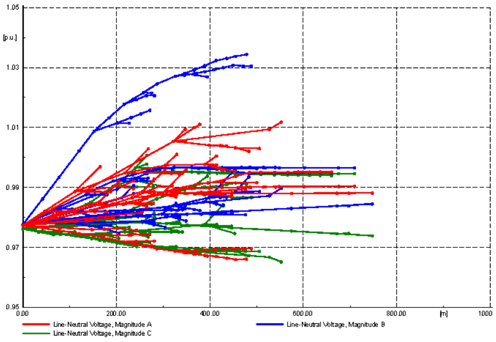


Figure 1 Exemplary voltage diagram for an unsymmetrical distribution of 47 PV installations (42 single-phase)on the considered LV network

Following the approach used in current connection rules for distributed energy resources (DER) the effect of the power infeed has been considered separately (loads are out of service in Figure 1). This figure shows that the unsymmetrical power infeed causes a voltage rise as expected, but also a voltage drop due to the neutral point displacement. In the considered case the highest voltage is reached on phase L3 of a feeder, which is not the longest in the network due to the distribution of the installations. Depending on the grounding conditions, the voltage rise caused by a single-phase generator is about six times greater than the voltage rise caused by a three-phase generator of the same power due to the additional voltage rise in the neutral conductor (factor 2). This means that the hosting capacity related to the voltage limitation is significantly affected by unsymmetrical power infeed in LV networks.

In order to solve the overvoltage problems that might occur in LV networks with high PV penetration, various concepts have been considered in several research and demonstration projects [4][7][8]. Among the different concepts, the use of a Q(U) characteristic (reactive power consumption as a function of the voltage at the inverters' terminal as specified in [9]) seems to be also suitable under unbalanced conditions: if the voltage is higher in one phase, inverters connected to this phase will consume more reactive power to reduce the voltage according to the Q(U) characteristic): by controlling phase voltages, single-phase inverters contribute de facto to unbalance mitigation. However, the single-phase reactive power consumption causes a neutral point displacement which affects the other two phase voltages. In some particular cases, this might lead to an additional increase or to an additional decrease of the voltage on another phase [2]. Figure 2 illustrates this phenomenon for a simple case: it shows the voltage diagram (voltage as a function of the distance on the feeder) for an imaginary feeder. The first inverter (closest to the transformer station) is connected to phase L1 and the second to phase L2; both operate in voltage control mode (Q(U)).

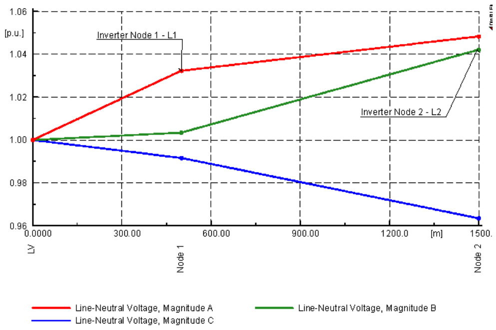


Figure 2 Voltage profile along a feeder with two PV generators with reactive power-based voltage control (first on L1 and second on L2)

This figure shows that the voltage on phase L1 increases between node 1 and node 2 despite the absence of active power infeed on phase L1. This side-effect is due to the voltage change on the neutral conductor resulting from the reactive power flow by the second inverter. On the other hand, the voltage on the third phase (L3) is further decreased. This simple example shows control schemes taking into account a possible voltage unbalance (e.g. Q(U) control for each single-phase inverter) are able to reduce the maximal voltage. However the actual benefit might be reduced due to the fact that the voltage on another phase which might be heavily loaded might be further decreased.

In [10] a concept has been introduced to compensate the voltage unbalance with three-phase PV inverters. For this, the deviation between each phase voltage and the positive sequence voltage is used as input to a controller. The output of the controller modifies the inverter operation point by increasing the active current in phases in which the voltage is smaller than the positive sequence voltage.

Having explained the challenges associated to voltage control under unbalanced conditions, the focus of the paper is laid on preventive measures to avoid higher levels of unsymmetry due to single-phase generators.

