Semir Hadžimuratović, M.Sc.

Resilience Analysis of the Future Bosnia and Herzegovina Transmission Grid

DOCTORAL THESIS

to achieve the university degree of

Doktor der technishen Wissenschaften

submitted to

Graz University of Technology

Supervisor

Lothar Fickert, Em.Univ.-Prof. Dipl.-Ing. Dr.techn.

Institute of Electrical Power Systems, TU Graz

Co-supervisor

Petr Toman, Assoc. Prof. Dr.

Faculty of Electrical Engineering and Communication, TU Brno

Graz, April 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.

13.03.2019

Date

Signature

... to my crew,

Isak,

Emina and

Elma...

Abstract

Thesis Title: Resilience Analysis of the Future Bosnia and Herzegovina's Transmission Grid

Key words: Transmission system, Congestions, High-Temperature Low-Sag Conductors, Phase Shifting Transformers, Optimal Positioning Methodology

Driven by the deregulation of power utilities, power lines are nowadays used to send more electric energy through longer distances to end consumers, compared to previous decades. Transmission system operators within interconnected electric power systems import and export not only electricity, but also transmission grid related problems.

The research goal is to propose a generalized approach and methodology for the integration of those technologies, as well as to identify the optimal set of location of a phase shifting transformer for the potential use within an interconnected system.

The focus of this thesis is to identify the transmission system weak spots in Bosnia and Herzegovina. Secondly, the goal is to determine the technologies that can be used to improve this grid. Thirdly, to propose approaches for the solution of the identified issues. Finally, a financial overview is given, as an additional input for relevant institutions when performing further financial analyses with the goal to identify the key economic impacts of the proposed technological solutions.

With regard to the selection and use of advanced technologies, the most important outcomes are: the evaluation methodology to be used for determination of phase shifting transformers installation location and the identification of potential applications for advanced conductors.

The mentioned outcomes are demonstrated in case studies on the example of Bosnia and Herzegovina's transmission grid, as part of larger interconnected ENTSO-E system.

Kurzfassung

Titel der Abschlussarbeit: Resilienzanalyse des zukünftigen Übertragungsnetzes von Bosnien und Herzegowina

Schlüsselwörter: Übertragungsnetz, Engpass, Hochtemperaturseile, Phasenschiebertransformatoren, optimale Positionierungsmethodik

Bedingt durch die Deregulierung der Energieversorger werden Stromleitungen heute genutzt, um im Vergleich zu früheren Jahrzehnten mehr elektrische Energie über längere Strecken zum Endverbraucher zu transportieren. Übertragungsnetzbetreiber innerhalb von Verbundstromnetzen importieren und exportieren nicht nur Strom, sondern auch Probleme im Zusammenhang mit dem Übertragungsnetz.

Das Forschungsziel ist es, einen verallgemeinerten Ansatz und eine Methodik für die Integration dieser Technologien vorzuschlagen sowie den optimalen Standort für ihren möglichen Einsatz eines Phasenschiebertransformators in einem vernetzten System zu identifizieren.

Der Schwerpunkt dieser Arbeit ist die Identifizierung der Schwachstellen des Übertragungssystems in Bosnien und Herzegowina. Zweitens ist es das Ziel, die Technologien zu bestimmen, die zur Verbesserung dieses Netzes eingesetzt werden können. Drittens werden Ansätze für die Lösung der identifizierten Probleme vorzuschlagen. Abschließend wird ein Finanzüberblick als zusätzlicher Input für relevante Unternehmen bei der Durchführung weiterer Finanzanalysen mit dem Ziel gegeben, die wichtigsten wirtschaftlichen Auswirkungen der vorgeschlagenen technologischen Lösungen zu identifizieren.

Im Hinblick auf die Auswahl und den Einsatz fortschrittlicher Technologien sind die wichtigsten Ergebnisse: die Bewertungsmethode für die Bestimmung des Installationsortes von Phasenschiebertransformatoren und die Identifizierung potenzieller Anwendungen für moderne Leiter verwendet wird.

Die genannten Ergebnisse werden in Fallstudien am Beispiel des Übertragungsnetzes von Bosnien und Herzegowina als Teil des größeren, miteinander verbundenen ENTSO-E-Systems gezeigt.

Contents

Abbreviations

The following abbreviations are sorted in alphabetical order.

AAAC	All Aluminum Alloy Conductor
ACCC	Aluminum Conductor Composite Core
ACCR	Aluminum Conductor Composite Reinforced
ACSR	Aluminum Conductor Steel Reinforced
ACSS	Aluminum Conductor Steel Supported
APG	Transmission System Operator in Austria – “Austrian Power Grid”
BIH	Bosnia and Herzegovina
BTAL	**B**lack **T**hermal Resistant **Al**uminum
CGES	Transmission System Operator in Montenegro– “Crnogorski Elektroprenosni sistem”
CIGRE	Conseil International des Grands Réseaux Électriques (fr.) / International Council on Large Electric Systems (eng.)
CPC	Conductor Comparison Program from CTC Global
CSE	Central South Europe
CTC	CTC Global – Manufacturer of ACCC
CTE	Coefficient of thermal expansion
ELES	Transmission System Operator in Slovenia – “Elektro Slovenia”
EMS	Transmission System Operator in Serbia – “Elektromreža Srbije”
ENTSO-E	European Network of Transmission System Operators for Electricity
EPBIH	Power utility “Elektroprivreda Bosne i Hercegovine”
EPHZHB	Power utility “Elektroprivreda Hrvatske zajednice Herceg-Bosne”
EPS	Electric power system
ERS	Power utility “Elektroprivreda Republike Srpske”
EU	European Union
FERK	Regulatory Commission for Electricity in the Federation Bosnia and Herzegovina
GACSR	Gap Type ACSR
HAWK	Type of conductor (240/40 mm2)
HOPS	Transmission System Operator in Croatia – “Hrvatski Operator Prenosnog Sustava”
HR	Croatia (two letter country code, ISO APPHA-2)
HTLS	High-Temperature Low-Sag
IEEE	Institute of Electrical and Electronics Engineers
IEF	Individual Electrical Factor
INVAR	Special nickel-iron alloy FeNi36 conductor type
LineProp	PSS’s accompanying software for line parameters calculations
ME	Montenegro (two letter country code, ISO APPHA-2)
MONITA	Montenegro – Italy HVDC Cable
MSC	Mechanically switched capacitor
N	N security criterion
N-1	N-1 security criterion
N-2	N-2 security criterion
NTC	Net Transfer Capacity
OEF	Overall Electrical Factor
OHL	Overhead Line

PSS-E	Power System Simulator for Electricity – Siemens power flow calculation program
PTDF	Power Transfer Distribution Factors
PV	Present Value
RERS	Regulatory Commission for Energy in the Republika Srpska
RES	Renewable Energy Source
RS	Republika Srpska
SCADA/EMS	Supervisory Control and Data Acquisition/Energy Management System
SEE	South East Europe
SERC	State Electricity Regulatory Commission
SIL	Surge Impedance loading
SPP	Solar Power Plant
SS	Substation
SVC	Static VAR Compensator
TERNA	Transmission System Operator in Italy – “Rete Elettrica Nazionale”
TPP	Thermal power plant (for the purposes of this thesis, this refers to coal fired thermal power plants).
TRM	Transmission Reliability Margin
TSO	Transmission System Operator
TTC	Total Transfer Capacity
TYNDP	Ten Year Network Development Plan
VSR	Variable Shunt Reactor
WPP	Wind Power Plant

Acknowledgment

Above all, I praise God Almighty, who blessed me with health and confidence to undertake and complete the work successfully.

This thesis appears in its current form due to the assistance and guidance of many people. I would therefore like to offer my sincere thanks to all of them.

- The management of **NOSBIH/ISOBIH**, for the having identified my passion for research and including me into researched-focused working groups, as well as for providing technical support.
- CTC Global for providing the Conductor Comparison Program (CPC) Software for calculation purposes in this thesis.
- Colleagues from Slovenian TSO (ELES), **Franc Kropec**, **Blaž Traven**, **Matjaž Dolinar**, **Aleksander Polajner** and **Matej Bratić**, who welcomed the author and organized the visit to PST in substation Divača.
- Colleagues from Austrian TSO (APG), **Michael Weixelbraun, Mika Gunter, Andrea Dummer** and **Tarik Bukarić** who welcomed the author in APG premises, as well as for the visit to PST in substation Ternitz.
- Colleagues from Croatian TSO – Regional office Split (HOPS PRP Split), **Snežana Cujić Čoko, Leo Klarić, Goran Čubra** and **Jure Bojčić** who welcomed the author at substation Vrboran, and organized a field trip to witness the installation of ACCC conductors in Split region.
- Colleague from Croatian TSO – Regional office Zagreb (HOPS PRP Zagreb), **Stipe Ćurlin** who welcomed the author at substation Žerjavinec, as well as for the visit to PST in substation Žerjavinec.
- Colleagues from Security Coordination Center (SCC) from Belgrade, **Miloš Đurđević** and **Momčilo Lukić**.
- Colleague **Dragutin Mihalic** from HOPS for introducing me to ACCC technology.
- Colleagues **dr. Goran Majstrović** and **dr. Davor Bajs** from Energy Institute Hrvoje Požar, for their inputs, ideas and suggestions since the earliest phases of my professional work.
- **Prof. Herwig Renner** from TU Graz, for his inputs and experiences with PST design and installations in European power systems,
- My previous mentors: **Rasim Gačanović, Salih Sadović, Kemo Sokolija** and **Mirsad Raščić** for opening my eyes to new stages of opportunity and strength. I will forever be grateful for your guidance and kindness.
- Colleagues from NOSBIH, with whom I had the pleasure to discuss these issues along the way.
- All of my other numerous colleagues.
- **Prof. Petr Toman**, from TU Brno for inviting us to the EPE Conference, and being a great second supervisor for the Doctoral Thesis.
- I express my deep sense of thankfulness to my honorable guide **prof. Lothar Fickert**, for valuable guidance, expert suggestions, kindness, supervision, constant encouragement and all other considerations throughout the research work and the preparation of this thesis.
- My family and friends, for their support and faith, but also for their help and assistance while I was away from home.
- My father and late mother, for their unconditional love, moral support, personal attention and care.
- My wife, for everything else, and much more.

Motivation

Bosnia and Herzegovina's transmission grid is **aged** and the relevant institutions will have to commit to **new technologies** in order to modernize it. In the very new future, power flows originating from widespread **energy policies** (such as low carbon development plans, etc...) will change. The network will be more exposed to **dangerous power shifts**, creating congestions that will further test the **resilience** of the entire electric system. Therefore, system operation will have to be done at the **margins** of operation stability in an increased number of cases.

As a scientist, engineer and expert in the field of system analysis employed in **Bosnia and Herzegovina's System Operator**, my motivation is to cope these issues on time, analyze the expected changes and **strategically plan** future outcomes by suggesting **concrete and tangible steps** in order to meet the future system requirements with optimal investments, at reasonable cost.

1. Introduction

Driven by the deregulation of power utilities, power lines are nowadays used to send more electric energy through longer distances to end consumers, compared to previous decades. Over the years, there have been various technical proposals for the improvement of old transmission conductors, with a goal of increasing ampacity, as well as increasing the reliability of the power system as a whole.

The interconnected power system of Europe, operated by European Network of Transmission System Operators for Electricity (ENTSO-E), is probably the biggest man-made system in the world. The entire network consists of 43 electricity transmission system operators (TSO) from 36 countries across Europe, thus extending beyond EU borders.

The goal of this thesis is to identify resilience issues in the future Bosnia and Herzegovina's transmission grid, as part of ENTSO-E. The issues are then researched, analyzed, and solved in order to improve the security of the supply for the final customers.

In order to evaluate the above-mentioned, and put the proposed factors, evaluations and methodologies to the test, several examples are given, and three case studies are performed on the example of Bosnia and Herzegovina:

- Case Study: Evaluation Matrix for PST Installation in Bosnia and Herzegovina
- Case Study: Impact of Gradually Replacement of Old Transmission Lines with Advanced Composite Conductors
- Case Study: ACCC as a Solution for Wind Integration

The security of supply is a question of common interest, and as such comes at a price. The financial aspect of the implementation of new technologies is also a subject of research.

Chapter overview

The thesis is structured in a total of ten (10) chapters. The subsequent chapters are described as follows:

2. Research Methodology, Questions and Published Papers

This chapter summarizes the researched methodology, it also postulates research questions, and links them to the chapters where the answers to the questions are further analyzed, researched and presented. A list of published papers with their according abstracts is given at the end of this chapter.

3. Current Situation in Bosnia and Herzegovina

Based on relevant documents and legislation, an overview of the electric power system (Bosnia and Herzegovina's transmission grid) is presented in short sections. This chapter represents the base for the creation of the model for further analyses and case studies, presented later in the thesis.

4. Regional Development Plans

This chapter highlights the relevant regional development plans that are of importance when analyzing the issues as part of a wider interconnected system.

5. Focusing point for improvement

This chapter is divided into two parts; defining issues (based on the previous chapter) and present the focus of the research in the thesis. Figure 5.3 – Scope of work of Doctoral Thesis (page 52) gives a graphical overview of the outline and contents of the thesis.

6. Phase Shifting Transformers (PST)

As determined in the previous chapter, phase shifting transformers (PST) is the first technology of interest that will be subject to detailed analysis. This chapter contains an overview of the technology, gives details why PSTs are important and will remain to be of significance in the future. In the next section of this chapter, "Key Factors for the Installation of PST", the author identifies the main reasons, prerequisites for the installation of PST, but also summarizes key factors related to the optimal positioning of the PST in relation to the micro-location (substation), as well as macro-location (system). As a follow-up of the identified key factors, the evaluation methodology for the optimal positioning is proposed, based on the evaluation matrix with weighting factors. The potential categories are presented, and followed by a case study demonstrating the use of the proposed evaluation methodology on the installation of a PST unit in a set of selected scenarios within the transmission grid of Bosnia and Herzegovina. At the end of the chapter, a summary is given in relation to this particular technology (PST).

7. Advanced Conductors Technologies

The chapter "Advanced Conductors Technologies" deals with a new generation of enhanced transmission capabilities conductors to be used on the high-voltage grid. An overview of the current technologies of conductors is given, together with the pros and cons for each. The best type of advanced conductors is identified and used for further analyses.

Within this chapter, two case studies are performed;

- Case Study: Impact of Gradually Replacement of Old Transmission Lines with Advanced Composite Conductors
- Case Study: ACCC as a Solution for Wind Integration

Each case study analyzes the impact of advanced conductors on different issues identified earlier, in Chapter 5.

8. Financial Aspects of the Proposed Solutions

In this part, the economic aspects of the proposed technologies are summarized, analyzed and presented through examples.

9. Development Policies Recommendations

The chapter "Development Policies Recommendations" addresses the entities in charge of drafting, reviewing, and adopting of relevant energy policies, with regard to the issues, technologies, case studies, and other topics and subjects analyzed in the thesis.

10. Summary

In the end, a conclusion is given with respect to the assessment of the resilience analysis of the future Bosnia and Herzegovina's transmission grid.

After the conclusion, the following chapters are given:

- Bibliography
- List of Figures
- List of Tables

A list of abbreviations is given right after the Contents.

The **Appendix** contains full published papers of the author, maps, additional figures, documents, reports, forms that are complementary to this thesis.

Note: In this thesis, the dot character "." is used as a decimal separator, while the comma character "," is used as a separator for thousands. For example, the value of 123,456.78 reads – one hundred twenty-three thousands four hundred fifty-six and 78/100.

2. Research Methodology, Questions and Published Papers

2.1. Research Methodology

Subject of research

The subject of research of this Doctoral Thesis is the identification of resilience issues in the future Bosnia and Herzegovina's transmission grid. The issues are then researched, analyzed, and solved in order to improve the security of the supply for the final customers.

Research goals

Transmission system operators within interconnected electric power systems import and export not only electricity but also transmission grid related problems. The local problem tends to become global problems, solvable by introducing a new generation of power engineering technologies. The research goal is to propose a generalized approach and methodology for the integration of those technologies, as well as to identify the optimal set of location for their potential use within an interconnected system.

Applied scientific methods

In accordance with the best practice of scientific work, and in order to achieve the research goals, several scientific methods have been applied which can encompass the overall complexity of the problem related to the analysis, modeling, and research of transmission grids resilience:

- Evaluation of the current state-of-affairs and the identification of issues,
- Assessment of available and published literature referenced to the implementation of advanced transmission technologies,
- Comparison of different advanced technology,
- Modeling of interconnected power systems,
- Creating algorithms describing the involved processes,
- Automating calculation procedures through complex multi-language programming skills,
- Creating questionnaires for evaluation purposes,
- Creation of a code list matrix for modeling system studies with different data inputs,
- Gaining operational experience from field trips and interviews,
- Report creating.

When performing the analyses and study cases, the following software platforms were used;

- **MS Excel** for data input, and for final editing of output data (charts, tables, etc.),
- **MS Visual Basic** for the purpose of programming and calculation automation,
- High-performance transmission planning and analysis software **Siemens PSS-E**,
- **Python** programing language, as the main language for PSS-E automation scripting.
- **LineProp**, PSS-E accompanying software for the calculation of lines parameters,
- **Conductor Comparison Program (CPC) Software** CTC Global for the comparison of lines parameters.

2.2. Research Questions

The research questions are a roadmap of the scope of work that was undertaken within this thesis. The following table presents the list of questions, as well as the corresponding chapters, where the answers are given. A total of four (4) papers were published, each giving answers for different research questions. The details about the papers can be found in the following chapter.

Table 2.1 – Research questions and structure of thesis

No.	Research questions	Chap.	Title	Published paper
1	What are the resilience constraints of the future Bosnia and Herzegovina transmission grid?	5.1	Issues	
2	How can these constraints be addressed by using advanced technologies	5.2	Focus	
3	What are the qualitative and quantitative factors for defining the optimal location of phase shifting transformers (PST)	6.5	Key Factors for the Installation of PST	[1]
4	What quantitative algorithm/ methodology can be used to determine the optimal location of phase shifting transformers (PST) within an interconnected electric power system?	6.7	PST Evaluation Methodology	
5	To what extent can the replacement of old lines with composite lines (High-Temperature Low-Sag, i.e. HTLS) improve the system from a technical perspective?	7.5	Case Study: Impact of Gradually Replacement of Old Transmission Lines with Advanced Composite Conductors	[2]
6	Can new conductor technologies help (and to which extent) increase renewable energy source penetration and integration?	7.6	Case Study: ACCC as a Solution for Wind Integration	[3]
7	Which are the financial impacts of replacing old transmission lines with composite lines?	8.2	Financial Aspects of ACCC Technology	[4]
8	What recommendations could be given to relevant authorities in charge of energy policies related to transmission system operation in order to improve the system's resilience?	9	Development Policies Recommendations	

3.2. Published Papers

In order to address the research questions from the previous table, the author published a total of four (4) papers. Each paper assesses a different topic related to the research questions. An overview of the scope of work is given in Figure 5.3 – Scope of work of Doctoral Thesis, where the algorithm boxes with published papers are colored in red. Full papers are given in Appendix [A].

Paper title [1]**: Determination of Critical Factors for Optimal Positioning of Phase-Shift Transformers in Interconnected Systems**

Details
Authors: *S. Hadžimuratović, L. Fickert*
Conference: *International Scientific Conference on Electric Power Engineering (EPE)*
Location: *Brno, Czech Republic*
Conference dates: *16-18 May 2018*
Referencing: *IEEE Xplore/Web of Science/Scopus*

Abstract:

Phase-Shifting Transformers (PST) are installed in order to block or facilitate certain power flows. The installation of a single device affects power flows in a wider geographical area. Therefore, determining the optimal location for the Phase Shift transformer is of the utmost importance.

Firstly, this paper presents summarizes the key factors for the installation of Phase Shift Transformers. Secondly, it give the prerequisites for the installation and finally, and thirdly it determines the deduced critical factors which have to be analyzed from the local (substation level), and global (system-wise) perspective.

Given the necessity for regional approach when determining optimal PST location, this paper focuses on selected results of possibilities for active power flow control using PSTs in the South Eastern Europe (SEE) transmission grid. At the end, in the form a power flow analysis, such an example is presented.

Keywords—Power Shifting Transformer (PST), power flows, optimal positioning

Paper title [2]**: Impact of Gradually Replacing Old Transmission Lines with Advanced Composite Conductors**

Details
Authors: *S. Hadžimuratović, L. Fickert*
Conference: *Innovative Smart Grid Technologies 2018 – ISGT 2018*
Location: *Sarajevo, Bosnia and Herzegovina*
Conference dates: *21-25 October 2018*
Referencing: *IEEE Xplore/Web of Science/Scopus*

Abstract:

Driven by higher energy demand, the complications of finding new corridors, construction, and slow commissioning procedures for transmission lines, an advanced technology has been innovated to adapt to the modern power system's needs.

A new type of overhead conductor with a polymer composite core (ACCC) have a greater ampacity, lower sag, and are lighter than traditional ACSR conductors. Therefore, it is this innovative technology is optimal choice when the decommissioning of old lines takes place.

This paper analyzes the impact of the gradual replacement of old transmission lines with all the benefits and disadvantages. It addresses the issues of equipment aging and proposes a replacement strategy for a cost-effective transition to a modernized power system functioning at improved performance.

Calculations and analyses are performed on a real interconnected system, composed of several South East European (SEE) transmission grids.

Keywords—ACSR conductor, ACCC conductor, HTLS, sag, ampacity, power flow

Paper title [3]**: High-Temperature Low Sag Conductors as a Solution for Increasing Renewable Energy Sources Penetration**

Details
Authors: *S. Hadžimuratović*
Conference: *13th Symposium of Power System Management by Croatian National Committee of CIGRE*
Location: *Rovinj, Croatia*
Conference dates: *04-06 November 2018*
Referencing: *Conference proceedings*

Abstract:

Overhead power lines are nowadays used to transmit more power than ever before. However, with the deregulation of the power sector, power lines as an essential asset are neglected. Due to the increasing costs of operation and maintenance, transmission system operators investments for reconductoring are not prioritized in the appropriate way.

This affects very much the third-parties investments in renewable energy sources, due to the fact that those sorts of power plants are very often aggregated and located in remote areas without local consumption and lines of adequate throughput capacity.

This paper address the issue of how new conductor technologies, also known as High-Temperature Low Sag (HTLS) conductors can mitigate that problem. In the end, a study of Bosnia and Herzegovina's network is presented, where several wind power farms are planned to be built in close proximity of each other, in a part of a system that has limited capabilities.