III. Smart Meters For Smart Network Planning

Besides the metering-related functions smart meters can offer a broad variety of additional features for network planning and operation such as interruption detection and remote intervention, assistance for maintenance scheduling, regional load balancing, remote control and power quality monitoring. As previously mentioned, the network hosting capacity for distributed energy resources (DER) is often limited by the voltage rise caused on the distribution lines. Since the major part of the normative voltage band (EN 50160 [2]) in the LV is foreseen for the voltage drop at maximum load, only a small part is available for the voltage rise caused by DER.

In order to avoid using conservative assumptions for the network planning, information is needed. In this chapter, some solutions providing valuable information during the network planning process are presented.

A. *The Power Snap-Shot Analysis: a planning tool for smart grids*

With the deployment of smart meters, new possibilities are offered in terms of monitoring. In [11] and [12], a novel method for capturing synchronous network measurements (voltages, active and reactive power per phase) has been introduced (Power Snap-Shot Analysis - PSSA). Snapshots are triggered by the highest or lowest value of the configured criteria (voltage, current, unbalance, etc.). For the selected trigger timestamps the measured 1 second-values of active, reactive powers, voltages for each phase and load are requested from the meters and sent to the analysis environment at a central server (PSS Host).

With the proposed concept, it is possible to gather thousands of snapshots helping in characterizing the considered LV network, quantifying the available network capacities, validating the network models in a simulation environment [13] or determining critical nodes for LV control concepts [14].

B. *Using smart meters for determining the connection phase*

Currently, in case of problems such as the repeated disconnection of small PV generators due to the trip of the overvoltage protection, distribution network operators (DNO) may try to connect the generator on another phase. As previously explained a precise knowledge of the phase assignment would be very valuable for DNOs. Devices allowing the determination of the phasing are basically available [15]. They usually provide the phasing in relation to a reference phase thanks to a GPS-based time measurement. Since their use is time-consuming and the number of single-phase PV generators can be very large in particular LV feeders, they can only be used to special purpose and are not suitable for determining the phase assignment on an area-wide basis.

An important prerequisite of the PSSA is the knowledge of the phase assignment [11]. For this, a concept has been developed and implemented into the AMIS meters [11]. The principle of this concept is schematically explained on Figure 3.

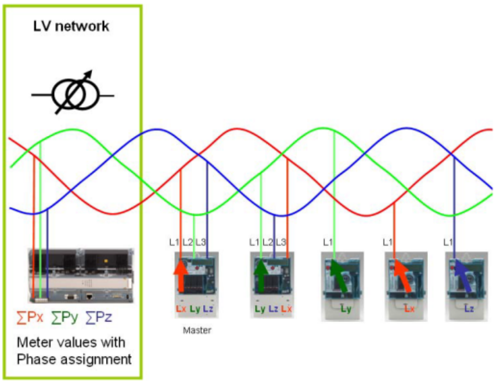


Figure 3 Principle of the phase assignment

In this concept a master meter is used as reference for all the other meters. In combination with the data concentrator, which is used in the smart meter infrastructure to gather and pre-process the meter measurements, the phase of all meters in the LV network can be determined in respect to the master meter.

This function is also used by the so-called Express Grid Data Access (EGDA) which has newly been developed in the project DG DemoNet – Smart LV Grid [6] and allows collecting on demand voltages, currents, active and reactive power from all the meters in a LV feeder with a high sampling rate. With this function it is possible to get a full picture of the voltage profile and level of unbalance. This concept will be used to provide measurements to a controller, which can operate the on-load-tap-changer of a distribution transformer, or to send set-points to PV inverters [6].

In a first step, a probabilistic method which allows estimating the expectable voltage rise caused by a set of unsymmetrical generators will be introduced and illustrated with a real example. In a second step, the pareto principle will be applied to the optimization of an existing LV network with a high share of single-phase PV generators in order to decrease the voltage rise.

IV. Probabilistic vs. Deterministic Quantification of the Expectable Voltage Rise

In this chapter, a real LV network with 47 PV generators (mostly single-phase) distributed over 11 feeders is used [6]. Since the phase assignment of these installations is unknown, a monte-carlo simulation is used to compute the voltage rise caused by all these installations. Indeed it is not possible to consider all the possible phase combinations ($3^{47}=2.6\times10^{21}$ combinations). To compute the voltage rise, only the impact of the PV generation has been considered (generators and loads are considered separately in accordance with the current planning practices [9]). Current planning rules allow a voltage rise (increase of the voltage due to the power generation) of 3 % in LV networks [9]. In order to compute the voltage rise, unbalanced power flow computations have been used together with a detailed network model with explicit neutral modeling and grounding. Details about the modeling can be found in [2]. The result of this computation is shown on Figure 4.

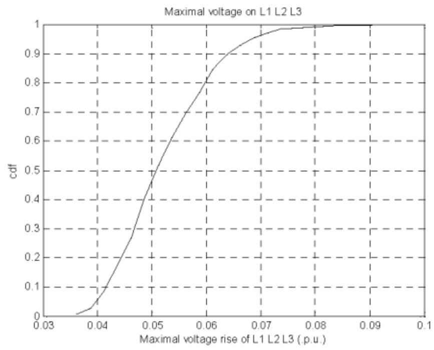


Figure 4 Cumulative probability distribution (cdf) of the voltage rise

On this figure the cumulative distribution of the maximal voltage rise caused by all the PV generators is shown. Using a 95 % percentile criterion would for example result in a voltage rise of about 7 %. However, the question of which percentile (or which confidence level) to use as a planning criterion in this determination of the maximal voltage rise is not straight forward to answer. While standards in the power quality area [2], [16] mainly uses a 95 % percentile, the nature of the problem is slightly different here. Even if large voltage rise values (in this example up to 9 %) due to the disadvantageous distribution of the infeed over the three phases are rather improbable, the effects would be recurrent (under low loading and nice weather conditions).

When having the information about the phase assignment for each PV installation the DNO can determine the exact voltage rise caused by all the PV installations. By doing this, the available voltage band can be better used without jeopardizing the voltage quality (voltage level and unbalance).

V. A New Balancing Concept For Network With Unsymmetrical Power Infeed

The concept proposed for balancing the PV generation is explained in the first sub-chapter, and application examples are provided in the following two ones.

A. *Pareto-efficient optimisation of LV feeders with monte-carlo power flow calculations*

When considering an existing LV network or feeder with a high PV penetration in which overvoltage problems are feared of even observed, the main question is how to improve the situation (balance the PV power over the phases). Of course, the larger the number of installations for which the phase assignment can be changed, the better the situation can be improved. Since changing the phase assignment of PV installations supposes some significant manpower efforts (e.g. coordination between DNO personal, customers and PV installer), the number of phase assignment changes should be limited. In this context, applying the concept of pareto-efficiency is interesting. According to this principle (also known as the 80–20 rule), roughly 80 % of the results can be achieved with 20 % of the efforts (numbers of course depend on the nature of the problem).

Optimizing the distribution of the unsymmetrical infeed is rather complex due to the non-linearity and coupling of the system (phases influence each other due to the voltage drop/rise on the neutral conductor). For this reason, a monte-carlo approach is proposed (see Figure 5). Starting from the status quo, the phase assignment is determined in a first step and the voltage rise is determined by an unbalanced power flow computation. Depending on the obtained voltage rise (compared to the worst and best case of Figure 4), the decision to balance the considered feeder or network can be taken.

In a second step, a large number of computations are performed by randomly changing the phase assignment of an increasing number of generators randomly selected. For each number of allowed change of the phase assignment (e.g. N_G=1:5), the best combination (smallest voltage rise) is stored. At the end of the process, a sorted list of improvements with increasing complexity is obtained (pareto curve). On the basis of this list, a decision can be taken.

This procedure can be implemented at network level (including all the feeders below a distribution transformer station) or at feeder level. Since the effect of unsymmetrical power flows on the distribution transformer is expected to be low, this analysis can be applied in priority to the most critical feeders (long feeders with a high number of single-phase generators).