Key words: High-Temperature Low Sag (HTLS), Overhead Lines, Wind Power Plants.

Paper title [4]**: Financial Impacts of Replacing Old Transmission Lines with Aluminum Composite Core Conductors**

Details
Authors: *S. Hadžimuratović*
Conference: *The International Symposium on Advanced Electrical Power Systems (Planning, Operation and Control) – ISAPS 2018*
Location: *Jahorina, Bosnia and Herzegovina*

Conference dates: *21-24 June 2018*
Referencing: *Springer Chapter Book Publication & Web of Science*

Abstract:

Driven by the deregulation of power utilities, power lines are nowadays used to send more electric energy through longer distances to end consumers, compared to previous decades. Over the years, there have been various technical proposals for the improvement of old transmission conductors, with a goal of increasing its ampacity, as well as increasing the reliability of the power system as a whole.

Aluminum Conductor Composite Core (ACCC) is the result of an interdisciplinary mission to engineer more efficient lines, using state-of-the-art components that result in significant financial savings for the operators who decide to entrust such a new technology.

This paper deals with a comparative analysis of the financial impacts that advanced conductor technologies represent versus standard conductors. The primary focus of this paper is the reconductoring of existing overhead transmission lines using old corridors, contrary to erecting new lines. In the end, an extensive cost comparison example is given to demonstrate the various aspects of revitalization with ACCC conductors.

3. Current Situation in Bosnia and Herzegovina

3.1. Organization of the Electric Power System

Bosnia and Herzegovina is a country in the South East Europe region, more precisely in the Balkan Peninsula. Bosnia and Herzegovina was a republic in the Socialist Federal Republic of Yugoslavia. After the disintegration of Yugoslavia, Bosnia and Herzegovina proclaimed independence in 1992, which was followed by the Bosnian war, lasting until late 1995. The Dayton Peace Treaty determines the constitution, therefore, the central government's power is highly limited, as the country is largely decentralized and comprises two relatively autonomous entities (Figure 3.1):

- the Federation of Bosnia and Herzegovina (consists of 10 cantons),
- Republika Srpska,

A separate district within Bosnia and Herzegovina, “Brčko District” is governed under local government. Note: “Republika Srpska” and “Republic of Serbia”/“Serbia” do not refer to the same.

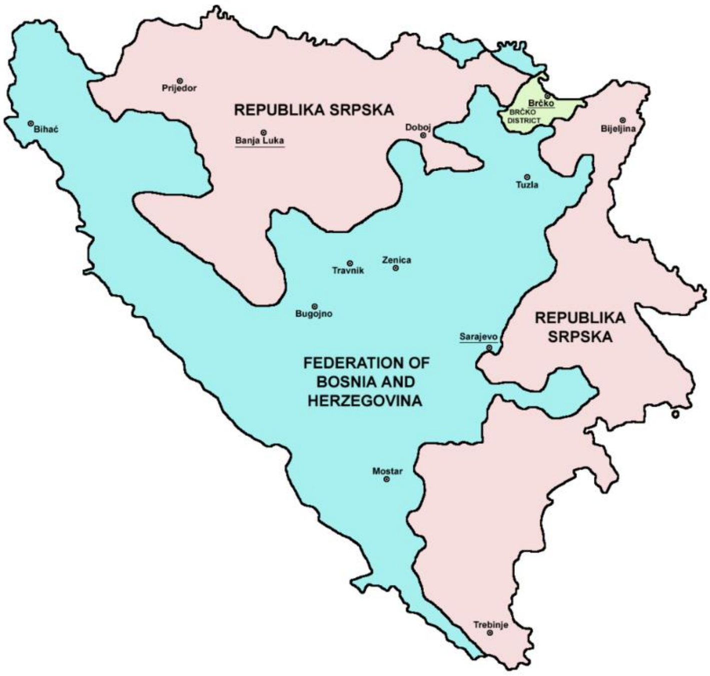


Figure 3.1 – Political map of Bosnia and Herzegovina

Before the war, the power company “Elektroprivreda Bosne i Hercegovine” was the only power utility, and had a vertically integrated structure. During the Bosnian war, the electric power system suffered huge damage, and the vast number of line towers, lines had to be reconstructed. The power utility company was dissolved into three power utility companies (as later described). Following the EU legislation, the transmission system was extracted from the ownership of the three utilities, and two new institutions were formed, the transmission company (Transco) as the owner of the transmission grid (and in charge of maintenance), while the Independent System Operator in Bosnia and Herzegovina (ISOBIH) is the transmission system operator.

The energy sector governance structure is separated into:

- State level – Transmission divided into a system operator (NOSBIH – known in English as ISOBIH) and a transmission company Elektroprenos BIH (usually known as Transco in English);

- Federation of Bosnia and Herzegovina (FBIH) – with two vertically integrated power utilities responsible for generation, distribution and supply (EPHZHB and EPBIH),
- Republika Srpska (RS) – with one vertically integrated holding company (ERS), but with 5 subsidiary generating companies and 5 subsidiary distribution and supply companies.

The following paragraphs describe and summarize the relevant factors in the regulatory framework, transmission system operation and the market structure for the electricity sector in BIH.

Main electricity related institutions

Energy policymaking in BIH is the responsibility of state and entity ministries (Ministry of foreign trade and economic relations BIH, Ministry of energy, mining and industry FBIH and Ministry of economy, energy and development RS) [5].

Ministry of foreign trade and economic relations BIH is responsible for activities on the state level relating to energy policy, basic principles, activity coordination and harmonization of entity bodies and institutions at international level, including energy sector, environmental protection, development and natural resources (Law on ministries and other authorities of BIH). Also, in accordance to the Law on transmission, regulator and system operator in BIH, the Ministry is responsible for energy policy creation [5].

In accordance to the Law on federal ministries and other authorities (article 9), Ministry of energy, mining and industry FBIH, among others, is responsible for energy policy creation. This Ministry acts in accordance to energy policy, adopts the laws and other acts, prepares legislative framework as well as other professional and activities defined by the Law and other legislation. In RS, energy policy is in responsibility of the Government of RS. Ministry of economy, energy and development RS is responsible for adoption of measures of economic and development policy in energy sector.

Basic characteristics of regulatory agencies, system operator, transmission company and distribution companies are given as follows [5].

State Electricity Regulatory Commission (SERC)

The State Electricity Regulatory Commission (SERC) regulates the electricity transmission system in Bosnia and Herzegovina and has jurisdiction and responsibility over transmission of electricity, transmission system operations and international trade in electricity as well as generation, distribution and supply of electricity customers in Brčko District of Bosnia and Herzegovina, [5].

Regulatory Commission for Electricity in the Federation Bosnia and Herzegovina (FERK)

FERK was established in 2002 by the Electricity Law FBIH as specialized, autonomous, independent and non-profit organization in the Federation of Bosnia and Herzegovina, [5].

Regulatory Commission for Energy in the Republika Srpska (RERS)

RERS was established in 2002 by the Electricity Law Republika Srpska as Regulatory Commission for Electricity as independent and non-profit organization in order to regulate monopoly and ensure transparent and non-discriminatory activities of all electricity market participants in Republika Srpska. In 2007 along with new Law on electricity RERS responsibilities and name was changed in Regulatory Commission for Energy [5].

Independent System Operator in BIH (ISOBIH)

Independent System Operator in Bosnia and Herzegovina (NOSBIH/ISOBIH) was established by the Law on Establishing Independent System Operator for the Transmission System in Bosnia and Herzegovina. The purpose of establishing the ISO is to ensure continuity of supply according to defined quality standards. Its main obligations are the management of the transmission system with the aim of ensuring reliability, development and application of guidelines which regulate the usage of the transmission system and development and enforcement of market regulations which are founded by provisions relating to the systems and auxiliary services in the transmission system. ISOBIH is responsible for the Grid Code but must develop it in cooperation with Transco and SERC. ISOBIH is also responsible for operation of the market and allocation of balancing costs. ISO's Board of Directors has representation of both Entities, which reflects the joint ownership of the institution between the governments of FBIH and Republika Srpska. ISOBIH is in charge of drafting the document „Indicative Generation Development Plan" that gives the overview of the future planned generation facilities on Bosnia and Herzegovina's transmission grid, expected electricity consumption growth, as well as planned interconnections with neighboring countries [6], [7]. ISOBIH is representing Bosnia and Herzegovina in the ENTSO-E, with headquarters in Brussels.

Transmission company (Transco)

Elektroprenos BIH a.d. Banja Luka (Transco) is a company for the transmission of electric power in Bosnia and Herzegovina. The Law on Transmission and System Regulator and Operator of Electric Power, passed in 2002, created conditions for the establishment of a joint company for the transmission of electric power, which was accomplished in 2004 by the Law Establishing the Company for the Transmission of Electric Power in Bosnia and Herzegovina. Transco BIH is regulated by SERC. Its main obligation is the transmission of electricity and all activities related to the transmission of electricity which include (but are not restricted to the transmission of electricity) maintenance, construction and expansion of the energy system of BIH but excludes those activities assigned to the ISO. Transco is a shareholding company owned jointly by FBIH and Republika Srpska with shareholders representation on the board in accordance to initial equity brought into the company. Transco is in charge of drafting the „Ten-Year Transmission Network Development Plan", which uses ISOBIH's Indicative Generation Development Plan as one of the main inputs [6], [8].

Power utility companies

In Federation of BIH there are two public power utilities, JP Elektroprivreda BIH d.d. Sarajevo (EPBIH) and JP „Elektroprivreda Hrvatske zajednice Herceg Bosne" d.d. Mostar (EPHZHB). Both are vertically integrated companies, whose activities are: generation of electric power, distribution of electric power and supply of electric power [5].

In Republika Srpska there is Elektroprivreda Republike Srpska – Trebinje (ERS). ERS is a publicly held vertically integrated electric utility. Its activities comprise electricity generation, distribution, supply, export and import and the management of the Republika Srpska power system. In 2005 the Company was reorganized and registered as a holding company which comprises the parent company and 11 public companies [5].

3.2. Transmission System

The transmission system is comprised of 400, 220 and 110 kV networks. Unlike in some countries, in Bosnia and Herzegovina, 110 kV voltage level is also used for transmission purposes. On the other hand, distribution levels are 35, 20 and 10 kV. The transmission system is owned and maintained by the Transmission Company (commonly referred to as Transco) and operated by the Independent System Operator in Bosnia and Herzegovina (ISOBIH), as described in the previous chapter. The distribution system is owned and operated by three power utilities, EPHZHB, EPBIH and ERS. All of the mentioned shareholders are state-owned.

Table 3.1 – Transmission line elements in Bosnia and Herzegovina

Nominal voltage	Total number of lines	Interconnectors	Length *(km)*
400 kV – OHL	15	4	864.50
220 kV – OHL	41	10	1,474.4
110 kV – OHL	231	16	3,886.65
110 kV – Cable	7	-	32.08
Total	**294**	**30**	**6,257.63**

Table 3.2 – High voltage substations in Bosnia and Herzegovina

Substation type	Total number
SS 400 kV	10
SS 220 kV	8
SS 110 kV	132
Total	**150**

The transmission system has a total of 294 power lines, spanning across 6,250 km over the entire country (Table 3.1). A total of 150 substations host 261 transformers (see Table 3.2 and Table 3.3) with an aggregated installed capacity of more than 12,500 MVA for secure and reliable grid operation.

Table 3.3 – Transmission grid transformers in Bosnia and Herzegovina

Transformation ratio	Number of transformers	Installed Apparent Power *(MVA)*
400 / 231 kV	7	2,800
400 / 115 kV	7	2,100
220 / 115 kV	14	2,100
110 / X* kV	234	5,668.5
Total	**262**	**12,668.5**

** X is a general symbol used to group the medium voltage levels – 35, 20 and 10 kV.*

Bosnia and Herzegovina is interconnected with all of its neighbors (Croatia, Serbia, and Montenegro). Due to the fact that all of these countries were part of the Ex-Yugoslavia, the systems are very well interconnected with a total of 30 interconnectors, as it can be seen in

Figure 3.2 – Interconnectors with neighboring TSOs. Given that 110 kV voltage level is used for the transmission purposes, and that it accounts for more than 50% of all interconnectors, all of these lines are used for parallel operation with neighboring TSOs. In other words, the normal operating state of all 110 kV interconnectors is switched on.

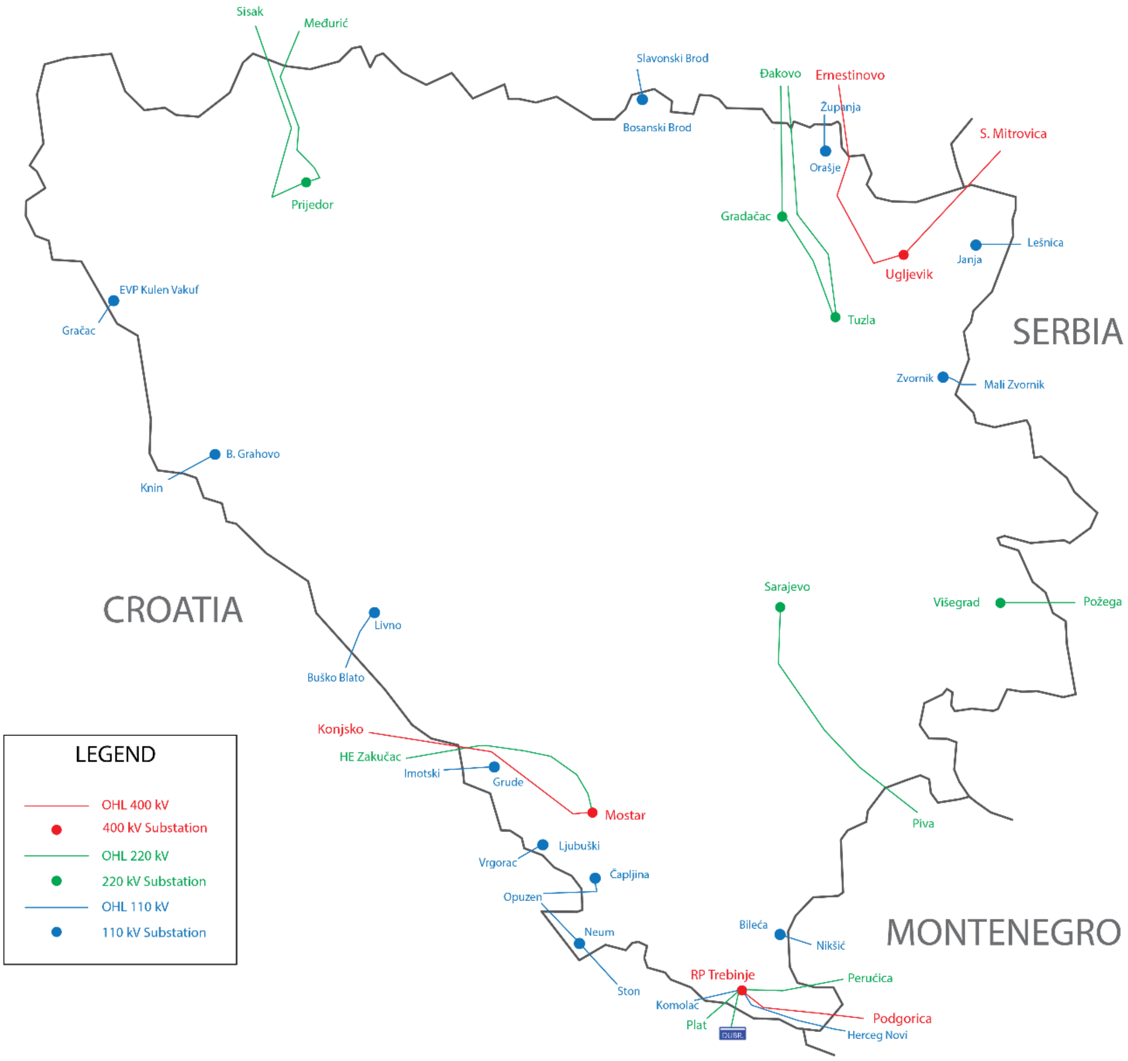


Figure 3.2 – Interconnectors with neighboring TSOs
(note: internal lines are not shown on this picture)

3.3. Electricity Generation

The total installed power is given in Table 3.4 - Table 3.8, for different types of power plants (HPP, WPP, TPP and PP connected to the transmission grid, respectively), and amounts to an aggregated value of 4,157 MW (of which 3,983.5 MW are fed directly on the high voltage grid). The majority of the power plants were built prior to the war (1992-1995). After 1995, only the following power plants were built:

- Thermal power plant (TPP): Stanari,
- Hydro power plants (HPP): Mostarsko Blato, Peć Mlini, and Ustiprača,
- Wind power plants (WPP): Mesihovina and Jelovača.

Except for TPP Stanari, HPP Ustiprača, and WPP Jelovača, which are privately owned, the other generating units are in the property of three state-owned power utilities.

Table 3.4 – Hydro power plants in Bosnia and Herzegovina [9]

Hydro power plant	Installed capacity of generators	Total Installed power	Accumulation Capacity	Average Yearly Production
	(MW)	*(MW)*	*(hm^3)*	*(GWh)*
Trebinje I	2x54 + 1x63	171	1,074.6	Range: 370-420
Dubrovnik*	1x108 + 1x126	126	9.30	1,168
Čapljina	2x220	440	6.47	400
Rama	1x80 + 1x90	170	466	731
Jablanica	6x30	180	288	792
Grabovica	2x57	114	5	342
Salakovac	3x70	210	16	593
Mostar	3x24	72	6	310
Jajce I	2x30	60	2	247
Jajce II	3x10	30	0.21	157
Bočac	2x55	110	42.9	307
Višegrad	3x105	315	101.0	1108
Mostarsko blato	2x30	60	1.6	167
Peć-Mlini	2x15.3	30.6	0.74	Range: 72-80
Ustiprača	2x3.45	6.90	N/A	35.35
Total Installed Capacity		2,095.5		

** Production of HPP Dubrovnik's G2 (located in neighboring Croatia) is balanced to Bosnia and Herzegovina's power utilities due to complex historical reasons.*

Table 3.5 – Wind power plants in Bosna and Herzegovina [9]

Wind power plant	Number of units	Installed Unit Capacity	Total Installed power	Average Yearly Production
		(MW)	*(MW)*	*(GWh)*
Mesihovina	22	2.3	50.6	165.2
Jelovača *	18	2	36	102.3 **
Total Installed Capacity			86.6	

** WPP Jelovača will be put into test operation in mid-2019.*
*** Expected production based on wind measurement.*

Table 3.6 – Thermal power plants in Bosnia and Herzegovina [9]

Thermal Power plant	Unit number	Installed capacity	Maximum available capacity[1]	Technical minimum	Apparent power	Coal Type	Maximum Yearly Production
		(MW)	*(MW)*	*(MW)*	*(MVA)*		*(GWh)*
Tuzla	G3	100	90	60	118	Lignite + Brown	300
Tuzla	G4	200	180	125	235	Lignite + Brown	1020
Tuzla	G5	200	180	125	235	Lignite + Brown	1020
Tuzla	G6	223	200	115	270.6	Brown coal	1150
TUZLA		723	650		858.6		3,500.00
Kakanj	G5	110	100	60	134	Brown coal	500
Kakanj	G6	110	85	55	137.5	Brown coal	500
Kakanj	G7	230	205	140	300	Brown coal	1200
KAKANJ		475	408		562.5		2,200
GACKO	G1	300	276	180	353	Lignite	1,149.4
UGLJEVIK	G1	300	279	155	353	Brown coal	1,457.7
STANARI	G	300	275	150	353	Lignite	2,000
Total Installed Capacity			1,888				

Furthermore, based on data from 2015, about 87 MW of installed power is installed in the distribution grids across the country [10]. This sum is calculated according to Table 3.7.

Table 3.7 – Installed capacity connected to the distribution grid [10]

	Small HPP	**SPP**	**Biomass**	**Total**
	(kW)	*(kW)*	*(kW)*	*(kW)*
Utility EPHZHB	4161	1,169.44	-	5,330.44
Utility ERS	4,7691.8	144.92	-	47,836.72
Utility EPBIH	34,048	178.5	45	34,271.5
Sum	85,900.8	1,492.86	45	**87,438.66**

The summed installed generation capacity from Table 3.4, Table 3.5,

---

[1] Please note that the maximum available capacity equals the difference of the total installed capacity and the own consumption of the generating unit, respectively.

Table 3.6 and Table 3.7 are aggregated and shown in Table 3.8.

Table 3.8 – Total installed capacity in Bosnia and Herzegovina

Generation type	**Total Installed Capacity *(MW)***
Hydro power plants	2,095.5
Wind power plants	86.6
Thermal power plants	1,888
Distribution network	87.43
Total installed Capacity	4,157.53

3.4. Electric Energy Balance

Total available electricity on the transmission network in 2017 amounts to 18,069 GWh. In the transmission network, a total of 14,627 GWh was produced, while additional 96 GWh were injected from the distribution network. Another 3,346 GWh of electricity was received from neighboring systems [9].

From [11], the following facts can be observed:

- HPP produced 3,805 GWh (26% of total energy produced).
- TPP produced 10,822 GWh (74% of total energy produced).
- Due to poor hydrologic condition, HPP produced 31.3% less energy compared to 2016.
- The consumption of electricity in 2017 was 2.15% higher compared to the previous year.

Figure 3.3 presents the generation structure for 2017, while Figure 3.4 shows the shares of different power utility companies in the generation mix for 2017. Please note that WPP Mesihovina and Jelovača were not in operation in the year 2017.