The proposed concept can in addition be extended with PSSA data. In such a case, the combined effect of loads and generators can be properly considered. By performing the combined analysis of relevant Power Snap-Shots, the optimum can be approached by ensuring that the voltage band is decreased for all the PSS. For this, the concept of voltage range (difference between the maximum and the minimum voltage over the feeder or network) can be used. By analyzing the PSSA data, the times at which the highest voltage range occurs can be identified and considered in the computation. For this, the load and the generation data of these timestamps are gathered for the whole network and fed into the simulation environment thanks to a dedicated tool [13]. Next, for each timestamp an unbalanced power flow computation is executed in the frame of a monte-carlo analysis to identify phase connection changes to decrease the voltage range and relieve part of the voltage band. The algorithm used to determine the optimum is shortly summarized below (details to improve the performance and to handle complex networks with two and three-phase generators are not shown):

N_{PSS} *number of Power Snap-Shot (e.g. 100)*
N_G *number of generators for which the phase connection might be changed (e.g. 5)*
N_{MC} *number of MonteCarlo trials (e.g. 1000)*

```
for k = 1: N_PSS
    [Δu(k)] = getVoltageBand()
end
for i = 1:N_G
    for j = 1: N_MC
        [G_i] = RandomGenSelect(N_G)
        [Φ_i] = RandomPhaseSelect([G_i])
        for k = 1: N_PSS
            setGenPhase(G_i, Φ_i)
            [Δu_actual(k)] = getVoltageBand()
        end
        if [Δu_actual] < [Δu]
            [Δu] = [Δu_actual]
            save G_i
            save Φ_i
        end
    end
end
```

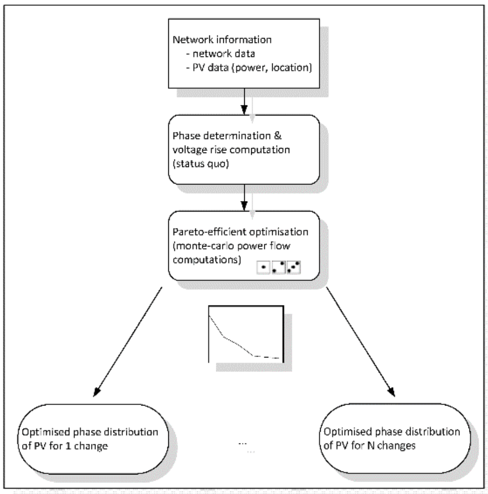


Figure 5 Flow chart of the pareto-efficient balancing

Alternatively, the phase assignment can be changed in connection cabinets instead of changing the phase of connection of the generator at the point of connection (usually the meter cabinet). This has the advantage that the changes can be done without accessing the house installation, and that unsymmetrical power flows caused by the non-uniform distribution of loads can also be balanced. By doing this not only the highest but also the lowest voltage in the network must be considered as previously explained.

B. Case study: balancing concept to reduce the voltage rise caused by single-phase PV generators

The results of these computations for the considered network are shown on Figure 6. As previously explained only the PV generation has been considered in order to compute the voltage rise. This figure shows that by changing the phase assignment in one installation only (on the basis of a set of 500 trials), a reduction of the voltage rise of more than 1 % can be achieved. By changing the phase assignment in three installations, a reduction of the voltage rise of 2 % can be achieved. Figure 7 shows the pareto curve corresponding to this minimization, where it can be clearly seen that the major improvement are already reached with few changes of the connection phase.

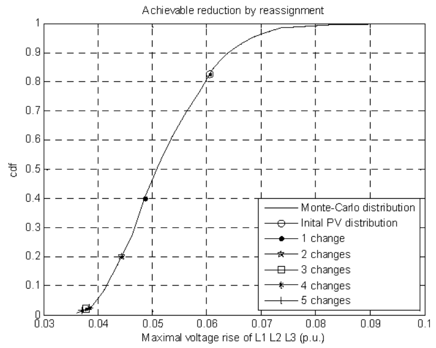


Figure 6 Pareto-efficient minimisation of the voltage rise (to five changes)

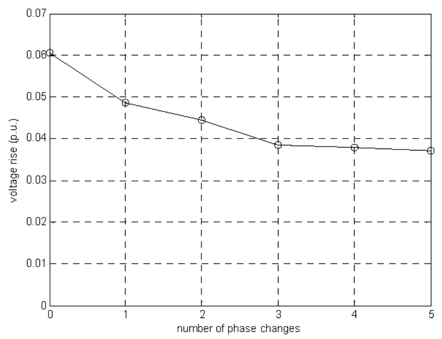


Figure 7 Pareto curve (minimisation of the voltage rise for up to five changes)

C. Case study: balancing concept to optimise the voltage profile of a LV network with Power Snap-Shots data

In the previous case study, the loads were not considered. However, when considering a LV network or feeder, the most challenging situation corresponds to situations with high voltage range (difference between maximal and minimal voltage). In this case study measured time series (1 minute average active and reactive power per phase[1]) for 18 characteristic days were used (combinations of: winter / summer – Monday / Friday / Sunday – cloudy / variable / sunny) for the same network as previously used (chapter IV). On the basis of the measured profiles the most challenging timestamps (highest voltage range) have been identified (Power Snap-Shots) and the proposed concept has been used (see previous chapter). Figure 8 shows the initial voltage profile for a selected Power Snap-Shot and for a particular feeder with high voltage range.

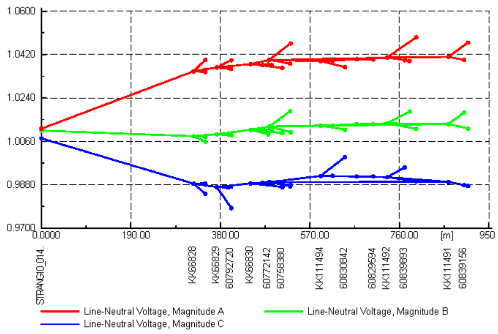


Figure 8 Initial voltage profile for the PSS with the highest voltage range

Figure 9 shows the voltage profile after a suggested change of phase assignment for only one installation (change from phase L1 to phase L3).

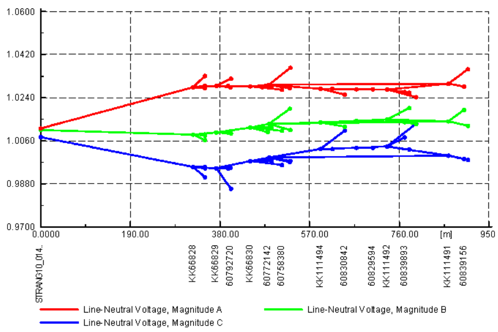


Figure 9 Optimized voltage profile for the PSS with the highest voltage range

[1] data generated in the research project "ADRES-CONCEPT" funded by the Austrian Climate and Energy Fund and performed under the program "Energie der Zukunft"

A comparison of the voltage profile with the initial profile shows that the voltage range can be reduced by about 2%. In this case the maximal voltage was decreased and the minimal voltage was increased. However, the proposed modification of the phase connection could result in a higher voltage range for other Power Snap-Shots. Therefore the simulation of the 18 days was repeated after the change of the phase connection at the proposed installation and the results were analyzed.

The effects of the phase assignment change during the year were estimated by weighting the voltage range of the 18 simulated days to reflect daily and seasonal effects. Figure 10 shows the boxplots the voltage range before and after the optimization (with the 0 %, 2.5 %, 50 %, 97.5 % and 100 % percentiles). The comparison between the highest voltages range in the initial case and the optimized case shows a reduction of almost 1 % (less than the 2 % obtained previously for the mentioned reason). The 97.5 percentile was decreased by more than 0.6 %.