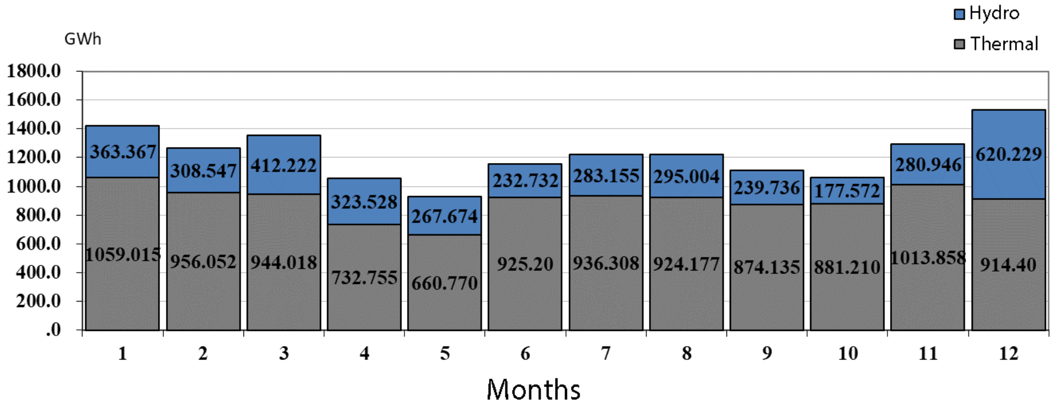


Figure 3.3 – Generation structure in 2017

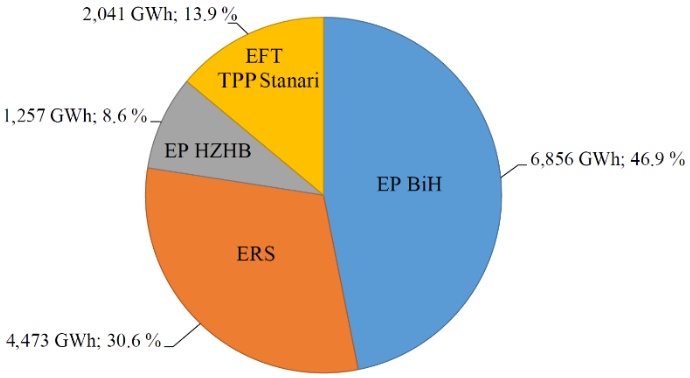


Figure 3.4 – Share of different power utilities in the generation mix for 2017

Bosnia and Herzegovina's electric power system supplies electric power to 3.5 million inhabitants. The total consumption in 2017 was 12,540 GWh, which is 2.15% more than the previous year.

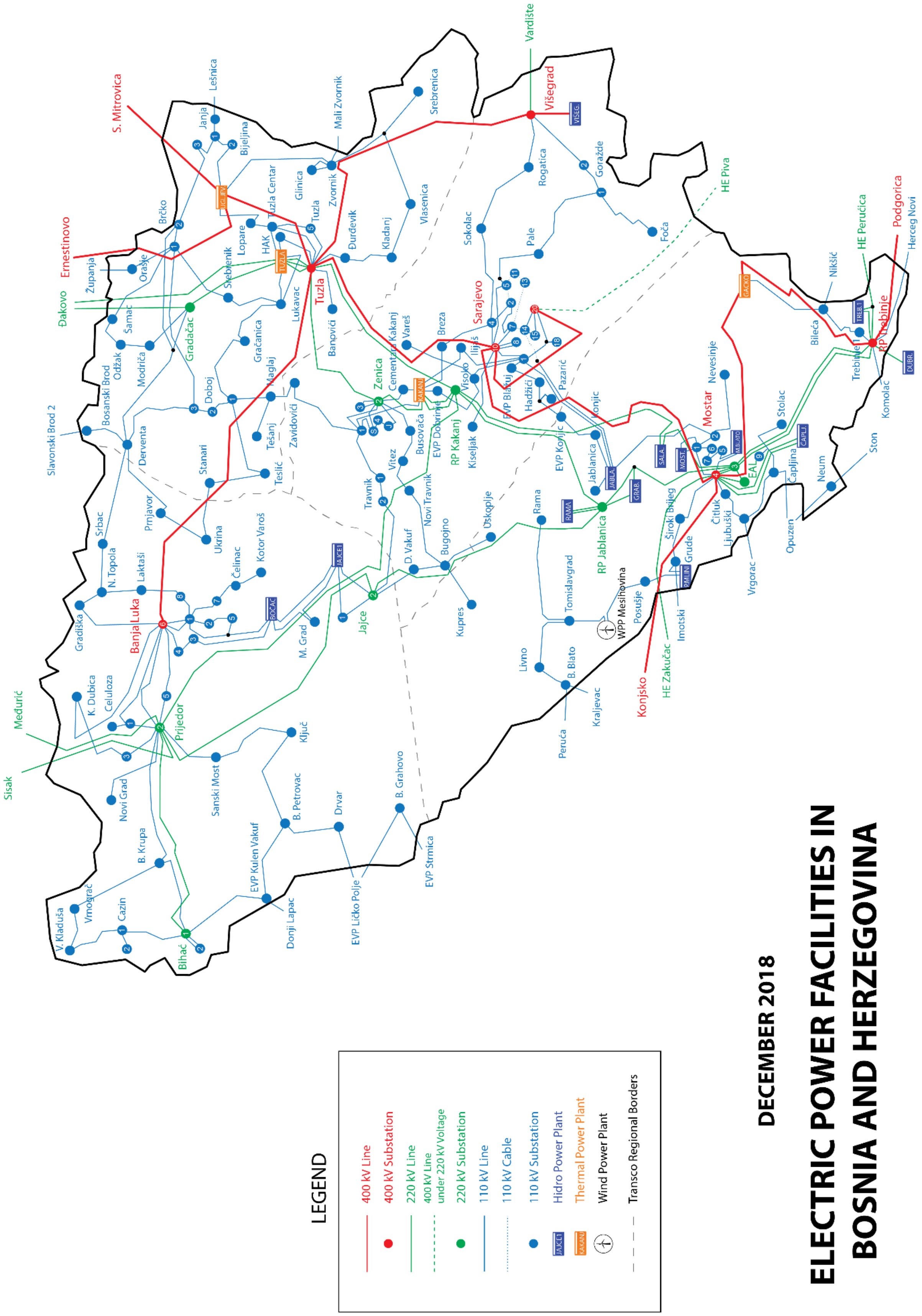


Figure 3.5 – Map of Bosnia and Herzegovina transmission system in 2018

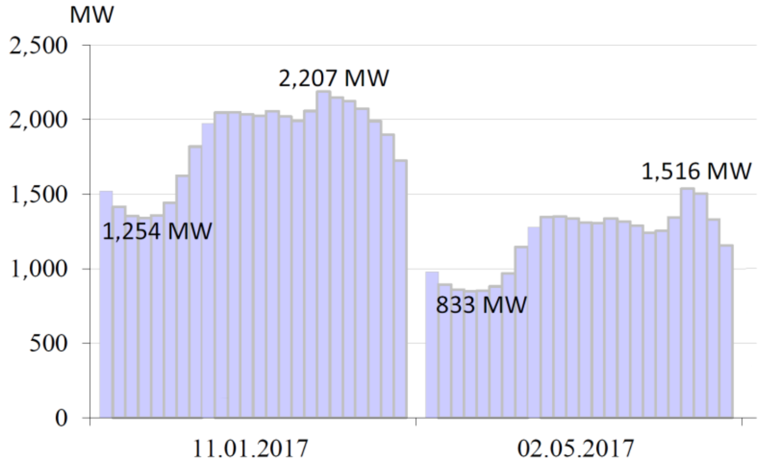


Figure 3.6 – Characteristic consumption daily diagrams for 2017

In 2017, the peak hourly consumption was achieved on 11.01.2017 at 18:00 and the measured value was 2,207 MWh/h. On the other hand, the minimum hourly consumption recorded was 847 MWh/h on the 02.05.2017 at 04:00. Figure 3.6 depicts the daily diagrams for those characteristic days.

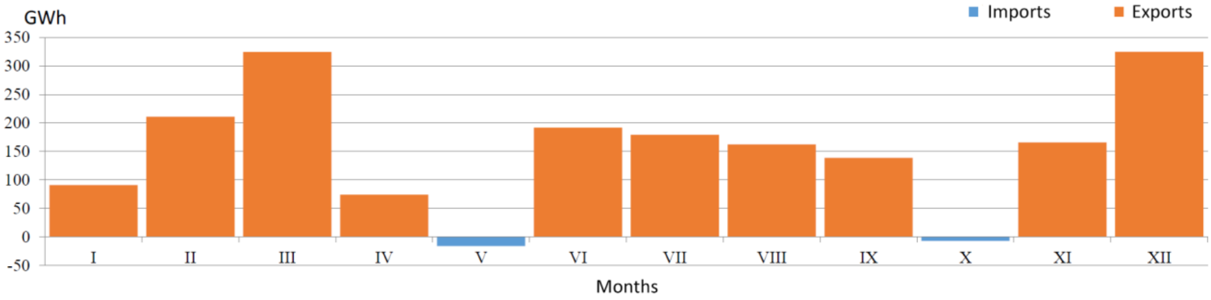


Figure 3.7 – The balance of declared exchange in 2017 per months

From [11], it can be observed that 6,597 GWh were imported, 8,436 GWh were exported, and that 3,275 GWh were transited through BIH's transmission system. The balance of declared exchange is positive and amounts to 1.839 GWh. Figure 3.7 shows that the balance was negative is two months, May and October 2017.

Figure 3.8 shows the realized exchange in 2017, and if the values are summed and analyzed, it can be observed that BIH is importing from Serbia, while exporting to Montenegro and Croatia.

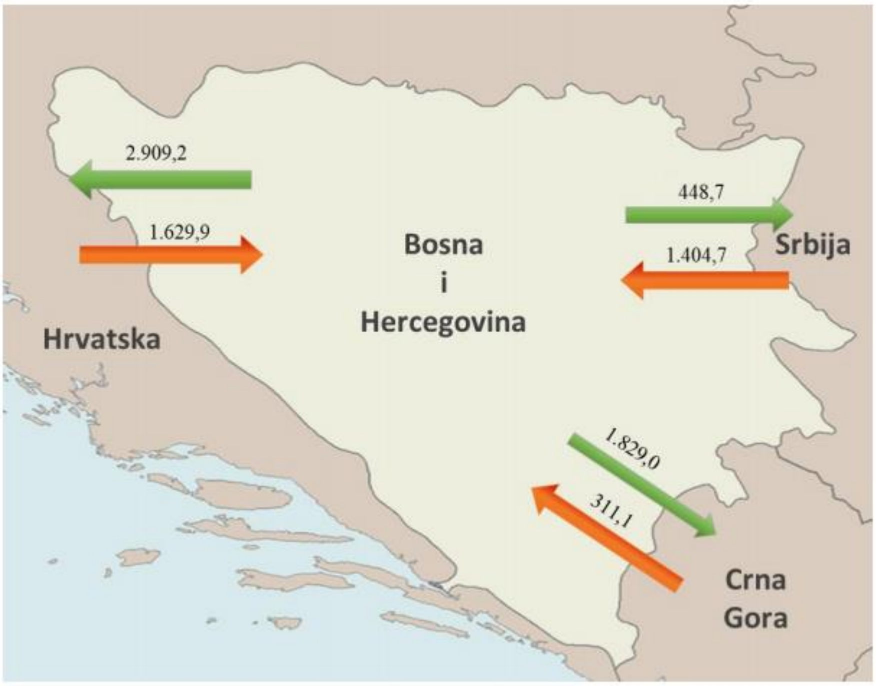


Figure 3.8 – Power exchange with neighboring countries in 2017

When analyzing and combining production and consumption statistical data from previous years (Figure 3.9) [9], it can be concluded that Bosnia and Herzegovina is, generally speaking, a net exporter of electric energy.

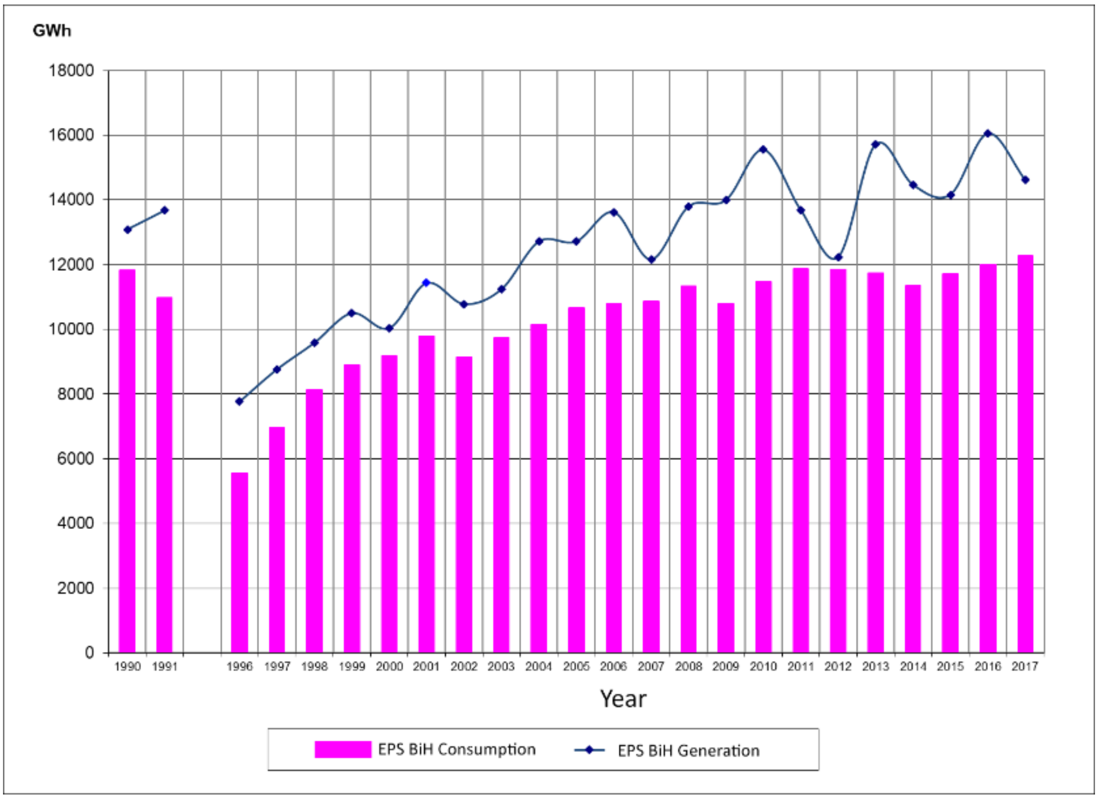


Figure 3.9 – Total yearly production and consumption of electricity in the period 1990 - 2017

3.5. Voltage Operating Conditions

Based on SCADA/EMS readings presented in [9], Table 3.10 gives more insights in the recurring and unfavorable voltage operating conditions in the transmission grid. Statistical SCADA/EMS data from 01.01.2017 to 21.12.2017 (for a total of 8,760 hours) are analyzed and presented.

Namely, the allowed range for the high voltage grid is defined in [12]. The allowed voltage fluctuations are given in Table 3.9. System operation above these voltages is considered as disturbed mode of operation.

Table 3.9 – Allowed voltage limits

Nominal voltage *(kV)*	**Allowed Voltage Range** *(kV)*	**Allowed Voltage range** *(per unit)*
400	360 - 420	0.9 - 1.05
220	198 - 245	0.9 - 1.114
110	99 - 123	0.9 - 1.118

Table 3.10 – Substations with increased voltages

Substation	**Voltage level**	**Maximum allowed voltage**	**Number of hours with $U > U_{max}$**	**Percentage of hours when $U > U_{max}$**	**Maximum recorded values**
	U_n (kV)	*U_{max} (kV)*		*%*	*U_{rec} (kV)*
Banja Luka 6	400	420	2,070	24%	430.95
	100	123	0	0%	122.89
Tuzla 4	400	420	5,838	67%	437.3
	220	245	780	9%	250.82
	110	123	0	0%	121.5
Prijedor 2	220	245	1,993	23%	252.85
	110	123	0	0%	122.55
Mostar 4	400	420	7,663	88%	441.6
	220	245	2,804	32%	253.28
	110	123	179	2%	125.39
Sarajevo 10	400	420	5,893	67%	438.19
	100	123	293	3%	125.96
Trebinje	400	420	7,865	90%	444.67
	220	245	3,237	37%	255.04
	110	123	0	0%	122.45

As it can be observed from Table 3.10, substation Trebinje has the far worst operating conditions, voltage-wise. Maximum recorded values for nominal voltage 400 kV and 220 kV were recorded as high as 444.67 and 255.05, respectively. Those values happened on the 02.05.2017 at 06:00. From Chapter 3.4 and Figure 3.6, it can be observed that it coincides with the minimum hourly consumption recorded in 2017.

This matter will be further explained and assessed in Chapter 5.1.1.

3.6. National Development Plans

This section presents the most prominent and consequential aspects of the future Bosnia and Herzegovina transmission grid that are presented in [9] and that are of the utmost relevance to this thesis.

3.6.1. Consumption Growth

According to [12], the Indicative Generation Development Plan contains three consumption scenarios (base, low, and high) for the following 10 years. The consumption scenarios are based on development plans submitted by the users, as well as internal analyses.

Given that the users, primarily power utilities have submitted high estimates, additional analyses had to be performed in [9]. Based on those analyses, the three consumption scenarios are:

- Pessimistic scenario – low consumption growth (yearly growth rate of 0.3%)
- Realistic scenario – base consumption growth (yearly growth rate of 0.9%)
- Optimistic scenario – high consumption growth (yearly growth rate of 2.1 %)

Forecast of consumption for the BIH transmission network for the period 2018 - 2028 years, for three scenarios, as well as the realized consumption in the period 2001 - 2017 years are given in Table 3.11 and Figure 3.10.

Table 3.11 – Forecast of electricity consumption in the BIH system for the period 2019 - 2028

Year	**Realistic Scenario**		**Pessimistic scenario**		**Optimistic scenario**	
	GWh	**growth ratio**	**GWh**	**growth ratio**	**GWh**	**growth ratio**
2001	9,185	3.49%				
2002	9,147	-0.41%				
2003	9,734	6.42%				
2004	10,141	4.18%				
2005	10,663	5.14%				
2006	10,797	1.26%				
2007	10,871	0.69%				
2008	11,338	4.30%				
2009	11,063	-2.43%				
2010	11,469	3.67%				
2011	11,880	3.58%				
2012	11,853	-0.23%				
2013	11,732	-1.02%				
2014	11,379	-3.01%				
2015	11,719	2.99%				
2016	12,015	2.53%				
2017	12,540	4.37%	12,540	4.37%	12,540	4.37%
2018	12,457	-0.67%	12,185	-2.83%	12,801	2.09%
2019	12,588	1.06%	12,259	0.61%	13,072	2.11%
2020	12,719	1.04%	12,330	0.58%	13,347	2.11%
2021	12,849	1.03%	12,398	0.55%	13,629	2.11%
2022	12,979	1.01%	12,463	0.53%	13,917	2.11%
2023	13,109	1.00%	12,526	0.50%	14,210	2.11%
2024	13,239	0.99%	12,586	0.48%	14,510	2.11%
2025	13,369	0.98%	12,644	0.46%	14,816	2.11%
2026	13,499	0.97%	12,700	0.44%	15,129	2.11%
2027	13,629	0.96%	12,754	0.43%	15,448	2.11%
2028	13,759	0.96%	12,807	0.41%	15,774	2.11%

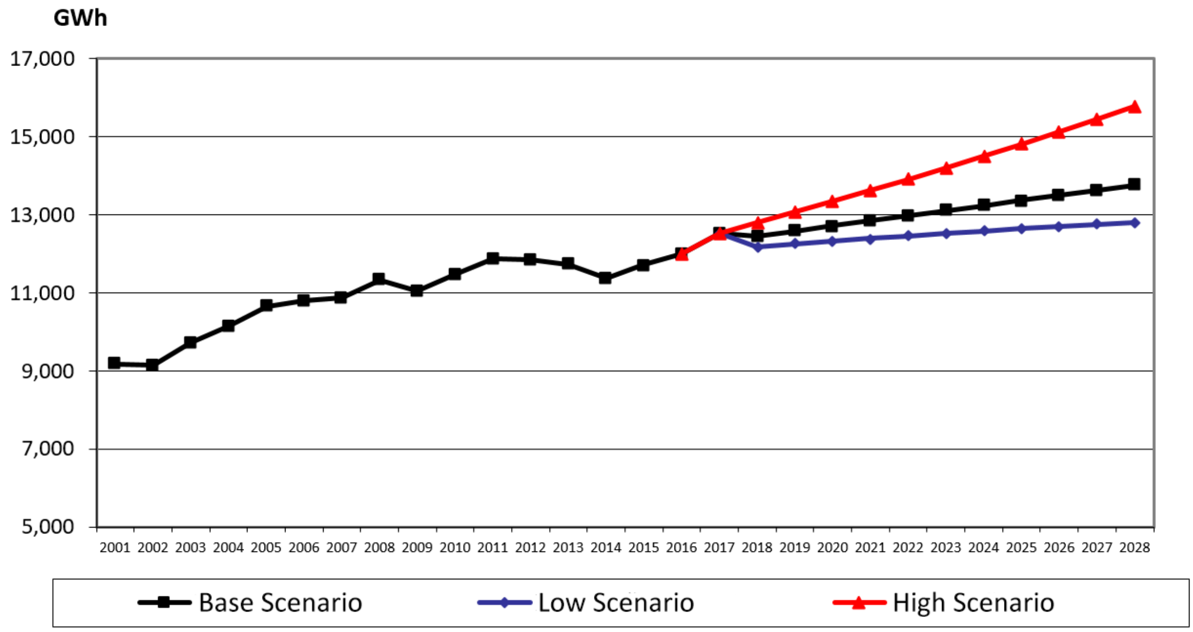


Figure 3.10 – Consumption forecast for the BIH transmission network for the period 2018 - 2028 and the realized consumption in the period 2001 - 2017

It should be noted that the year-on-year forecast was taken into account based on available data at that time. Therefore, the forecasted consumption in 2018 is lower than the balanced consumption for 2018. The balance for the year 2018 was made on the basis of data submitted by the electric power system beneficiaries (power utilities and directly connected consumers) [9].

Average consumption growth rates in all scenarios are lower than in the previous Indicative Plans. As for the base scenario (0.9%), it is significantly lower than the average for the period 2001 to 2017 (1.97%). In 2018, there was a noticeably lower consumption growth in the base scenario (0.14%), which is even negative in the pessimistic scenario (-1.23%). However, this is in line with the goals of achieving energy efficiency [13], [9].

3.6.2. Wind Energy Integration

The maximum estimated power of wind power plants (WPP) that can be connected to the transmission system in BIH, from the aspect of the required regulation reserve, is 350 MW. From Table 3.12, it is evident that the installed power of potential WPP is greater than the WPP integration limit of 350 MW, as approved by the relevant regulator. An indicative map with some of the potential WPP is presented in Figure 3.11.