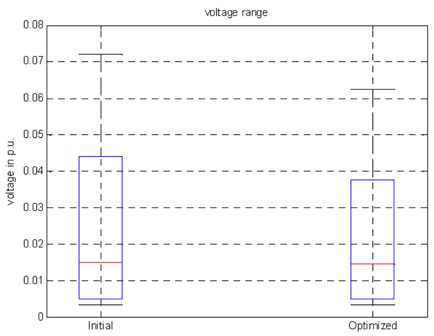


Figure 10 Voltage range before and after phase change

VI. Conclusion

By having a better knowledge of the actual network status, low voltage networks can be significantly better used by relieving some of the conservative assumptions. With the area-wide rollout of smart meters which can be seen as distributed measurement devices, new tools can be developed for the planning and operation of smart grids. In this paper, a novel concept for optimizing the distribution of photovoltaic generation has been introduced. This smart meter use case allows enhancing the hosting capacity of existing network. The proposed concept uses monte-carlo trials and the pareto principle to propose a reduced set of changes of the connection phase at selected generators. This method allows identifying the most effective changes while limiting the necessary efforts. The phase information which is necessary for the optimization is provided by smart meters. In addition, the use of Power Snap-Shots allows considering the loads in the optimization by ensuring that the voltage profiles are improved under various conditions. Instead of performing the phase change directly in house installations the change might be done in connection cabinets. This solution is particularly relevant for countries with widespread single-phase connection for normal households (e.g. France, Spain, Italy) and is in practice easier to implement since all the changes are done at the network side. Besides the benefits in terms of voltage band usage, a decrease of the losses can be expected from balancing the network.

Acknowledgement

The authors acknowledge the co-funding of the project *DG DemoNet – Smart LV Grid* from the Austrian Climate and Energy Fund through New Energies 2020 managed by the Austrian Research and Promotion Agency (FFG).

References

[1] Bundesnetzagentur, "Meldungen Januar-Juni 2012", August 2012
[2] B. Bletterie, A. Gorsek, A. Abart, M. Heidl, "Understanding the Effects of Unsymmetrical Infeed on the Voltage Rise for the Design of Suitable Voltage Control Algorithms with PV Inverters", in *Proc. 26th EUPVSEC 2011*, pp. 4469 - 4478
[3] EN 50160, *Voltage characteristics of electricity supplied by public electricity networks*, March 2011, CENELEC
[4] T. Degner, G. Arnold, T. Reinmann, B. Engel, M. Breede, P. Strauß, "Increasing the photovoltaic-system hosting capacity of low voltage distribution networks" , in *Proc. 21st International Conference on Electricity Distribution*, June 2011
[5] B. Bletterie, M.Stifter, D. Burnier de Castro, H. Brunner, S. Kadam, "Characterizing LV networks on the basis of Smart Meter data and accurate network models" in *Proc. CIRED Workshop on Integration of Renewables into the Distribution Grid*, May 2012
[6] A. Einfalt, F. Kupzog, H. Brunner, A. Lugmaier, "Control strategies for smart low voltage grids - the Project DG DemoNet - Smart LV Grid", in *Proc. CIRED Workshop on Integration of Renewables into the Distribution Grid*, May 2012
[7] T. Stetz, W. Yan, M. Braun, "Voltage Control in Distribution Systems with High Level PV-Penetration -Improving Absorption Capacity for PV Systems by Reactive Power Supply", in *Proc. 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy*, September 2010
[8] Adrian Constantin, Radu Dan Lazar and Dr. Søren Bækhøj Kjær, "Voltage control in low voltage networks by Photovoltaic Inverters – PVNET.dk", PVNET.DK Project report ForskEL 10698
[9] VDE-AR-N 4105:2011-08: "Power generation systems connected to the low-voltage distribution network, Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks", August 2011
[10] R. D. Lazar, "Voltage balancing in LV residential networks by means of three phase PV inverters", in *Proc. 27th EUPVSEC 2012*, pp. 4068 - 4071.
[11] A. Abart, D. Burnier de Castro, B. Bletterie, M. Stifter, H. Brunner, A. Lugmaier, A. Schenk, "Power SnapShot Analysis: A new method for analysing low voltage grids using a smart metering system", in *Proc. 21st International Conference on Electricity Distribution*, June 2011
[12] A. Abart, M. Stifter, B. Bletterie, H. Brunner, D. Burnier, R. Pointner, A. Schenk, R. Pitz, H. Taus, "Eyes to the Grid: New ways to analyze electrical low voltage networks", e & i Elektrotechnik und Informationstechnik, Volume 128, Issue 4 , pp 122-127
[13] M. Stifter, B. Bletterie, D. Burnier, H. Brunner, and A. Abart, "Analysis Environment for Low Voltage Networks," in *Proc. IEEE First International Workshop on Smart Grid Modeling and Simulation (SGMS)*, October 2011, pp. 61 –66.
[14] M. Stifter, P. Palensky, "Smart Meter Data as a basis for Smart Control in Low Voltage Distribution Networks," in *Proc. IEEE International Symposium on Industrial Electronics (ISIE)*, May 2013 (accepted)
[15] Chen, C.S., "Design of phase identification system to support three-phase loading balance of distribution feeders", in Proc. Industrial and Commercial Power Systems Technical Conference (I&CPS), May 2011
[16] IEC/TR 60725, *Consideration of reference impedances and public supply network impedances for use in determining the disturbance characteristics of electrical equipment having a rated current ≤75 A per phase*, June 2012

7 Further publications

7.1 Refereed international journals

S. Khan, B. Bletterie, A. Anta, and W. Gawlik, “On Small Signal Frequency Stability under Virtual Inertia and the Role of PLLs”, p. 18, 2018.

J. Varela, N. Hatziargyriou, L. J. Puglisi, M. Rossi, A. Abart, and B. Bletterie, “The IGREENGrid Project: Increasing Hosting Capacity in Distribution Grids,” IEEE Power Energy Mag., vol. 15, no. 3, pp. 30–40, May 2017.

S. Kadam, B. Bletterie, and W. Gawlik, ‘A Large Scale Grid Data Analysis Platform for DSOs’, Energies, vol. 10, no. 8, p. 1099, Jul. 2017.

P. Kotsampopoulos, F. Lehfuss, G. Lauss, B. Bletterie, and N. Hatziargyriou, ‘The limitations of digital simulation and the advantages of PHIL testing in studying Distributed Generation provision of ancillary services’, IEEE Transactions on Industrial Electronics, pp. 1–1, 2015.

T. Fawzy, D. Premm, B. Bletterie, and A. Goršek, ‘Active contribution of PV inverters to voltage control – from a smart grid vision to full-scale implementation’, Elektrotech. Inftech., vol. 128, no. 4, pp. 110–115, Apr. 2011.

7.2 Book chapters

F. Gonzalez-Longatt and J. L. Rueda Torres, Eds., Advanced Smart Grid Functionalities Based on PowerFactory. Cham: Springer International Publishing, 2018.
Chapter 3 - Benoît Bletterie, Roman Bolgaryn and Serdar Kadam: Smart Network Planning—Pareto Optimal Phase Balancing for LV Networks via Monte-Carlo Simulations

F. M. Gonzalez-Longatt and J. Luis Rueda, Eds., PowerFactory Applications for Power System Analysis. Cham: Springer International Publishing, 2014.
Chapter 14 - Matthias Stifter, Serdar Kadam and Benoît Bletterie: Advanced Applications of DPL: Simulation Automation and Management of Results

7.3 Patents

S. Kadam and B. Bletterie, “Verfahren zum Anschluss von zweipoligen Schaltkreiselementen”, AT 515625 B1 2016-07-15.

R. Schwalbe, A. Einfalt, B. Bletterie, W. Tremmel, and F. Zeilinger, “Method for preventing voltage range deviations”, WO 2015/128119.

7.4 Refereed conference proceedings

B. Bletterie et al., “Local voltage control by PV inverters first operating experience from simulation, laboratory tests and field tests,” in Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, 2012, pp. 4574–4581.

B. Bletterie, S. Kadam, M. Heidl, C. Winter, D. Hanek, and A. Abart, “Techno-Economic Evaluation of Voltage Control in LV Networks: A Smart Grid Case Study,” in Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition, Paris, 2013, pp. 4210 – 4216.

B. Bletterie, S. Kadam, and J. Le Baut, “Increased hosting capacity by means of active power curtailment,” in Proc. CIRED Workshop 2016, Helsinki, 2016.