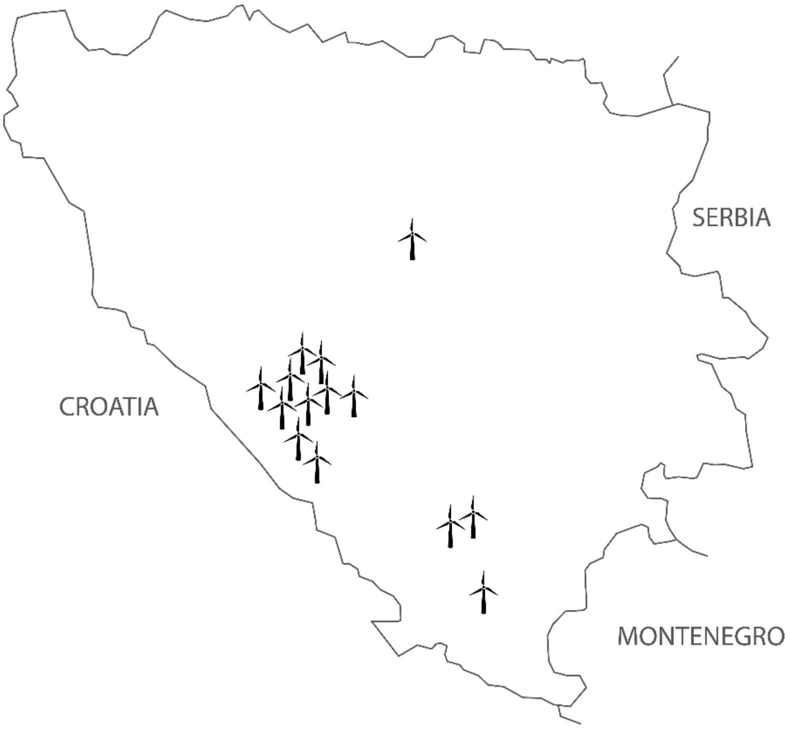


Figure 3.11 – Potential WPP locations in Bosnia and Herzegovina

Table 3.12 – Overview of WPP potential in BIH

Wind power plant	**Installed power *(MW)***	**Ownership**	**Balanced in 2019 YES / NO**
VE Mesihovina	**50.6**	State-owned	**YES**
VE Gradina	41.6	Private investor	NO
VE Orlovača	42.9	Private investor	NO
VE Debelo brdo	54	Private investor	NO
VE Ivovik	84	Private investor	NO
VE Mučevača	59.9	Private investor	NO
VE Trusine	**49.5**	Private investor	**YES**
VE Podveležje 1	**48**	State-owned	**YES**
VE Baljci	48	Private investor	NO
VP Kupres 1	48	Private investor	NO
VP Pakline I	48	Private investor	NO
VE Jelovača	**36**	Private investor	**YES**
VP Pakline II	48	Private investor	NO
VE Vlašić	50	Private investor	NO
VE Galica	50	Private investor	NO
VE Pločno	48	Private investor	NO
VE Podvležje 2	48	Private investor	NO
VE Hrgud	48	Private investor	NO
VE Tušnica	40	Private investor	NO
VE Škadimovac	110	Private investor	NO
VP Vlašić	130	Private investor	NO
VE Oštrc	28.2	Private investor	NO
TOTAL	**1,210.7**		

In order to be balanced in the forecasted period, the WPP has to achieve the following two conditions [9]:

- valid terms for connection to the transmission system and user acceptance statements, and
- appropriate confirmation by the relevant governmental agency that the power plant is within the maximum possible regulation limit.

So far, the aforementioned criteria are fulfilled by four WPP:

- WPP Mesihovina (50.6 MW) – state-owned power utility
- WPP Podveležje (48 MW) – state-owned power utility
- WPP Trusina (49.5 MW) – privately owned power company
- WPP Jelovača (36 MW) – privately owned power company

Increasing the WPP integration limit depends on two major factors:

- Construction of high voltage grid infrastructure and
- Increasing regulation reserves.

Both factors will eventually lead to augmented electricity prices, by increasing network fees and tariffs to all final customers, in order to achieve both goals.

With regard to the construction of high voltage grid infrastructure, the main issue is that the majority of WPPs from Table 3.12 are located very close to each other, and are in the part of the grid that doesn't have adequate transmission capabilities. Unfortunately, due to complex permitting procedures, the timeframe for the construction of new lines is quite long and uncertain. These issues are further assessed as part of Chapter 5.1.3.

As for the increased regulation reserves, the Independent System Operator in Bosnia and Herzegovina (ISOBIH) performed a study, entitled „Estimating the required power of the regulation reserve for the integration of the WPP into the BIH's EPS", [5]. The results of that study are given in Table 3.13 [14], [15].

Table 3.13 – Amount of regulation reserves for different WPP integration scenarios

WPP integration scenario	**Range of additional required regulation reserve**	**Regulation reserve Cost Range**
(MW)	*(MW)*	*(Million €)*
150	28 – 31	17.5 - 21.8
350	65 – 72	23.6 - 32.6
500	93 – 102	28.1 - 40.5
640	119 – 131	32.3 - 48.1
900	167 – 184	40.1 - 61.9

It is obvious that the increased WPP penetration will lead to higher transmission system costs, from operational, capital investments and maintenance points of view.

3.6.3. Solar Energy Integration

Bosnia and Herzegovina is in a group of countries that have not yet exploited the potential for electricity generation in solar power plants. According to solar radiation data in the Balkans, Bosnia and Herzegovina has significant solar energy resources, which are even above the European average with an exceptionally favorable seasonal schedule, giving it the opportunity for its efficient and long-term use [9], [16].

For the expansion of the construction of new electricity generation capacities from solar power around the world, significant incentive measures have to be made. The implementation of electricity generation projects from solar power plants in BIH will partly depend on the incentive measures and strategies the country will undertake. On the other hand, there is a constant downward trend in the price of technology needed to build solar power plants, and it is certain that in the near future the price of electricity produced from these sources will be competitive on the free market. This will probably, by implementing the abovementioned measures of stimulation, lead to the construction of the first solar capacities in the transmission system in Bosnia and Herzegovina [9], [16].

It should be emphasized that until the moment of issuing [9], ISOBIH hasn't issued any Project Task for drafting according to Connection Protocol, [17] to the BIH Transmission System, and for this reason, no SPP has been balanced in [9]. In the Study [16], on the basis of solar radiation maps, some perspective locations are shown in Figure 3.12.

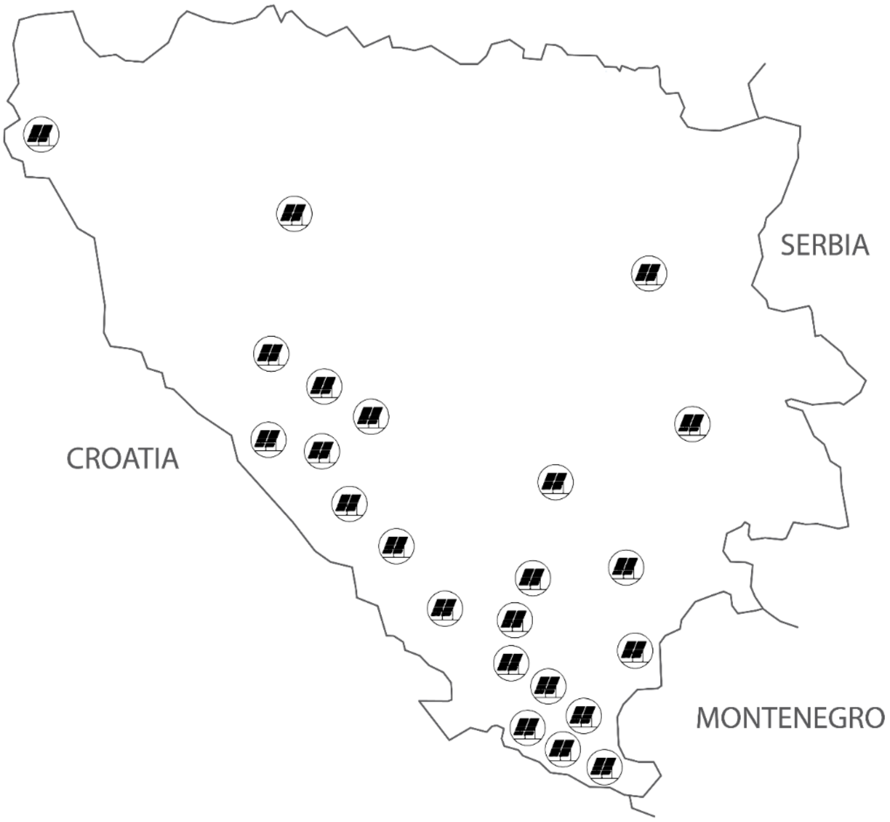


Figure 3.12 – Potential SPP locations in Bosnia and Herzegovina [16]

There are other projects that have been realized (small power plants as photovoltaic cells, in the distribution level). However, it is irrelevant to the scope of work of this thesis.

3.6.4. Energy and Power Balance for 2019 - 2028

According to [12], the criteria for balancing new generating units in future development ten-year plans are:

- For WPP and SPP:
  - Valid Terms for Connection to the Transmission System and User Acceptance Statements and
  - Appropriate confirmation by the relevant governmental agency that the power plant is within the maximum possible regulation limit.
- Other generating units (HPP and TPP):
  - Valid Terms for Connection to the Transmission System and User Acceptance Statements
- Any other criteria defined in the Indicative Generation Development Plan.

Table 3.14 gives detailed information about new generation units that have fulfilled the above-mentioned criteria for balancing. It also gives aggregated installed capacities of new generating units, summed with existing generating units.

Table 3.14 – Installed power of new generation units for the period 2019 - 2028

New Generating Units	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
HPP DUB	9.4									
HPP ULOG			35.12							
HPP VRANDUK				19.6						
TPP TUZLA, unit 7				450 (410*)						
TPP KAKANJ, unit 8						300 (270*)				
TPP KTG ZENICA										387.5 (373.1*)
TE UGLJEVIK 3,							600 (528*)			
TPP BANOVIĆI						350 (318.8*)				
WPP TRUSINA		49.5								
HPP DABAR				159.2						
WPP PODVELEŽJE	48									
WPP MESIHOVINA	50.6									
HPP MRSOVO				36.8						
WPP JELOVAČA	36									
HPP LJUTA			7.66	1.045						
New generating units	144.0	49.5	42.8	666.6	0.0	650.0	600.0	0.0	0.0	387.5
New generating units. Accumulated values	144.0	193.5	236.3	902.9	902.9	1,552.9	2,152.9	2,152.9	2,152.9	2,540.4
Total installed Capacity of Existing generating units	4,169.0	4,169.0	4,169.0	4,169.0	4,069.0	3,869.0	3,869.0	3,869.0	3,751.0	3,751.0
Maximum Available capacity of Existing generating units	3,968.0	3,968.0	3,968.0	3,968.0	3,878.0	3,698.0	3,698.0	3,698.0	3,598.0	3,598.0
Total Installed Capacity	4,313.0	4,362.5	4,405.3	5,071.9	4,971.9	5,421.9	6,021.9	6,021.9	5,903.9	6,291.4
Maximum Available Capacity	4,128.0	4,177.5	4,220.3	4,846.9	4,756.9	5,165.7	5,693.7	5,693.7	5,593.7	5,967.2

** Maximum available capacity*

According to the development plans delivered from power utilities, the following three generating units will be decommissioned [9]:

- Generating unit 3 at TPP Tuzla in 2023,
- Generating unit 4 at TPP Tuzla in 2024,
- Generating unit 5 at TPP Kakanj in 2027.

Figure 3.13 gives a graphical representation of the adopted agenda for the commissioning and decommissioning of generating units.

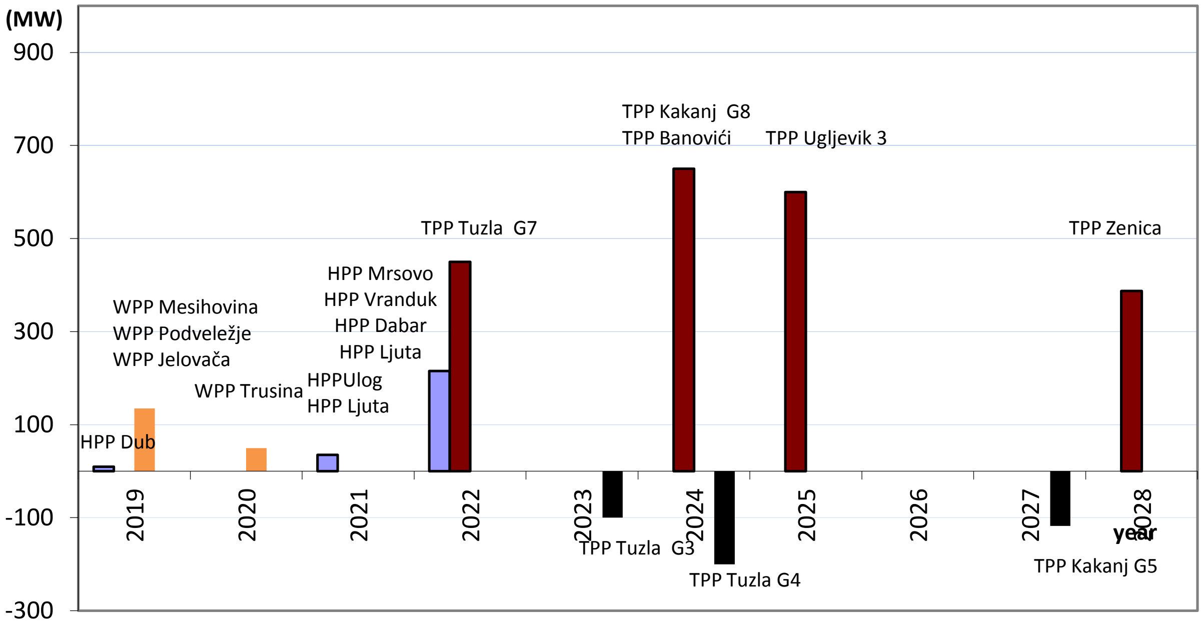


Figure 3.13 – Capacities to be commissioned and decommissioned in the period 2019 - 2028

Finally, Figure 3.14 shows three consumption scenarios from Figure 3.10 and Table 3.11, with the aggregated energies, obtained based on installed capacities presented in Figure 3.13 and Table 3.14.

For different consumption growth scenarios, confronted with adopted investment plans for the period 2019 – 2028, it can be concluded that the balance is positive and that significant energy can be exported from Bosnia and Herzegovina, given that all above-mentioned plans are realized in due time, [9].

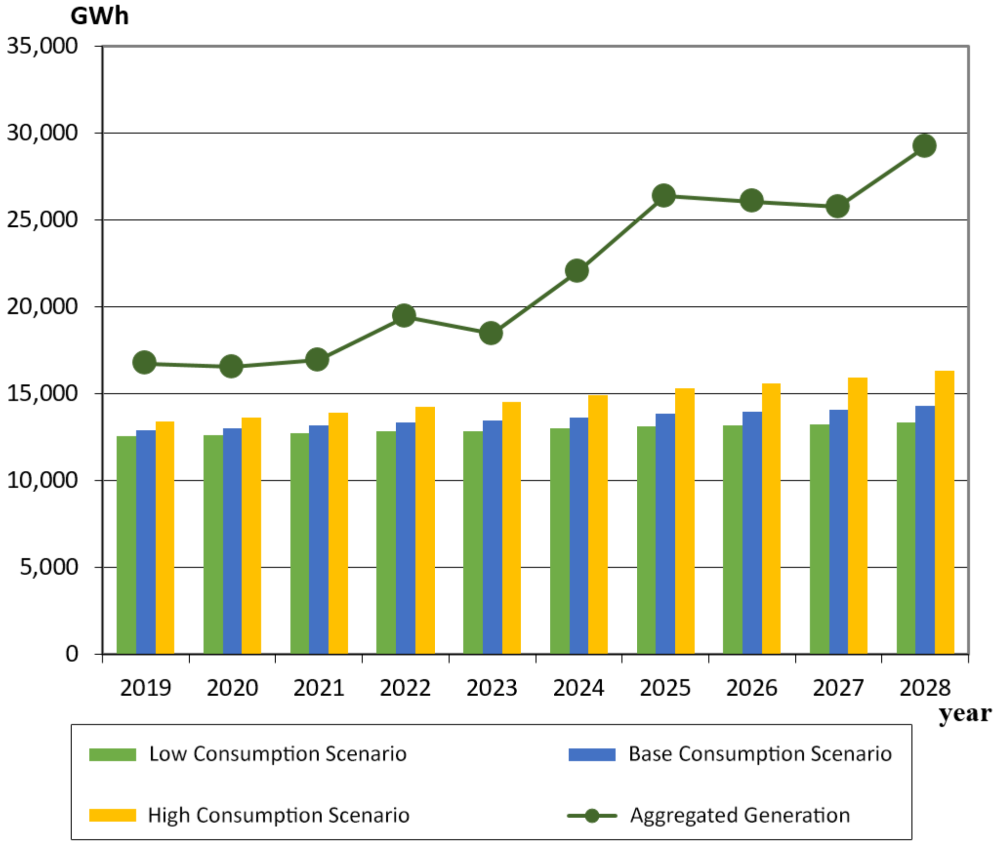


Figure 3.14 – Three consumption scenarios and planned production of existing and new generating units for the period 2019 - 2028

3.6.5. Estimation of Absolute Consumption Values for the Future Transmission Grid

For strategical planning purposes, ENTSO-E recommends basing the consumption on the following timestamps:

- 3rd Wednesday in January at 11:00 and 19:00
- 3rd Wednesday in July at 11:00

For Bosnia and Herzegovina, in the previous years, according to [9], those values are presented in Table 3.15.

Table 3.15 – Recorded consumption in characteristic timestamps for 2016 and 2017

Month	Time	Consumption MWh/h
January 2016	11:00	1,787
	19:00	1,829
July 2016	11:00	1,413
January 2017	11:00	1,891
	19:00	1,989
July 2017	11:00	1,446

However, the maximum recorded value for 2017 was 2,189 MWh/h, and it was recorded on the 11.01.2017. Given that this value was about 10% higher than the proposed ENTSO-E methodology, in order to have the worst-case scenario for planning purposes, ISOBIH decided to take the absolute maximum and minimum values.

Table 3.16 – Maximum recorded consumption values for period 2011 - 2017

Year	**31.12.2011 18th hour**	**10.02.2012 18th hour**	**24.12.2013 18th hour**	**31.12.2014 18th hour**	**31.12.2015 18th hour**	**31.12.2016 18th hour**	**11.01.2017 18th hour**
P_{max} (MW)	2,150	2,143	2,074	2,207	2,105	2,098	2,189

Table 3.17 – Minimum recorded consumption values for period 2011 - 2017

Year	**22.07.2011 4th hour**	**21.06.2012 5th hour**	**02.05.2013 6th hour**	**05.08.2014 6th hour**	**02.05.2015 4th hour**	**23.05.2016 4th hour**	**02.05.2017 4th hour**
P_{min} (MW)	872	833	866	833	858	845	847

It was decided that the growth rate for maximum consumption is 0.9% and 2.1% for minimum consumption. The base year is with the value recorded in 2017 (2189 MW).

Table 3.18 – Peak consumption power on transmission grid for period 2019 - 2028

(MW)	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
Peak consumption power on transmission grid	2,209	2,229	2,249	2,269	2,289	2,310	2,331	2,352	2,373	2,394

3.6.6. New Interconnectors in Bosnia and Herzegovina

Based on [18], new interconnectors between Bosnia-Herzegovina and neighboring TSOs are shown in Table 3.19.

Table 3.19 – New interconnectors between Bosnia and Herzegovina and neighboring TSOs

Element name	**Present status**	**Expected year of commissioning**	**Details**
OHL 400 kV Višegrad (BIH) – Bajina Bašta (Serbia)	Permitting Phase	2024	Interconnecting OHL between BIH and Serbia
OHL 400 kV Banja Luka (BIH) – Lika (Serbia)	Planning Phase, Feasibility Study	2030	New interconnecting OHL between BIH and Croatia

4. Regional Development Plans

The following section presents the regional development plans that are relevant to the scope of work of this thesis.

4.1. HVDC Cable MONITA

In 2009 Montenegro and Italy achieved the intergovernmental agreement on a strategic partnership to build power interconnection between their transmission systems. This agreement is implemented by the Italian operator TERNA Rete Elettrica Nazionale S.P.A, as the main contractor and the investor, and by the Montenegrin Transmission System AD – CGES [19]. Due to the fact that it will connect Montenegro and Italy, this HVDC cable had been dubbed "MONITA" (MONtenegro - ITAly).

Ministry of Sustainable Development and Tourism of Montenegro issued to the investor legal and technical requirements and conditions for the development of technical documentation, which include the construction of converter station and the 500 kV submarine bipolar cable with optical cable Montenegro - Italy [19].

The planned power interconnection, with the whole infrastructure, will link Montenegro and Italy power systems in order to ensure better transmission of electricity from South East Europe to Italy (Figure 4.1) [19]. The total length of the cable through Montenegro is 53 km, whereby the length of the submarine cable through the territorial waters of Montenegro is around 47 km, and length of land cable route is about 6 km [20]. The overall length of the HVDC cable is 415 km, of which 393 km is submarine [20].

For high power cable connection between Montenegro and Italy, a modern technical solution - the application of 500 kV high voltage direct current (HVDC) system was chosen. Rated (nominal) power of this type of connection is 1000 MW (2x500 MW), with the possible overload to 1200MW (2x600 MW). At its ends, the cable will be connected to converters stations which converts ± 500 kV DC voltage to 400 kV three-phase, 50 Hz.

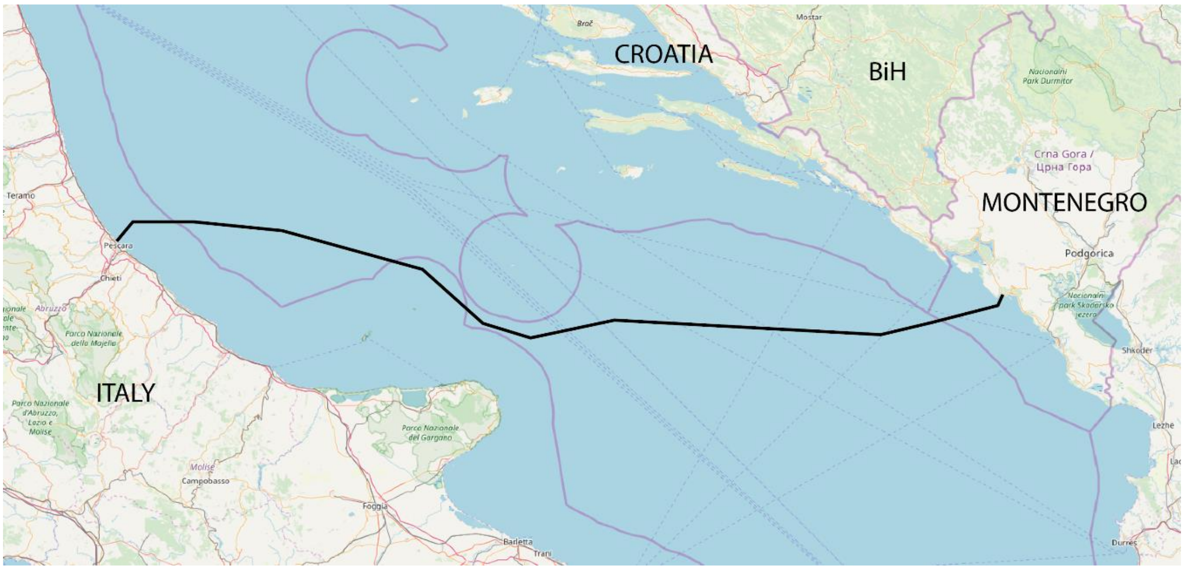


Figure 4.1 – HVDC MONITA submarine cable map

As of 2019, one bipolar cable has been laid, preparations are being made for tests. It is expected that the cable will be put into commercial operation in 2020. The second bipolar cable is delayed until further notice.

4.2. Transbalkan Corridor

Transbalkan Corridor refers to ENTSO-E projects 227 and 146, as explained below:

- Project 146:
    - OHL 400 kV from Pljevlja to new SS Lastva in Montenegro (160 km), and
    - OHL 400 kV Kragujevac – Kraljevo (60 km).
- Project 227:
    - “Upgrade of transmission network in Western Serbia at 400 kV voltage level between SS Obrenovac and SS Bajina Basta, which implies new double 400 kV OHL SS Obrenovac – SS Bajina Basta, reconstruction of existing SS Obrenovac and SS Bajina Basta (111 km)” [18].
    - “New 400 kV interconnection between Serbia, Bosnia and Hercegovina and Montenegro, which implies double 400 kV OHL between SS Bajina Basta, SS Visegrad (BIH), and SS Pljevlja (Montenegro), (84 km)” [18].

As defined in [18], the Transbalkan Corridor, with its projects 227 and 146, has the following objectives, in line with the basic goals of EU energy policy:

1. improve functioning and reliability of the electricity markets in Serbia, Montenegro, Bosnia and Herzegovina, Romania and Italy and to overall electricity system in the Balkan region;
2. facilitate further integration and expansion of the 400kV network in the region;
3. facilitate a higher level of integration of renewable energy sources in the CSE region;
4. alleviate the congestion on the transmission system that is permanently present in the flow direction from East to West in Serbia that restricts trade across the whole of the region and with Italy;
5. help to bring the integration of European electricity markets, thereby allowing for increased cross border trade and competition among suppliers.

The need for project Transbalkan Corridor was confirmed by network and market simulation identifying bottleneck on the Serbia-Montenegro-BIH border in all regimes because of presence HVDC MONITA which will have capacity 1200 MW. The predominant direction of bulk flows is from Serbia to Montenegro. Presence of project Transbalkan corridor will increase transfer electrical power from Serbia to Montenegro and further to Italy for 75%, from 4,000 GWh up to 7,000. Also, the presence of project Transbalkan corridor will increase the transfer of electrical power from Serbia to Montenegro for about 300 GWh [18].

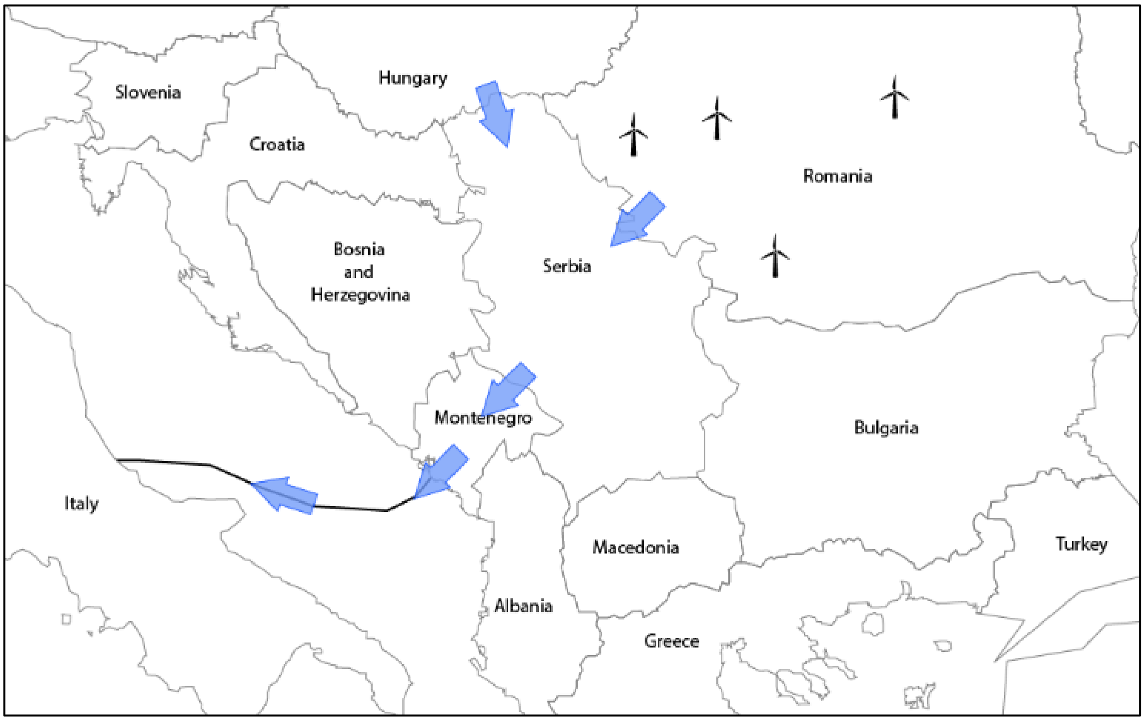


Figure 4.2 – Transbalkan Corridor

The Transbalkan Corridor supports market integration and brings significant benefit to socio-economic welfare of nearly 30 million € [18].

Please note that the construction of the OHL 400 kV Višegrad (BIH) – Bajina Bašta (Serbia), from Chapter 3.6.6 is part of the Transbalkan Corridor project.

4.3. Sincro.grid Project

“Many years of cooperation between the power systems of Croatia and Slovenia achieved technical perfection with the construction of the 400 kV TESLA loop and a strong interconnection to mainland Europe. Political changes in the 1990s and legislative changes after 2000 in these two countries have left them with a system that has to operate in conditions for which it was not designed or constructed. In recent times, the system's flexibility deficiency in terms of voltage and frequency control has reached its limit, which could potentially endanger the future development of electricity generation from dispersed and renewable energy sources and threaten the reliability of the power system's operation” [21].

“Bilateral technical discussions between the two countries in 2014 have shown numerous similarities in technical deficiencies. In this period the transmission system operators (HOPS and ELES) and distribution networks of Croatia and Slovenia began to search for joint solutions. The most promising solution appeared to be the establishment of international cooperation in the implementation of smart grids. This would increase the technical and economic efficiency of invested capital, human resources, and technical know-how. And the idea of the Sincro.grid project was thus born” [21]

The implemented technologies will be [21]:

1. a virtual cross-border control center for renewable energy sources in Croatia and Slovenia;

2. advanced algorithms for Volt-VAR control (VVC) optimization, secondary reserve, advanced real-time operation of the grid using dynamic monitoring of transfer capacities, and a communication platform on the demand side;
3. reactive power compensation devices used by the two transmission grid operators – Static VAR Compensator (SVC) technology of ± 500 Mvar in Slovenia and of ± 500 Mvar in Croatia;
4. installation of an advanced dynamic thermal rating system in the power grid;
5. installation of 10 MW electricity storage systems (battery storage) with 30 MWh energy capacity for the purpose of relieving local power flows in the 110 kV network and serving as an alternative source for secondary control;
6. integration of 2 MW of distributed generation sources into the virtual power plant for the purpose of storing primary energy (small hydro power plants, biogas);
7. adaptation of SCADA/EMS-based information system to RES control, optimization of voltage profile control and battery storage systems for multiple uses by system operators;
8. implementation of advanced forecasting tools at the DSO and TSO levels through the virtual cross-border control center;
9. telecommunication support to RES control, virtual cross-border control center support and advanced dynamic thermal rating system support;
10. a common communication platform providing for an additional 5 MW of tertiary reserve.

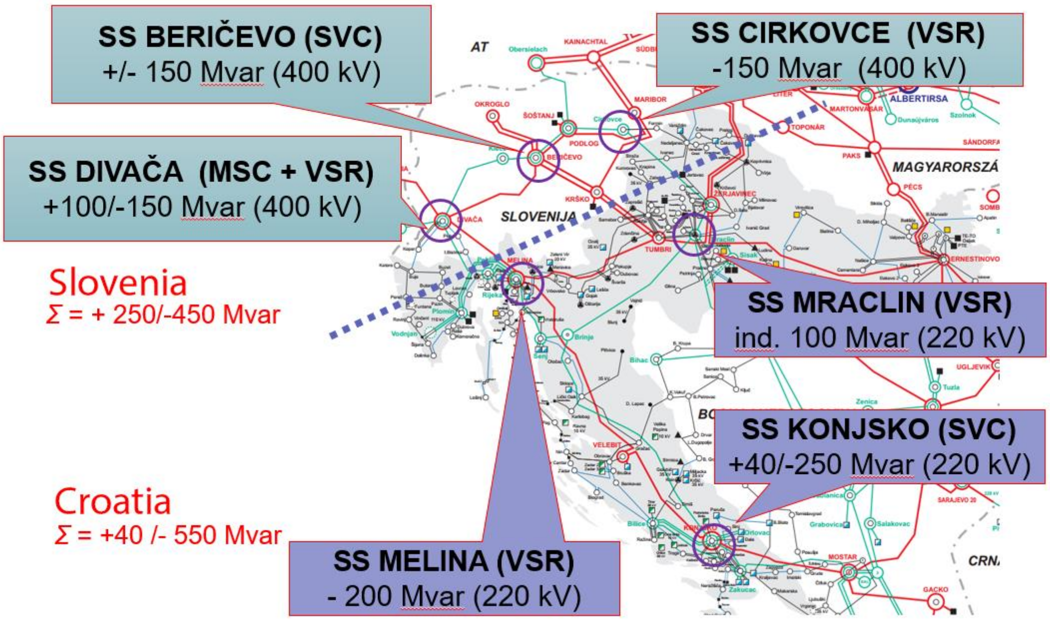


Figure 4.3 – Location of compensation devices in ELES and HOPS networks [21]

From the point of the EPS of Bosnia and Herzegovina, the most important part of the Sincro.grid project is the installation of reactive power compensation devices that will be installed in Slovenia and Croatia (second item from the list above). The preliminary location of compensation devices is presented in Figure 4.3.

5. Focusing point for improvement

In this chapter, the most relevant issues and threats to the resilience of the BIH's transmission system are summarized, explained and the scope of work of the thesis is determined and presented.

5.1. Issues

Based on a [5] - [21], but also extensive analyses on power system simulators, discussions within relevant technical groups, and last but not least experience, it can be summarized that the most prominent resilience constraints to the future Bosnia and Herzegovina transmission system are:

- Increased voltage operating conditions (see Chapters 3.5 and 4.3),
- Future power flows (see Chapters 3.6.1, 3.6.5, 3.6.6, 4.1 and 4.2),
- Wind energy integration (see Chapter 3.6.2).

5.1.1. Increased Voltage Operating Conditions

The occurrence of increased voltages in Bosnia and Herzegovina's transmission grid was first observed as soon as the 400 kV network of ex-Yugoslavia was commissioned. This issue was mostly perceptible in low consumption regimes, such as night period, weekends, holidays, etc. Back then, the solution was the installation of 50 Mvar compensation devices to the tertiary of 400/110 kV power transformers. However, such investments were never realized and the problem was dealt with operational measures such as the disconnection of high voltage lines, redispatching, or generation operation in capacitive mode.

Shortly after, the Balkan region was troubled by war and the BIH's EPS was divided into two systems with different frequencies and no interconnecting lines. During that period, as parts of the system were on the edge of their control areas, the high voltage issue wasn't so explicit. It is only after the reconnection of the two control areas, in 2004, that the problem reoccurred.

Operation of overhead lines below the surge impedance loading (SIL) is the main reason for the occurrence of increased voltages. This phenomenon is most observable in 220 and 400 kV networks. Due to the fact that compensation devices were never installed, and that redispatching was no longer a non-costly remedial action, operational solutions became limited. Namely, by the current regulation, generators are not financially compensated for providing services for Q-U regulation.

The Independent System Operator in Bosnia and Herzegovina addressed this situation seriously and responsibly, first by publishing the study [22] and then engaging the Energy Institute Hrvoje Požar (EIHP) from Croatia to put together the study [23] and perform in-depth analyses and propose a solution to this re-emerging problem.

The conclusions from [23] are as follows:

- Mvar regulation from existing generating units connected to the 400 kV transmission system does not possess adequate regulation capabilities to deal with increased voltages.
- Existing power transformers could be seasonally set to lower the voltages on the secondary side. However, that would lead to an increase in primary level voltages and deepen the issue in 400 kV grid.
- Reactive power flows from neighboring TSOs are negatively reflected to BIH's EPS, especially from Croatia and Montenegro. Both countries do not possess compensation devices to deal with the issue.

Positive factors that will help solve the problem, [23]:

- the motivation of generator operation in capacitive mode, primarily those units connected to the 400 kV network, including the possibility of compensation operation mode of pump storage power plant Čapljina,
- new planned generating unit on 400 kV network (see Table 3.14),
- expected consumption growth that will lead to greater loadings of the 400 kV overhead lines,
- higher transits through BIH transmission grid that will also lead to greater loadings of 400 kV overhead lines,
- planned compensation devices in the Croatian transmission system,
- construction and operation of MONITA cable (see Chapter 4.1), will shift flows in a positive way (with regards to load flows) with SEE Region.

Negative factors might be [23]:

- construction of new interconnectors between neighbors from Table 3.19,
- delay of MONITA project and planned compensation devices in Croatian system (Figure 4.3),
- economic, social and environmental factors that could delay new generation investments.

Possible solutions are [23]:

- Introducing financial compensation to generators (electric power utilities) for providing Q-U regulation services or synchronous compensation.
- Installation of compensation devices in the following two substations:
    - Mechanically Switched Capacitor (MSC) of installed reactive power 150 Mvar (3x50 Mvar units) in substation Mostar 4 (on 400 kV bus bars).
    - Mechanically Switched Capacitor (MSC) of installed reactive power 100 Mvar (2x50 Mvar) in substation Tuzla 4 (on 110 or 400 kV bus bars).

After public consultations, the transmission company - TRANSCO (see Chapter 3.1), in their ten-year development plan [24] has included the following investments:

- MSC in Substation Mostar 4 – 150 Mvar (planned in 2020), and
- MSC in substation Banja Luka 6 – 100 Mvar (planned in 2026).

In the meanwhile, the project Sincro.grid was drafted by ELES and HOPS, submitted, and granted EU funds. Among other deliverables, this project will install about 1000 Mvar of compensation devices in the networks of Croatia and Slovenia as shown in Figure 4.3.

Furthermore, as explained in Chapter 4.1, the MONITA cable has been laid and is awaited to be put into commercial use in the near future (2020). The expected outcomes will further relieve the critical voltage operating conditions.

Therefore, even though this issue will continue to be present in the future, it is expected that future developments will diminish it. From a technical point of view, regional factors will have a favorable influence (MONITA, Sincro.grid). On the other hand, internal (national) measures for the solution of the over-voltage issue have been presented (installation of compensation devices, and financial rewards for Mvar regulation). Therefore, it can be considered that this issue is mostly a financial matter, and given that several technical solutions have already been proposed, this issue will not be further investigated through detailed analyses within the scope of this thesis.

5.1.2. Future Power Flows

Due to a large number of reasons, diligently described in Chapter 3, mostly focusing on consumption growth, wind energy integration, internal development plans, regional development plans (MONITA Cable, Transbalkan corridor, and others), the need and justification exists to further research future power flows, as a matter of grid's resilience.

Given the expected growth of numerous statistical factors with regard to energy (especially consumption growth), power lines will be used to a greater extent, closer to the thermal rating in order to supply final customers and fulfill adequate security of supply. Due to trade, as well as unplanned activities in the network related to malfunctions in power plants, lines or other elements, significant congestions will occur, threatening the stability of the entire system. In the worst case, a major blackout can occur, affecting the power supply of hundred thousands of customers around Europe.

Historically and operationally speaking, interconnections between different countries have proven to be the weak link and location of congestion occurrence. In today's world, infrastructure construction and investments can be hard to realize, due to a mix of social, economic and environmental issues. For that reason, investments in phase shifting transformers (PST) have been trending for the last 15 years (Figure 5.1 and Figure 5.2).

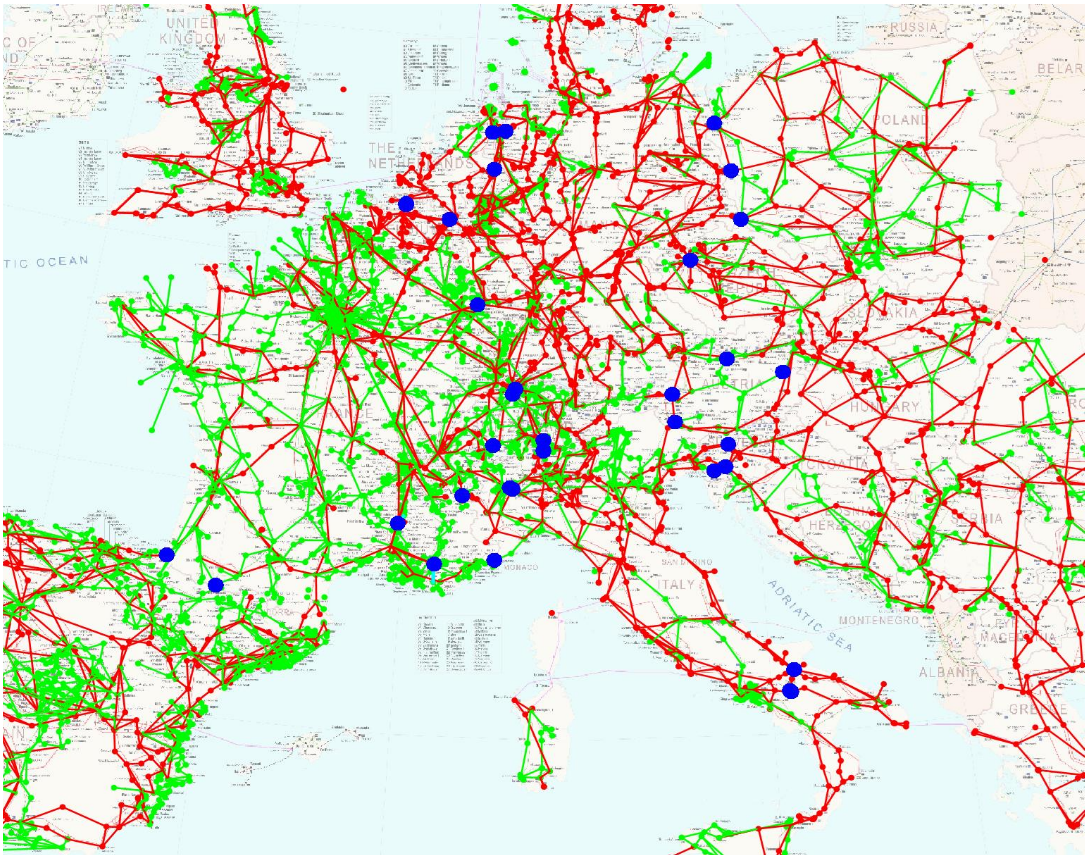


Figure 5.1 – Location of phase shifting transformers in Europe (blue circles) [25]

Phase shifting transformers (PST) are a good solution to the congestion problem, from both technical and financial aspects. What makes PSTs the optimal solution is the fact that they are installed in a single location (PSTs don't require the construction of several hundreds of kilometers of overhead lines), project realization is relatively quick (generally speaking 2-3 years from plans to realization), and the investments costs are compensated through ancillary services tariffing methodology. At the same time, the permitting process is expected to be less complicated due to the fact that PSTs can be installed in existing substations (contrary to very complex property-legal procedures required for the construction of new overhead lines).

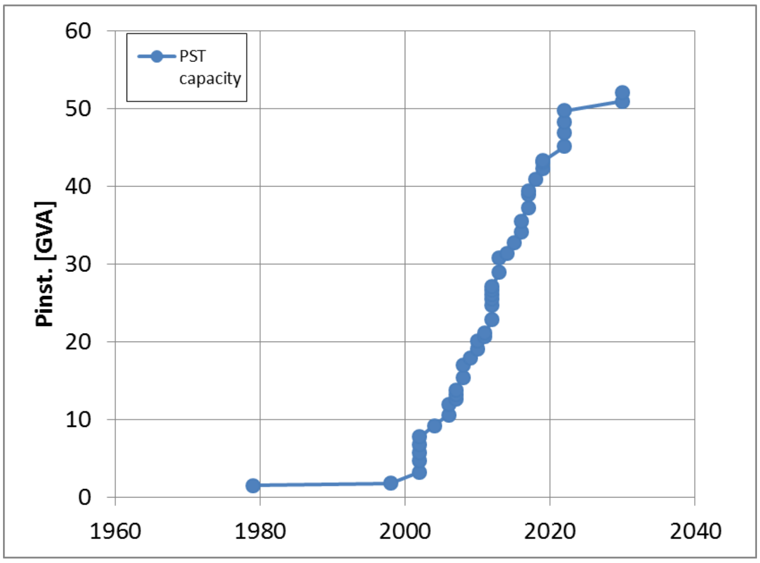


Figure 5.2 – Installed and planned capacities of PST in ENTSO-E (as of 2015)

As can be seen from Figure 5.1, there are no installed PSTs in South East Europe (SEE) region. With regards to new development plans, this thesis will further research and identify the key factors for the installation of the PSTs, as well as to provide a methodology for the identification of the optimal location for PST. The evaluation methodology is tested and demonstrated on a concrete possibility of PST installation in Bosnia and Herzegovina. Several scenarios are examined, and the final evaluation matrix reveals the proposed PST installation location.