B. Bletterie, A. Latif, P. Zehetbauer, S. M. Villanueva, E. Romero-Ramos, and H. Renner, “On the impact of load modelling on distribution network studies,” in Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2017 IEEE PES, 2017, pp. 1–6.

B. Bletterie, A. Tayyebi, S. Kadam, J. L. B. J. Stöckl, J. Kathan, and A. Einfalt, “A novel concept for combining distribution network and system support services for storage systems,” in PowerTech, 2017 IEEE Manchester, 2017, pp. 1–6.

A. Kulmala, S. Repo, and B. Bletterie, ‘Avoiding adverse interactions between transformer tap changer control and local reactive power control of distributed generators’, in PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2016 IEEE, 2016, pp. 1–6.

J. Le Baut et al., ‘Probabilistic evaluation of the hosting capacity in distribution networks’, in Proc. IEEE Innovative Smart Grid Technologies ISGT Europe, Ljubljana, 2016.

A. Abart et al., ‘Power Snapshot Analysis: A new method for analyzing low voltage grids using a smart metering system’, in Proc. Electricity Distribution (CIRED 2011), 21st International Conference and Exhibition on, Frankfurt, 2011.

G. Lauss, R. Bründlinger, B. Bletterie, M. Nagelmüller, R. Pieler, and Z. Miletic, ‘New P/Q control functions of grid-connected PV inverters: Do they have an impact on the anti-islanding detection behaviour in European Grids?’, in Proc. 32nd European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 2015.

R. Schwalbe, M. Stifter, B. Bletterie, A. Abart, R. Pointer, and F. Herb, ‘DG DemoNet: impact of volt/VAR control on increasing the voltage band reserve-results from field trial validations’, 2013.

A. Einfalt, F. Zeilinger, R. Schwalbe, B. Bletterie, and S. Kadam, ‘Controlling active low voltage distribution grids with minimum efforts on costs and engineering’, in Proc. Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE, 2013, pp. 7456–7461.

B. Bletterie, A. Gorsek, A. Abart, and M. Heidl, ‘Understanding the effects of unsymmetrical infeed on the voltage rise for the design of suitable voltage control algorithms with PV inverters’, in Proc. 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 2011, pp. 4469–4478.

S. Kadam et al., ‘Evaluation of voltage control algorithms in smart grids: results of the project: morePV2grid’, in Proc. 29th European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, 2014.

B. Bletterie, S. Kadam, R. Pitz, and A. Abart, ‘Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters’, in Proc. PowerTech 2013 IEEE Grenoble, 2013, pp. 1–6.

B. Bletterie et al., ‘Local voltage control by PV inverters first operating experience from simulation, laboratory tests and field tests’, in Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, 2012, pp. 4574–4581.

C. Bucher, J. Betcke, G. Andersson, B. Bletterie, and L. Küng, ‘Simulation of distribution grids with photovoltaics by means of stochastic load profiles and irradiance data’, in Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, 2012, pp. 3795–3800.

R. Bründlinger, B. Bletterie, G. Arnold, T. Degner, and C. Duvauchelle, ‘PV inverters supporting the grid – First experiences with testing and qualification according to the new grid interconnection guidelines in Germany, Austria and France’, in Proc. 24th European Photovoltaic Solar Energy Conference, Hamburg, 2009, pp. 3170–3178.

B. Bletterie et al., ‘Enhancement of the network hosting capacity – clearing space for/with PV’, presented at the 25th European Photovoltaic Solar Energy Conference and Exhibition, Valencia, Spain, 2010, pp. 4828–4834.

B. Bletterie, S. Kadam, M. Heidl, C. Winter, D. Hanek, and A. Abart, ‘Techno-Economic Evaluation of Voltage Control in LV Networks: A Smart Grid Case Study’, in Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition, Paris, 2013, pp. 4210–4216.

B. Bletterie, A. Abart, S. Kadam, D. Burnier, M. Stifter, and H. Brunner, ‘Characterising LV networks on the basis of smart meter data and accurate network models’, in Proc. Integration of Renewables into the Distribution Grid, CIRED 2012 Workshop, 2012, pp. 1–4.