Also, within this topic and field of research, the possibility of further enhancing the resilience of the grid by using advanced conductoring technology is examined, in the form of questioning to what extent can the replacement of old lines with composite lines improve the system from a technical perspective.

5.1.3. Wind Energy Integration

With regards to Chapter 3.6.2, the integration of renewable energy sources is a trending issue with no formal and tangible solution so far. More concretely wind power plants in the electric power system of Bosnia and Herzegovina.

In the last 20 years, a new generation of advanced conductors has emerged and proven itself in practical application in several thousand completed projects around the globe. These conductors have greater ampacity, lower sag, and are lighter than traditional conductors.

Therefore, the subject of wind energy integration through the use of advanced conductoring technologies is examined and proposed in a very detailed manner.

5.2. Focus

To resume the matters described up to this part, the scope of work of the thesis focuses on the possible implementations of the following two advanced transmission system technologies:

- Phase Shifting Transformers (PST) in Chapter 6, and
- Advanced Conductors in Chapter 7.

In order to answer the research question appointed in Chapter 2, both topics comprise of extensive overview of the appropriate technology, followed by specific analyses and case studies.

Furthermore, the financial aspect of the proposed implementation of technologies is given in Chapter 8, while recommendations for relevant energy institution are given in Chapter 8.2.

A flowchart describing the scope of work of the thesis is given in Figure 5.3. It comprises of the following parts:

- introductory part,
- problem identification,
- in-depth research of available technologies,
- technical solutions,
- financial overview, and finally,
- recommendations and conclusion.

The published papers from Chapter 2 are given in red color in Figure 5.3.

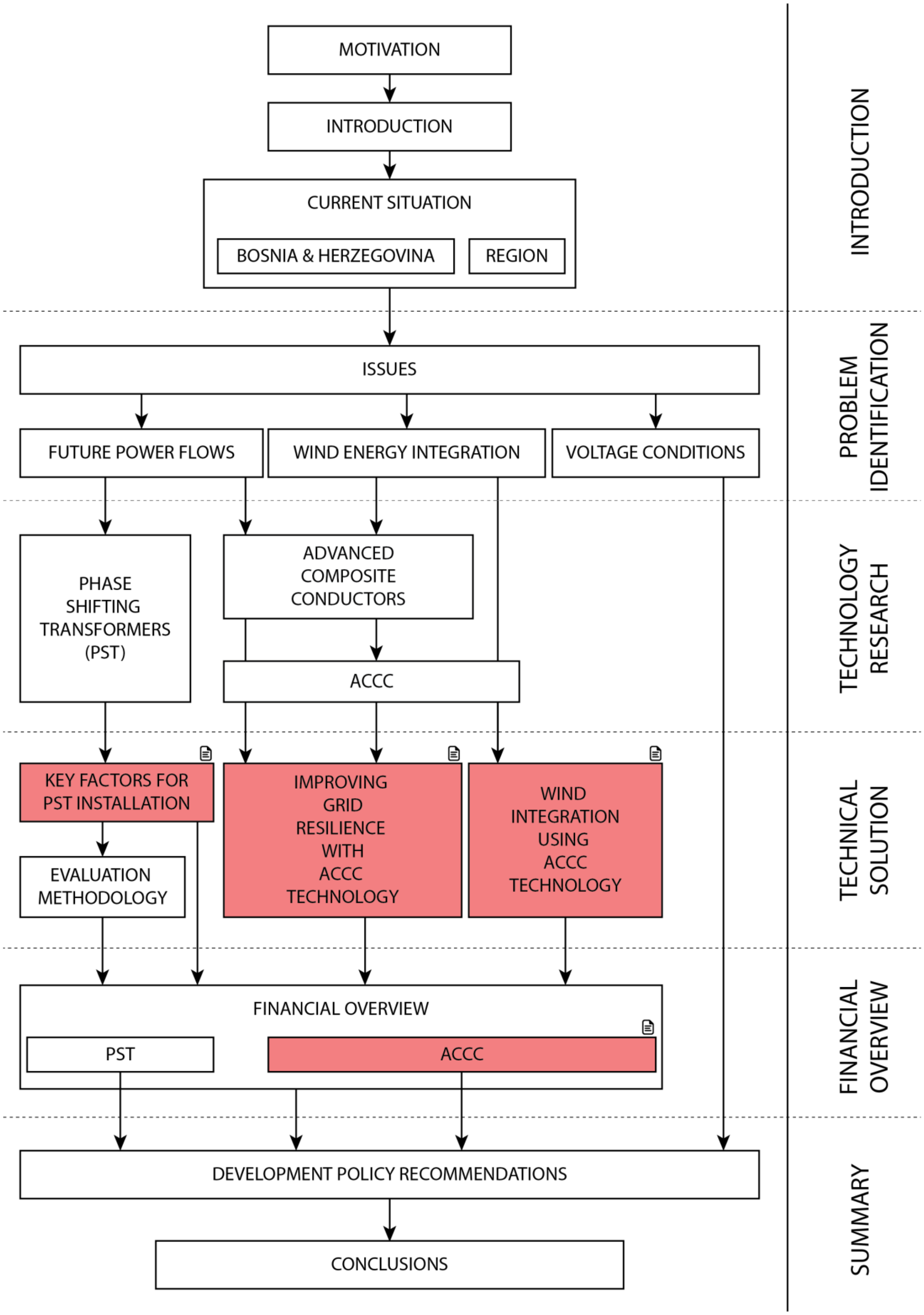


Figure 5.3 – Scope of work of Doctoral Thesis

6. Phase Shifting Transformers (PST)

6.1. Introduction

Following the liberalization of the electricity markets, trade has been made possible between countries. However, trade has to comply with the physical (technical) limitation of the system and equipment. Due to trade, as well as unplanned activities in the network related to malfunctions in power plants, lines or other elements, significant congestions can occur, that threaten to the stability of the entire system. In the worst case, a major blackout can occur, affecting the power supply of hundred thousands of customers around Europe.

Phase-Shifting Transformers (PST) are installed in order to block or facilitate certain power flows. The installation of a single device affects power flows in a wider geographical area. Therefore, determining the optimal location for the phase shifting transformer is of the utmost importance.

There are various ways to address and relieve congestions. Most often congestions occur on the interconnecting lines between two different countries or TSOs. The reason for this is the fact that building new interconnectors has become a complex process because of the following reasons:

- In today's society, the permitting process is very complicated.
- New corridors are difficult to find.
- Construction takes a long time.
- Costs are very high.
- The process has to be coordinated between neighbors.

The alternative to constructing new lines is to install active power flow control devices. The most common choice is to install phase shifting transformers.

This chapter assesses phase shifting transformer (PST) technology, determines the key factors for optimal positioning of PST (prerequisites, substation level, and system level). Those key factors are then subject to quantification in order to determine the optimal positioning of a PST unit within an interconnected system. At the end of the chapter, a case study is presented, putting the quantification methodology to the test on the example of Bosnia and Herzegovina.

6.2. Purpose, function and types of Phase Shifting Transformers

Basically, a phase shifting transformer (PST) creates a phase shift between the primary (source) and the secondary (load) side [26]. Except for very specific applications, the purpose of this phase shift is usually the control of power flow in a complex network [26].

The equivalent PST circuit is given in Figure 6.1. The associated phasor diagram in given in Figure 6.2 [27], [28].

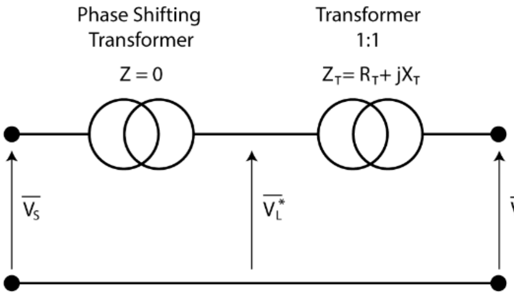


Figure 6.1 – PST equivalent scheme

where:

$\overline{V_L}^*$ = Load Voltage (No Load)
$\overline{V_L}$ = Load Voltage (Loaded)
Z_T = Transformer Impedance
$\overline{I_L}$ = Load Current
$\overline{V_{S(a)}}$ = Source Voltage (advanced)
$\overline{V_{S(r)}}$ = Source Voltage (retarded)
β = Transformer Load Angle
α = Phase Shift Angle (No Load)
+ Advanced (Leading)
- Retard (Lagging)
α^* = Phase Shift Angle (Loaded)

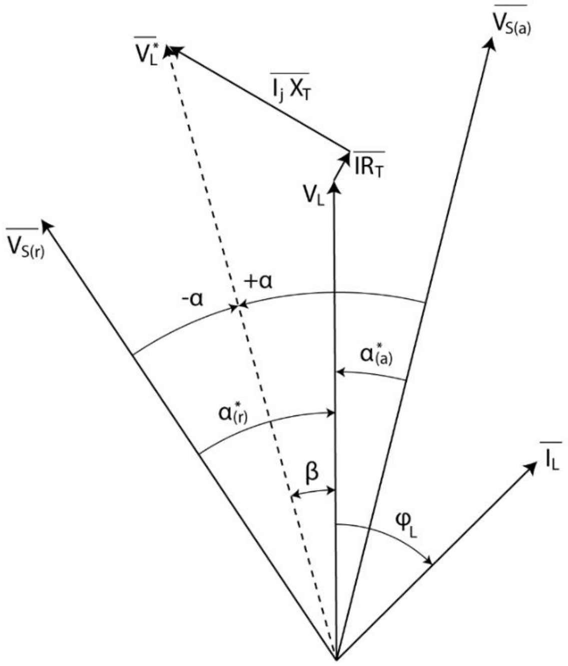


Figure 6.2 – PST phasor diagram (principle diagram)

Phase shifting transformers can be classified from different points of view. A phase shifting transformer can be symmetric or non-symmetric, it can be a quadrature or a non-quadrature type, with a single or a dual core design, and finally with a single tank or a dual tank design [26], [27], [28].

6.3. PST Investigations

Within the scope of research, the author visited the following substations with installed phase shifting transformers:

- Divača (Slovenia), operated by ELES,
- Ternitz (Austria), operated by APG, and
- Žerjavinec (Croatia), operated by HOPS.

Figure 6.3 – PST 1 (foreground), PST 2 (background) in SS Divača (ELES, Slovenia).

Figure 6.4 – PST in SS Divača (ELES, Slovenia)

Figure 6.5 – Two-tank design, PST in SS Divača (ELES, Slovenia)

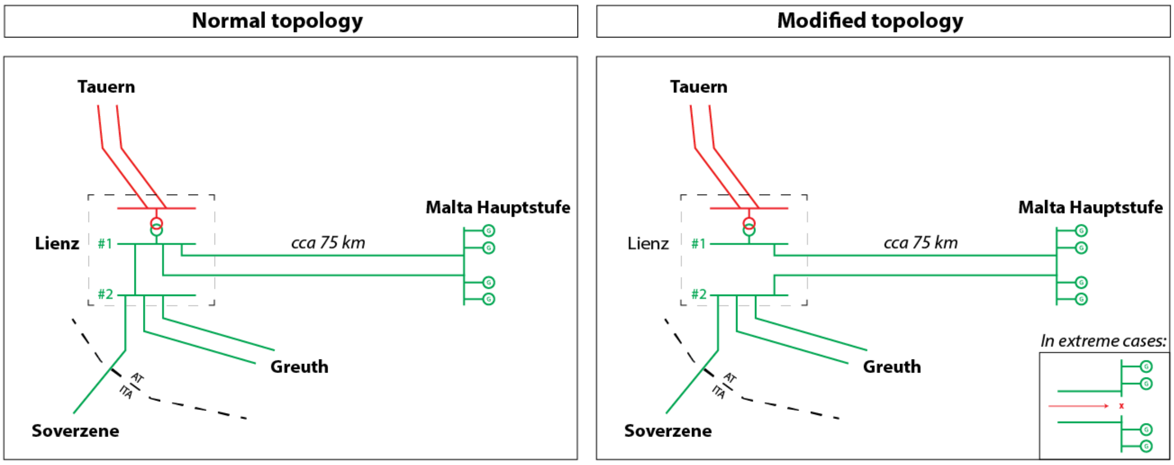
While discussing with colleagues from strategic and operational planning departments, but also with dispatchers that are using PST in everyday work, the following paragraphs present the experiences that were noted.

Prior to the installation of PST in all three TSOs, in order to reduce the flows on critical elements, the dispatchers would use topology changes in the network such as:

- Redirecting flows through network topology changes:
  Please note that more detailed maps of this region are given in Appendix [B].
    - **OHL 220 kV Lienz - Soverzene**
      In normal operation, all 220 kV lines in substation Lienz were connected to the same buses. When APG wanted to decrease the power flow on the Lienz – Soverzene line, they would perform a modification of the switching state; Northern elements would be connected on one bus bar system, and southern elements to the other, and the parallel 220 kV line Lienz – Malta Hauptstufe would no longer be connected to the same bus bar. The newly formed 150 km line would create additional resistances and inductances and therefore limit the power flow going from Austria to Italy. The author modeled this scenario in PSS-E, and the results are shown in Table 6.1 and Figure 6.6.

Table 6.1 – Power flow between Lienz – Soverzene line in different scenarios

Normal Topology (WITH PST)	Normal Topology (NO PST)	Modified Topology (NO PST)
220 MW	256 MW	390 MW



Normal topology

Modified topology

Figure 6.6 - Normal vs. Modified topology at SS Lienz (APG, Austria)

    - **220 kV connection Obersielach – Podlog – Cirkovce - Žerjavinec**
      Redirecting flows to neighboring TSOs, by switching the disconnectors on the sectioned 220 kV bus bars in Podlog, thus connecting APG directly to HOPS (Figure 6.7).
- Redirecting flows between voltage levels (disconnection of transformer 400/200 kV in SS Podlog).

Note: More detailed reports made after the visits to PST can be found in Appendix [C].

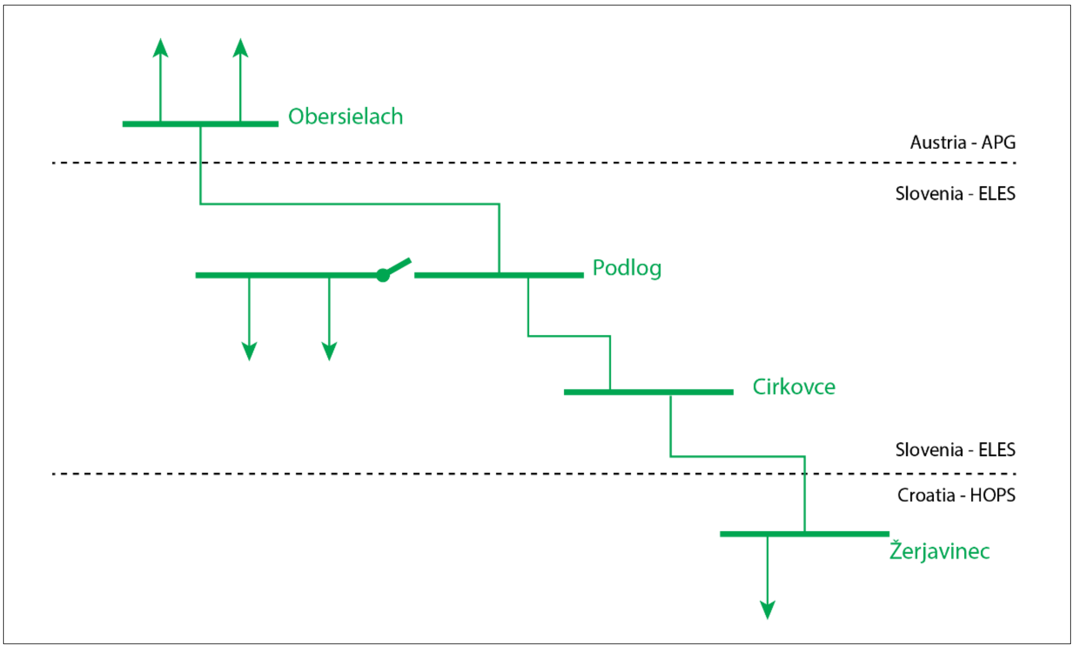
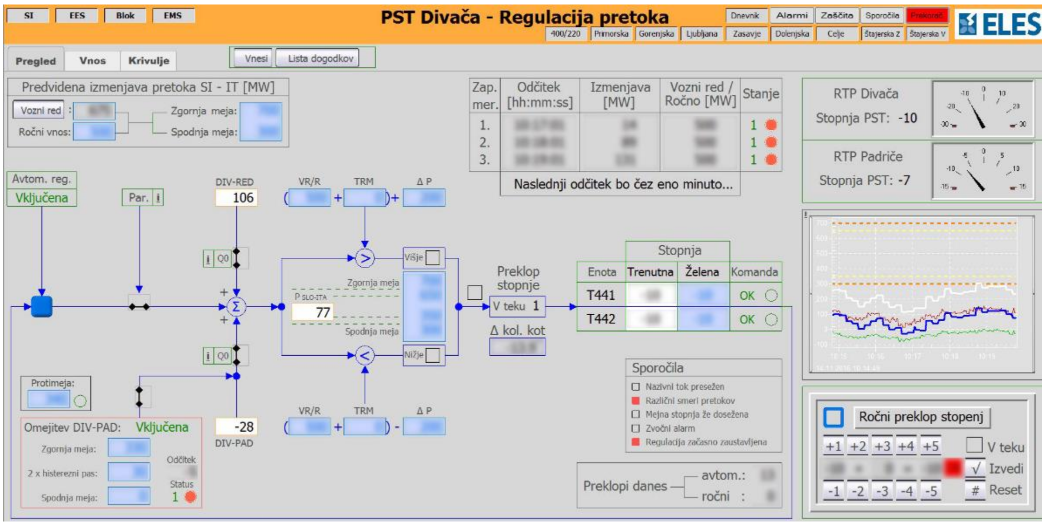


Figure 6.7 – Modified topology at SS Podlog (ELES, Slovenia)

The controllers of PST Divača and PST Padriciano are coordinated together. The interchange value is staggered on both interconnectors OHL 400 kV Divača – Redipuglia and OHL 220 kV Padriciano – Divača accordingly, as shown in Figure 6.8.



Zap. mer.	Odčitek [hh:mm:ss]	Izmenjava [MW]	Vozni red / Ročno [MW]	Stanje
1.	[redacted]	[redacted]	[redacted]	1 ●
2.	[redacted]	[redacted]	[redacted]	1 ●
3.	[redacted]	[redacted]	[redacted]	1 ●

Naslednji odčitek bo čez eno minuto...

DIV-RED: 106

P SLO-ITA: 77

DIV-PAD: -28

Omejitev DIV-PAD: Vključena

Zgornja meja: [redacted]

2 x histerezni pas: [redacted]

Spodnja meja: [redacted]

Odčitek: [redacted]

Status: 1 ●

V teku 1

RTP Divača Stopnja PST: -10

RTP Padriče Stopnja PST: -7

Enota	Trenutna	Želena	Komanda
T441	[redacted]	[redacted]	OK ○
T442	[redacted]	[redacted]	OK ○

Sporočila
- ☐ Nazivni tok presežen
- 🟥 Različni smeri pretokov
- ☐ Mejna stopnja že dosežena
- ☐ Zvočni alarm
- 🟥 Regulacija začasno zaustavljena

Figure 6.8 – Screenshot of SCADA/EMS module for PST Control in Divača

Generally speaking, the PST can act as a controller of reactive power. At the moment of the visit in Divača, one PST unit loaded with 300 MW was consuming about **38 Mvar.** However, it is possible to influence voltages through load flow changes, with regard to surge impedance load (line natural power).

- In case of **low voltage scenario** (<400 kV), by **increasing** the load through PST, it is possible to decrease voltages.
- In the case of **high voltage scenario** (>400 kV), by **decreasing** the load through PST, it is possible to increase voltages.

Figure 6.9 – PST in SS Ternitz (APG, Austria)

Figure 6.10 – Nameplates of PST in SS Ternitz (APG, Austria)

Figure 6.11 – PST in SS Žerjavinec (HOPS, Croatia)

6.4. Results of Power Transfer Distribution Factors (PTDF) Analysis

Power Transfer Distribution Factors (PTDF) indicate the incremental change in real power that occurs on transmission lines due to real power transfers between two regions [29].

Table 6.2 shows an example of PTDF application on the European level. It gives power flow percentage achieved directly between two neighboring control areas for a transaction of 100 MW, for different months in the year. It can be concluded that a significant percentage of power flows, ranging from 25 to 60%, is achieved through surrounding third-party areas, which are unwittingly loaded. The results of PTDF analyses have to be interpreted with regard to the specifics of the network, the number of interconnectors, etc. It is important to note that due to unscheduled or unplanned works, these percentages can be subject to further changes.

Table 6.2 – Power flow percentage for PTDF calculations [1]

	SHB[a]-SMM[b]	**DE-AT**	**DE-FR**	**PL-CZ**	**CZ-AT**
Months	%	%	%	%	%
January	73.8	39.4	39.1	52.1	45.8
March	77.4	38.3	39.5	45.7	48.8
May	79.2	46.3	40.8	49.4	49.3
July	72.2	46.3	37.6	47.8	38.3
September	75.6	43.4	40	49.5	49.2
November	73.8	39.4	39.1	52.1	45.8
Average	**75.3**	**42.2**	**39.4**	**49.4**	**46.2**

[a] SHB is the control block composed of Slovenia, Croatia, and Bosnia and Herzegovina

[b] SMM is the control block composed of Serbia, Montenegro and Macedonia

Thus, it needs to be said that poor PST location can lead to a further increase in the aforementioned percentages. Poor PST design can also lead to an increasing number of unwanted flows, and create additional loop flows. Also, by taking into account the increasing number of PST installation in the interconnected power system of Europe (ENTSO-E), special caution has to be taken in the harmonization procedure in regional groups prior to the installation.

6.5. Key Factors for the Installation of PST

6.5.1. Major Reasons

The major reasons for a phase shifting transformer investment, from the point of view of modern transmissions system operator, can be summarized as follows [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40]:

- to increase the efficiency of the existing transmission system,
- to avoid overloading of grid elements,
- to take advantage of existing margins on the network,
- to make interconnections more secure,
- to increase transmission network operation reliability in the electric transmission system,
- to reduce large uncontrolled electric power transit over the electric transmission system,
- to enable larger and controlled electric power flows between the electric transmission system of neighboring systems,

- to reduce the losses in the system resulting from too large and uncontrolled electric power transits,
- to enable greater income from free cross border transfer capacity lease,
- to enable faster and controlled restoration of the network after its potential collapse.

6.5.2. Control Strategies

In principle the main control strategies can be classified as the following [33]:

- **Curative:** The PST is operated with a small phase shift in normal operating conditions. In case of a sudden line outage, the phase shift is automatically controlled in order to reduce the power flow on the overloaded lines and to avoid tripping out.
- **Preventive:** The PST is operated with a permanent phase shift which redistributes the power flows in normal operating conditions and avoids stresses on the network in case of a line outage.

6.5.3. Prerequisites for PST Installation

When determining the optimal location for a PST, it is necessary to analyze spacious plans from a narrowed selection of substations. Namely, the phase shift transformer requires quite a lot of space, especially the dual tank design. Therefore, planners have to take into account that fact and choose a location according to these requirements.

Even though it is complicated to generalize the size of a PST, as well as the total substation area needed for it, with the following example, the author gives an estimation. For example, the 400 kV, 1200 MVA phase shifting transformer located in Divača, for use on the overhead Line (OHL) 400 kV Divača (SLO) – Redipuglia (ITA) was built on a plateau measuring 115 x 130 m, for a total of 15.000 m2. The PST in Divača is composed of two units of 600 MW, (each with a dual tank design), and each unit measures 25 x 10 m [41]. The remaining space of the plateau was used to build accompanying buses, as well as to house control, protection, measurement, and power equipment.

Figure 6.12 – Graphical representation of PST on OHL Divača – Redipuglia

6.5.4. Optimal PST Location in a Substation

Even though the PSTs are represented on geographical representations as if they are located at the end/beginning of a line (Figure 6.12), whereas in reality they are located elsewhere (usually behind the bus bars – Figure 6.13), mainly because of three reasons:

- **Existing line bays** – Namely, PST are installed historically after the lines. In most cases, line bays are the last entity before the substation fence. So it would be very complicated and ill-advised to install them as they are usually shown on maps (Figure 6.12).
- **Space** – As explained in the previous chapter, the first prerequisite for PST is that they are PSTs located where there is enough space. They are then connected galvanically to form an optimal configuration.

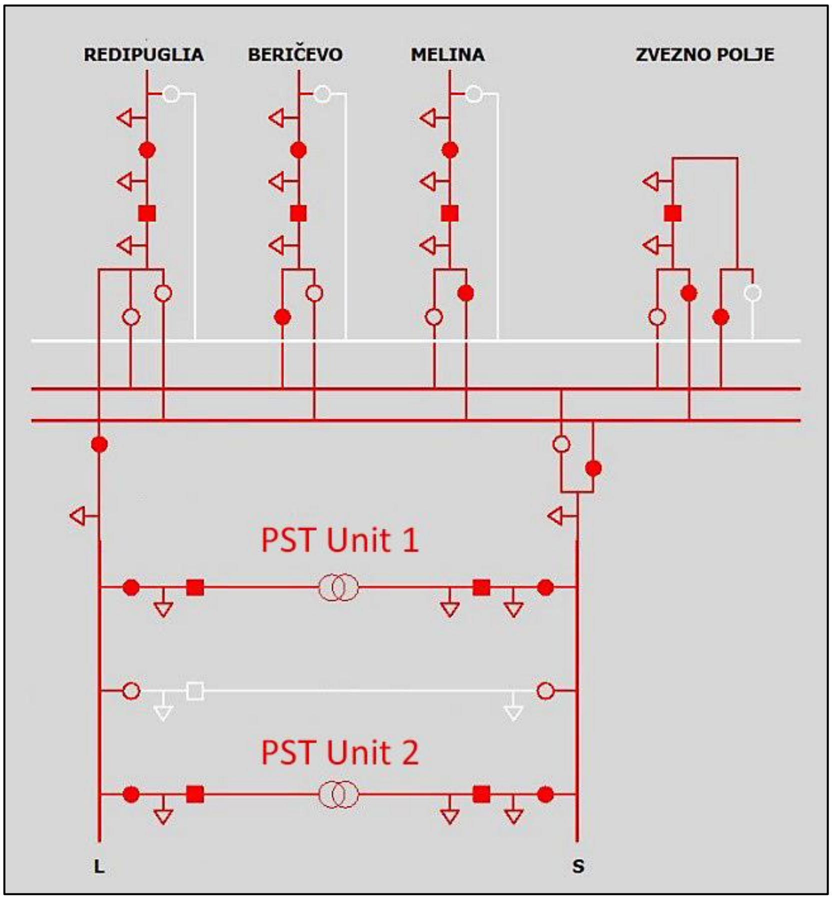


Figure 6.13 – Single line diagram of PST in SS Divača

- **Interoperability** – Through different switching states, PST can be used for different purposes. For example to help restore the system after a major blackout, or to restrict the flows upon the maintenance of surrounding lines. If PSTs were located as in the geographical maps, there would be no such possibility. Therefore, by strategically installing the PST "behind" the bus bars (Figure 6.13), it is possible to use it on other lines, when such necessity occurs.

In other words, interoperability means that the PST is used with the designated line for most of the time. Nonetheless, on occasions when the flows on that line are not critical (such as night time, or specific periods during the year, winter/summer), or in other cases (either preventive or curative), the PST has the possibility to be used to perform other tasks.

6.5.5. Optimal PST Location in the Power System

Upon analyzing the installations of European phase shifting transformers in the last two decades [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [42], it can be concluded that the final location for the vast majority of devices was preselected by experience, and later on confirmed by analyses.

The most common criteria that lead to the determination of the optimal location of phase shifting transformers in interconnected systems are listed below.

6.5.5.1. Determination of Network Loadability

Before committing to the investment of a PST, it is necessary to analyze the loadings of all lines, for different time periods (day, night, winter, summer, maximum, minimum, etc.). Determining this factor should justify the following steps for investment in PST.

6.5.5.2. Determination of Bottlenecks

Bottlenecks have to be singled out by various power flow analyses, including contingency analyses, Net Transfer Capacity (NTC) analyses, etc.

A simple approach is to insert a phase shifter on each bottleneck line, in order to reduce the flow on these lines. But this “one constraint-one phase shifter” approach is not sufficient, because it leads to creating constraints on new lines [43]. Therefore, a broader and more detailed analysis is recommended.

6.5.5.3. Future Network Developments Plans

Network development plans have to be analyzed in order to check impact of future investments on present bottlenecks. National and regional plans should be taken into account.

6.5.5.4. Alternative Solutions

Alternative solutions for present bottlenecks should be analyzed. A possible solution could be the construction of a new line, or replacement of weak lines using new conductor technologies, such as Aluminum Composite Core Conductor (ACCC).

6.5.5.5. Financial Factors

Different financial factors should be analyzed at this point. What would be the savings from re-dispatching, capacity allocation, and what would be the pay-off time of such an investment. Market analysis, showing an influence of the PST installation on expected market conditions, especially concerning an average electricity price and generation costs should be performed.

6.5.5.6. Regional Impact

By their purpose and definition, effects of phase shifting transformers go beyond national borders, especially if installed on interconnectors. It is necessary to perform analyses on neighboring systems, as well as to get the project approved by all affected parties.

Other minor factors that can lead to more efficient usage of phase shifting transformers:

6.5.5.7. Existence of Double Lines

Installation of a PST on buses connected to double lines (through special topology change, by switching operations) can always be observed as added value. In case of maintenance of one line, using a PST, the flows on the other line can be limited to allowed values.

6.5.5.8. Increasing PST Capacity

Experiences from several transmission system operators indicate that increasing PST capacity by up to 5-10% compared to the calculated values, has had a positive effect on the future operation and also added value to the system when confronted with severe overloading of lines.

6.5.5.9. Determination of Weak Spots

Recommendations from transmission system operators also indicate that it is preferable and beneficial to allocate a PST in a location that has more than one weak line.

6.6. PST Installation Example

6.6.1. Model

The following example was chosen to show the effect of PST installation into an overhead line. The analysis was performed on the merged winter maximum model of South East European transmission systems with high transits from east to west. The merged models include transmission grids of Albania, Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Hungary, Macedonia, Montenegro, Romania, Serbia, and Slovenia. The analysis was performed using Siemens PSS-E software. The model was created using relevant inputs described in Chapter 3, as well as [24] and ENTSO-E Transparency Platform, as well as ENTSO-E TYNDP Data Set.

A generic PST model was used from the PSS-E Model Library. The PST was modeled as a 220/220 kV two-winding transformer with a Control Mode set to Active Power (Symmetric design). The throughput capacity was adjusted with regard to the loading of the line it was placed on (See Figure 6.15).

6.6.2. Scenarios

After performing an N-1 contingency analysis of the model, it was determined that upon tripping of the OHL 400 kV Mostar – Konjsko, OHL 220 kV Mostar – Zakučac becomes overloaded.

Therefore, three more detailed scenarios were analyzed:

- **Reference case** (Figure 6.14)

  Before the tripping of OHL 400 kV Mostar – Konjsko.
- **Contingency case**

  After the tripping of OHL 400 kV Mostar – Konjsko.
- **Remedial case** (Figure 6.15)

  After the tripping of OHL 400 kV Mostar – Konjsko, a phase shifting transformer is inserted on OHL 220 kV Mostar – Zakučac. The permitted flow through the PST is adjusted to 92 % of existing line thermal rating in this case.

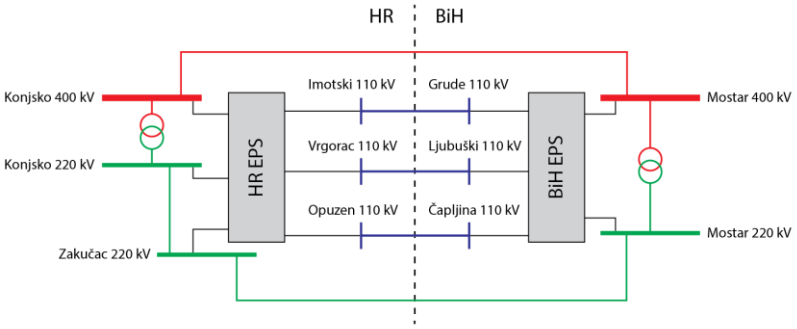


Figure 6.14 – Reference case

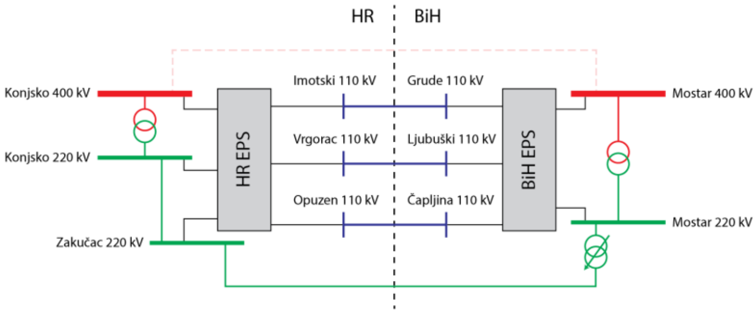


Figure 6.15 – Remedial case (with PST)

6.6.3. Results

Table 6.3 shows the loadings of the relevant lines for all three scenarios.

Table 6.3 – Loadings of lines according to the scenarios

	Reference	**Contingency**	**Remedial**
OHL 400 kV Konjsko - Mostar	43.64%	N/A	N/A
OHL 220 kV Mostar - Zakučac	36.78%	**116.57%**	92.80%
OHL 220 kV Zakučac - Konjsko	19.96%	84.93%	71%
OHL 110 kV Imotski - Grude	34.54%	81.75%	91.78%
OHL 110 kV Vrgorac - Ljubuški	18.31%	37.52%	41.12%
OHL 110 kV Opuzen - Čapljina	8.91%	19.08%	20.47%

6.6.4. Analysis Conclusion

It can be concluded that after the tripping of the OHL 400 kV Konjsko – Mostar, the OHL 220 kV Mostar - Zakučac becomes overloaded with 116.57% of the allowed line thermal rating. After a PST is introduced into the overloaded line, the unwanted flows are restrained within allowed limits. It is important to notice that the flows on 110 kV lines have increased in the remedial scenario.

6.7. PST Evaluation Methodology

In order to identify the optimal location of a phase shifting transformer within a system, an evaluation methodology with weighting factors is presented. The methodology quantifies the key factors for the installation of phase shifting transformers described in Chapter 6.5. When performing the evaluation, different categories can be used in order to identify the optimal location. Those categories can be changed and modified according to a specific case and can take into account different country specifics with regards to technical and non-technical criteria.

Due to the fact that not all factors from Chapter 6.5. can be quantified, it is important to single out the most important factors that can be calculated, estimated and analyzed. The relevant set of categories can be summarized into the following categories:

- **Overall Electrical Factor**, shows an influence of different scenarios on the load flows during normal conditions (all lines in operation), security criteria (N-1, N-2, N-1-1, etc.), related to observed time frame, demand level, new generation developments, generation engagement, with regard to Chapters 6.5.5.1, 6.5.5.2, 6.5.5.3, and 6.5.5.6.
- **Administrative Factor,** showing an estimation of all preparatory formal and legal activities which have to be done in order to install the PST, before the observed time frame.
- **Market Factor,** showing an influence of the PST installation on expected market conditions, especially concerning an average electricity price and generation costs.
- **Cost Factor,** showing a relative position of each PST installation with respect to its capital expenditure.
- **Environmental and Social Factor,** showing an impact of each PST installation on the environmental and social issues.
- **Space Prerequisites Factor,** taking into account the prerequisites described in Chapters 6.5.3 and 6.5.4, especially to space requirements for the installation of the PST with all its equipment.
- **Interoperability Factor,** as mentioned in Chapter 6.5.4, the term „interoperability“ is introduced to give importance to the possibility of using the PST on other lines in the same substation, by strategically installing the PST "behind" the bus bars as shown on Figure 6.13 – Single line diagram of PST in SS Divača.
- **Control Strategies Factor,** as mentioned in Chapter 5.5.2, control strategies of a PST can be classified either as curative or preventive. From a strategic, as well as a financial point of view, it can be said that preventive PST installation has greater importance. Thus, preventive installation can be awarded a greater value than curative ones.
- **Added value factors**, shows the additional values that the PST installation can give to the existing system, with regard to:
    - **Double Lines Factor**, giving importance to the benefits of having a PST on double lines, especially when performing maintenance, with regard to Chapter 6.5.5.7,
    - **Interconnector Factor**, quantifies the number of interconnectors in the substation analyzed for PST installation, giving accent to the regional impact.
    - **Throughput Factor**, shows quantification of weak lines, as explained in Chapter 6.5.5.9.
    - **Age Factor**, showing quantification of weak lines, as explained in Chapter 6.5.5.9.
- **Operational Experience Factor**, as mentioned in Chapter 6.5.5, upon the analysis of the realized PST installations in Europe, for the last two decades, it is concluded that the final

location was determined by experience. Therefore, a certain degree of pertinence should be given to the experience of operational engineers in charge of running the system.

The chapters 6.7 and 6.8, are based on the example of [44] and [45], and were adapted, modeled and designed to evaluate PST installation within an interconnected system.

6.7.1. Methodology summary

Table 6.4 gives an overview of the possible categories that can be used for the evaluation methodology, with the quantification method as well as the overall weight of the factor.

Table 6.4 – Quantification method and weighing factor

Category	Quantification method	Weighting factor
Overall electrical factor	Numerical value	Very High
Administrative factor	YES/NO	High
Market factor	Numerical value	High
Cost factor	Numerical value	Medium
Environmental and social factor	Numerical value or YES/NO	Medium
Space prerequisites factor	YES/NO	High
Interoperability factor	Numerical value	Medium
Control strategies factor	Numerical value	Medium
Double lines factor	Numerical value	Low
Interconnector factor	Numerical value	Low
Throughput factor	Numerical value	Low
Age factor	Numerical value	Low
Operational Experience	Numerical value	Medium / Low

The quantification method “YES/NO” can either be used as an eliminative criterion, or as a mean to add points to a specific category for the PST installation.

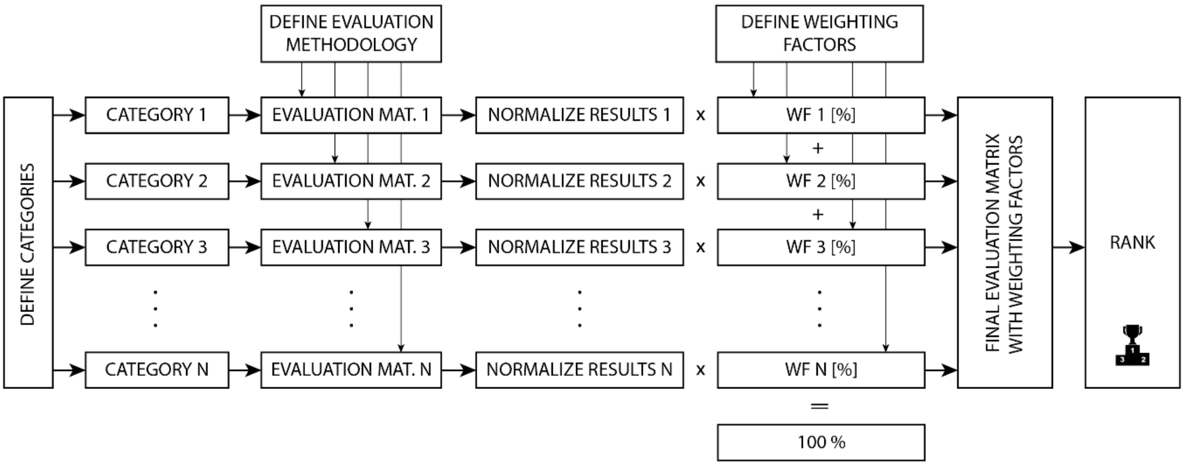


Figure 6.16 – PST Evaluation Methodology Overview

Figure 6.16 shows a generalized overview of the proposed methodology using evaluation matrices with weighting factors as a way to determine the optimal location of PST installation within an interconnected power system. As explained below, the number of categories can vary depending on the specificity of the installation, stage of the project, available data and other requirements.

Relative scores for each observed category are placed in the final evaluation matrix. In order to mutually compare all analyzed scenarios and observed categories, relative scores are transposed to a certain number of points (for example between 0 and 10), by using the following procedure:

- the minimum value of a relative score in each observed category would bring 0 points,
- the maximum value of a relative score in each observed category would bring 10 points,
- scenarios with relative scores between zero and maximum value are awarded points calculated by assuming a linear relationship between zero and maximum relative scores.

The final evaluation matrix is created by transposing the relative scores into the points. By applying the weighting factors which give different significance to each observed category, the overall and final assessment is given as the sum of weighted points for each scenario.

The significance of this evaluation methodology is that it can be adapted to fit the need of specific systems (taking into account country specifics). New explicit categories can be added, but proposed ones can be excluded from the evaluation due to justified reasons.

Given that categories are prioritized by weighting factors, the significance for each category is assigned so that all scenarios are assessed in a universal, non-discriminatory approach.

6.8. Case Study: Evaluation Matrix for PST Installation in Bosnia and Herzegovina

6.8.1. Introduction

The methodology presented in the previous chapter is tested on the example of Bosnia and Herzegovina. Namely, a set of scenarios is defined, and a list of categories are chosen among the list presented in Table 6.4. Other categories are excluded from this case study, and justification is given for each category. The selected categories are then explained, analyzed, and quantified. The general evaluation methodology given in the previous chapter is further expanded with concrete equations, steps, and examples.

6.8.2. Case Study Scenarios

For this case study, the installation of a PST unit is evaluated for a total of five scenarios. The chosen set of scenarios comprises of five 220 kV interconnectors between Bosnia-Herzegovina and Croatia (Figure 6.17), respectively:

- Scenario 1: PST on OHL 220 kV Mostar – Zakučac,
- Scenario 2: PST on OHL 220 kV Prijedor – Sisak,
- Scenario 3: PST on OHL 220 kV Prijedor – Međurić,
- Scenario 4: PST on OHL 220 kV Gradačac – Đakovo,
- Scenario 5: PST on OHL 220 kV Tuzla – Đakovo.

The location of the PST unit is designed to be on the BIH side, in one of the substations (Mostar, Prijedor, Gradačac or Tuzla).

Figure 6.17 – Locations of selected PST installation scenarios

All lines are ACSR STARLING (Al/Fe 360/57 mm2), with a maximum throughput capacity of 790 A. The generic PSS-E model is used for the PST unit, with parameters given in Table 6.5.

Table 6.5 – PST parameters used for scenarios

Parameter	Value
Installed Capacity	300 MW
Voltage level	220 kV
Tank configuration	Symmetrical
Taps	33
Phase shifting angle	±30°

6.8.3. Case Study Overview

In this particular example of the proposed methodology, due to the scientific nature of the thesis, as well as data available to the author, the evaluation matrix will include assessment of the following categories:

- Overall Electrical Factor,
- Interoperability Factor,
- Double Lines Factor,
- Interconnector Factor,
- Throughput Factor,
- Age Factor, and
- Operational Experience.

Therefore, the following categories will not be evaluated, due to the reasons listed below:

- **Administrative Factor** – legal and formal issues are not within the focus of the thesis and would require a very broad interdisciplinary research.
- **Market Factor** – even though this is category has a high weighting factor, in this particular evaluation, the author doesn't have the means, ends, and knowledge to perform a purposeful evaluation.
- **Environmental and Social Factor** – due to the same aforementioned reasons.
- **Space prerequisites factor** – as explained in 6.5.3, this category is an eliminatory criterion. However, due to the unavailability of spatial plans, ownership proofs, and other relevant input data, this category will not be further evaluated.
- **Cost Factor** – due to the fact that all scenarios evaluate identical PST installation with the same parameters (as explained in the previous chapter), the costs are considered to be identical. Therefore, in this particular evaluation, there is no need to further compare costs.
- **Control Strategies Factor** – experience-wise, in all the evaluated scenarios the PST installation is not regarded as critical, the control strategy in all of the cases is curative. Therefore, there is no need to further compare control strategies for each scenario, as the relative scores would be identical.

Anyhow, the unanalyzed categories could, theoretically, be evaluated in later steps of the PST installation agenda, or within some specific time frame during the investment agenda.

6.8.4. Overall Electrical Factor (OEF)

6.8.4.1. Power System Model Details

The model consists of two target years, 2020 and 2030. PST installation is generally requested due to the violation of security criteria (or congestions on overhead lines). For that reason, the summer and winter peak models for 2020 and 2030 target years are used. The characteristics of each model are given below.

Table 6.6 – Model characteristics for selected models

Model	Generation		Consumption		Interchange	
	BIH	HR	BIH	HR	BIH	HR
Summer Peak 2020	2104	2519	1804	3519	300	-1000
Winter Peak 2020	2364	3488	1914	4538	450	-1050
Summer Peak 2030	3197	2600	2697	3700	500	-1100
Winter Peak 2030	3334	3525	2784	4525	550	-1000

The merged models include transmission grids of Albania, Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Hungary, Macedonia, Greece, Montenegro, Romania, Serbia, and Slovenia. The analysis was performed using high-performance transmission planning and analysis software Siemens PSS-E. This model was created using relevant inputs described in Chapter 3, as well as [24], [9], [46], ENTSO-E Transparency Platform, as well as ENTSO-E TYNDP Data Set.

The models also include the cable MONITA (Chapter 4.1). It is modeled as a load, with the following parameters:

- in 2020, modeled as a positive load (with 500 MW exports from SEE region to Italy),
- in 2030, modeled as a positive load (with 1000 MW exports from SEE region to Italy).

6.8.4.2. Defining Security Analyses

The main task of all these analyses is to find a differentiation between five (5) considered scenarios regarding their impact on the transmission network security. This system analysis result comparison is done through the evaluation matrix as explained in the next chapters. Three main security analyses are performed for each calculation, N criterion, N-1 criterion, and N-2 criterion.

Generally speaking, overloading represents the loading of a system element above a certain threshold. The threshold is determined on the basis of experience, and if generally in the range 80-100%, depending on the type of performed analysis. The criterion is considered violated if one or more overloadings occur as the result of a security analysis.

N criterion

N criterion refers to topological conditions where all 400, 220 and 110 kV branches in BIH and Croatian transmission network are in operation. The result of this analysis is the number of scenarios and number of transmission network branches which are highly loaded (in this case: over 90%) with respect to lines ampacity and transformers apparent power.

N-1 criterion

N-1 criterion refers to a topological condition with one 400, 220 or 110 kV branch in BIH and Croatian transmission network out of operation. The result of this analysis is the number of scenarios and number of transmission network branches which are overloaded (in this case: over 90%) with respect to lines ampacity and transformers apparent power.

N-2 criterion

N-2 criterion refers to a topological condition with two branches in BIH and Croatian 400 kV and/or 220 kV network out of operation at the same time. The output of this analysis is the number of scenarios and number of branches which are overloaded (in this case: over 100%), with respect to 400 kV and 220 kV lines ampacity and transformers apparent power.

6.8.4.3. List of Performed Analyses

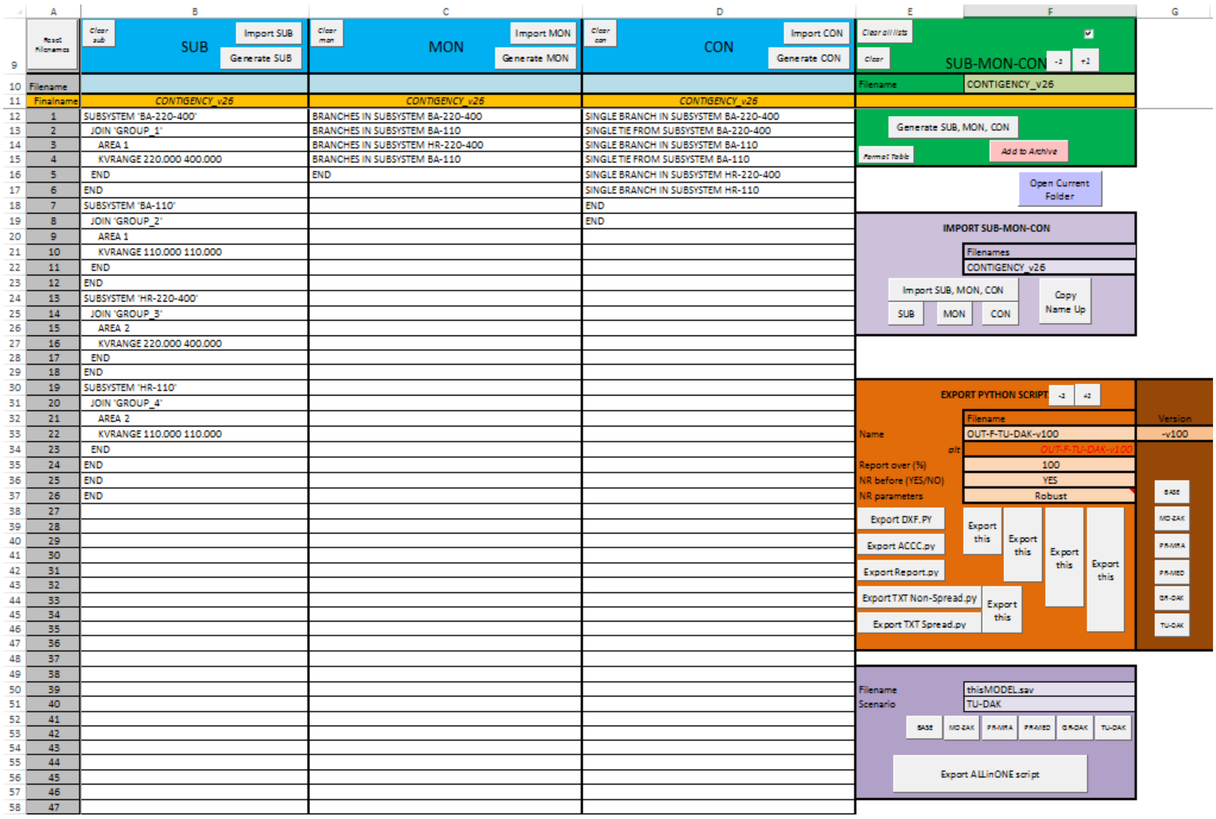
Five (5) considered scenarios are compared in four (4) different system steady states (two of them in 2020 and another two of them in 2030) through three main analysis: N criterion, N-1 criterion, and N-2 criterion. For each of the 20 different topological models, the three security analyses were performed, for a total of 60 different analysis were calculated, analyzed and aggregated. The results are presented for 2020 and 2030 combined. Table 6.7 shows a list of all performed analyses.

Table 6.7 – List of performed analyses for the overall electrical factor

SCENARIO	MODEL	SECURITY ANALYSES	CODE NAME
Scenario 1	Summer Peak 2020	N criterion N-1 criterion N-2 criterion	A-SP-20
	Winter Peak 2020		A-WP-20
	Summer Peak 2030		A-SP-30
	Winter Peak 2030		A-WP-30
Scenario 2	Summer Peak 2020		B-SP-20
	Winter Peak 2020		B-WP-20
	Summer Peak 2030		B-SP-30
	Winter Peak 2030		B-WP-30
Scenario 3	Summer Peak 2020		C-SP-20
	Winter Peak 2020		C-WP-20
	Summer Peak 2030		C-SP-30
	Winter Peak 2030		C-WP-30
Scenario 4	Summer Peak 2020		D-SP-20
	Winter Peak 2020		D-WP-20
	Summer Peak 2030		D-SP-30
	Winter Peak 2030		D-WP-30
Scenario 5	Summer Peak 2020		E-SP-20
	Winter Peak 2020		E-WP-20
	Summer Peak 2030		E-SP-30
	Winter Peak 2030		E-WP-30

The Code List Matrix, explaining each the code naming methodology is given in Appendix [D].

In order to automate the calculation process, but also to quicken the calculation of the described 60 calculation/analyses, and to eliminate the possibility of human error when changing parameters of the analysis, a separate program called „SubMonConPy“ was created (Figure 6.18).



	A	B	C	D
10	Filename			
11	Finalname	CONTIGENCY_v26	CONTIGENCY_v26	CONTIGENCY_v26
12	1	SUBSYSTEM 'BA-220-400'	BRANCHES IN SUBSYSTEM BA-220-400	SINGLE BRANCH IN SUBSYSTEM BA-220-400
13	2	JOIN 'GROUP_1'	BRANCHES IN SUBSYSTEM BA-110	SINGLE TIE FROM SUBSYSTEM BA-220-400
14	3	AREA 1	BRANCHES IN SUBSYSTEM HR-220-400	SINGLE BRANCH IN SUBSYSTEM BA-110
15	4	KVRANGE 220.000 400.000	BRANCHES IN SUBSYSTEM BA-110	SINGLE TIE FROM SUBSYSTEM BA-110
16	5	END	END	SINGLE BRANCH IN SUBSYSTEM HR-220-400
17	6	END		SINGLE BRANCH IN SUBSYSTEM HR-110
18	7	SUBSYSTEM 'BA-110'		END
19	8	JOIN 'GROUP_2'		END
20	9	AREA 1		
21	10	KVRANGE 110.000 110.000		
22	11	END		
23	12	END		
24	13	SUBSYSTEM 'HR-220-400'		
25	14	JOIN 'GROUP_3'		
26	15	AREA 2		
27	16	KVRANGE 220.000 400.000		
28	17	END		
29	18	END		
30	19	SUBSYSTEM 'HR-110'		
31	20	JOIN 'GROUP_4'		
32	21	AREA 2		
33	22	KVRANGE 110.000 110.000		
34	23	END		
35	24	END		
36	25	END		
37	26	END		
38	27			
39	28			
40	29			
41	30			
42	31			
43	32			
44	33			
45	34			
46	35			
47	36			
48	37			
49	38			
50	39			
51	40			
52	41			
53	42			
54	43			
55	44			
56	45			
57	46			
58	47			

Filename: CONTIGENCY_v26

Filenames: CONTIGENCY_v26

Name: Filename OUT-F-TU-DAK-v100; Version -v100
alt: OUT-F-TU-DAK-v100
Report over (%): 100
NR before (YES/NO): YES
NR parameters: Robust

Filename: thisMODEL.sav
Scenario: TU-DAK

Figure 6.18 – Interface screenshot of the developed program SubMonConPy

As graphically and analytically described in Figure 6.19, in the section „Calculation“, the program „SubMonConPy“ was coded in Visual Basic code within a macro-enabled Excel Macro Workbook, with the aim to perform the following activities;

- Easily create, modify, export and import PSS-E contingency related files – „.sub“/“.mon“/“.con“,
- Create automated PSS-E scripting files in Python programing language to automate the calculation procedure.

The details, functionality, and code of the „SubMonConPy“ software are described in more details in Appendix [E].

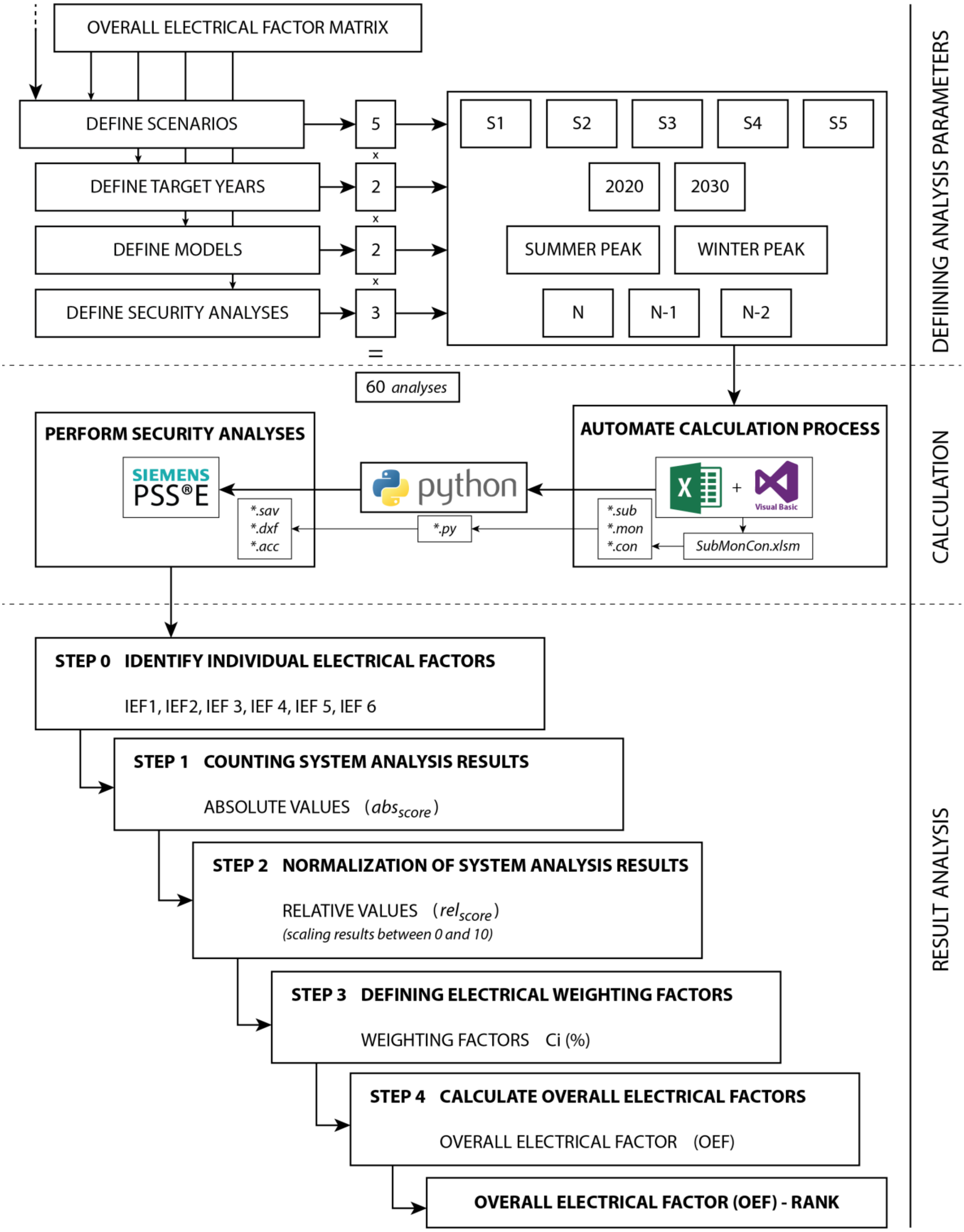


Figure 6.19 – Algorithm for defining the Overall Electrical Factor (OEF)

6.8.4.4. OEF System Analysis Results

After performing a total of sixty (60) analyses, the results were evaluated, counted and put into tables. This chapter presents the results of Step 1 from Figure 6.19. In this phase, the results are given in absolute values. For example, the value 69 from Scenario 1 (in Table 6.8), represents the sum of all N-1 criterion violations with branches loaded over 90% in the case when the PST is installed on OHL 220 kV Mostar – Zakučac (Scenario 1).

Table 6.8 – System analysis results - All topologies summary (STEP 1)

CRITERIA / TOPOLOGY		**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
N CRITERION *(Violation: branch loading ≥ 90% Sn)*	Number of scenarios with a criterion violation	2	2	2	2	2
	Number of critical branches identified	4	4	4	4	4
N-1 CRITERION *(Violation: branch loading ≥ 90% Sn)*	Number of scenarios with a criterion violation	4	4	4	4	4
	Number of critical branches identified	69	76	65	71	82
N-2 CRITERION *(Violation: branch loading ≥ 100% Sn)*	Number of scenarios with a criterion violation	4	4	4	4	3
	Number of critical branches identified	100	90	74	103	179

Scenario 1: PST on OHL 220 kV Mostar - Zakučac
Scenario 2: PST on OHL 220 kV Prijedor - Sisak
Scenario 3: PST on OHL 220 kV Prijedor - Međurić
Scenario 4: PST on OHL 220 kV Gradačac - Đakovo
Scenario 5: PST on OHL 220 kV Tuzla - Đakovo

6.8.4.5. OEF Evaluation Matrix

The evaluation matrix for system analysis is a tool for comparing system analysis results between considered PST installation scenarios [44]. The main task of the evaluation matrix is to rank considered scenarios regarding their impact on the transmission network security in accordance with N criterion, N-1 criterion, and N-2 criterion. The evaluation matrix for system analysis is created in a way that previously stated system analysis results are transposed to electrical factors which are then weighted and summed as showed in Figure 6.19 and described below.

In the process of creating the evaluation matrix for system analysis Step 1 and Step 2 include performing system analysis, counting criterion violations and their normalization. Results are normalized to values between 10 and 0. The value 10 is given to the topology that least violates network security, respectively 0 is given to the topology that most violates network security.

$$rel_{score}(i,j) = 10 \cdot \left(\frac{\max\_value(j)}{\max\_value(j) - \min\_value(j)} - \frac{1}{\max\_value(j) - \min\_value(j)} \cdot abs_{score}(i,j)\right)$$

where:

i is the number of analyzed scenario (i = 1 to 5; scenario 1…scenario 5),
j is the number of the observed Individual Electrical Factor (IEF) category (j=1 to 6; IEF 1…IEF 6),
max_value (j) is maximum value of the relative scores in the observed category j,
min_value (j) is minimum value of the relative scores in the observed category j,
rel_score (i,j) is relative score of the scenario i in the observed category j.

The Individual Electrical Factor (IEF) represents different categories (in relative values). When those categories are weighted by according weighting factors and summed, they will form the Overall Electrical Factor (OEF). For example, IEF 4 is the individual electrical factor that represents the number of critical branches where a violation of the N-1 criterion was identified.

Table 6.9 – Relative (normalized) values - All topologies summary (STEP 2)

CRITERIA / TOPOLOGY		**IEF**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
N CRITERION *(Violation: branch loading ≥ 90% Sn)*	Number of scenarios with a criterion violation	IEF1	0	0	0	0	0
	Number of critical branches identified	IEF2	0	0	0	0	0
N-1 CRITERION *(Violation: branch loading ≥ 90% Sn)*	Number of scenarios with a criterion violation	IEF3	0	0	0	0	0
	Number of critical branches identified	IEF4	7.6	3.5	10	6.4	0
N-2 CRITERION *(Violation: branch loading ≥ 100% Sn)*	Number of scenarios with a criterion violation	IEF5	0	0	0	0	10
	Number of critical branches identified	IEF6	7.5	8.4	10	7.2	0

Step 3 implies defining electrical weighting factors. Identical weighting factor is given to C1, C3, and C5 refer to the number of scenarios with violations. For the number of critical branches identified, a higher ratio is given in order to give importance to the results of security analyses. However, the highest importance is given to the results of N-1 analysis (30%), due to the fact that in all of these preventive scenarios, it is the most likely security criterion to take place. N-1 criterion is also the most relevant for purposes of strategical and operational planning [24]. Electrical weighting factors are given in Table 6.10.

Table 6.10 – Defining the electrical weighting factors (STEP 3)

CRITERIA / WEIGHTING FACTOR		**Individual electrical factor**	**Electrical weighting factor**	**Overall Electrical factor**
		IEFi	**Ci [%]**	**OEF**
N CRITERION *(Violation: branch loading ≥ 90% Sn)*	Number of scenarios with a criterion violation	IEF1	C1 = 10%	OEF = ∑ IEFi * Ci
	Number of critical branches identified	IEF2	C2 = 20%	
N-1 CRITERION *(Violation: branch loading ≥ 90% Sn)*	Number of scenarios with a criterion violation	IEF3	C3 = 10%	
	Number of critical branches identified	IEF4	C4 = 30%	
N-2 CRITERION *(Violation: branch loading ≥ 100% Sn)*	Number of scenarios with a criterion violation	IEF5	C5 = 10%	
	Number of critical branches identified	IEF6	C6 = 20%	

Step 4 implies applying electrical weighting factors (Table 6.10) on normalized values (The Individual Electrical Factor (IEF) represents different categories (in relative values). When those categories are weighted by according weighting factors and summed, they will form the Overall Electrical Factor (OEF). For example, IEF 4 is the individual electrical factor that represents the number of critical branches where a violation of the N-1 criterion was identified.

Table 6.9), according to OEF column from Table 6.10. The goal is to calculate the overall electrical factor (OEF) for each scenario. Overall electrical factor represents relative score between considered scenarios. For each topological scenario OEF is consisted of six (6) individual electrical factors (IEF) which are summed as showed in the table below.

Table 6.11 – Evaluation matrix for system analysis (STEP 4)

SCENARIO	IEF1	IEF2	IEF3	IEF4	IEF5	IEF6	Overall electrical factor	RANK
Scenario 1	0	0	0	2.294	0	1.505	3.80	2
Scenario 2	0	0	0	1.059	0	1.695	2.75	4
Scenario 3	0	0	0	3	0	2	5.00	1
Scenario 4	0	0	0	1.941	0	1.448	3.39	3
Scenario 5	0	0	0	0	1	0	1.00	5
Weighting factor	10%	20%	10%	30%	10%	20%	100%	

Scenario 1: PST on OHL 220 kV Mostar - Zakučac
Scenario 2: PST on OHL 220 kV Prijedor - Sisak
Scenario 3: PST on OHL 220 kV Prijedor - Međurić
Scenario 4: PST on OHL 220 kV Gradačac - Đakovo
Scenario 5: PST on OHL 220 kV Tuzla - Đakovo

Since the absolute numbers (counting violations) are the same for EF1-3, the weighted results have a minimal score – zero (0). Final result for system analyses is that scenario 3 (OHL 220 kV Prijedor - Međurić) has the best weighted score and therefore least violates network security. Scenario 1 (OHL 220 kV Mostar - Zakučac) is the second best with almost the same weighted score as topological scenario 4 (OHL 220 kV Gradacač - Đakovo). Topological scenario 5 (OHL 220 kV Tuzla - Đakovo) has the smallest weighted score and therefore most violates network security for considered criterions.

It is interesting to observe that the final results for scenarios 2 and 3, with the PST installation in the same substation (SS Prijedor), have a different overall score and ranks.

6.8.5. Interoperability Factor

As more thoroughly described in Chapter 6.5.4, the term „interoperability“ is introduced to give importance to the possibility of using the PST on other lines in the same substation, by strategically installing the PST "behind" the bus bars as shown in Figure 6.13, and for providing the necessary galvanic connections in order to perform this functionality.

The interoperability potential is given as a number of lines the PST could potentially be connected to in real case scenarios. Note that the interoperability factor is given in accordance to the substation, not the line.

Interoperability possibility “YES” was assigned to all lines that have operational legitimacy to be used as an alternative to the nominal scenario. The possibility “NO” was assigned to lines connecting the substation to generating units, where the PST would have no operational functionality. In some specific cases, such as the unavailability of the line, or for any other justified reason or set of reasons, the possibility “NO” can be assigned.

For each substation, the "YES" are counted and the result is put in the column "Operational Interoperability". It gives the referent evaluation for the Interoperability Factor, to be used in the final evaluation and are shown in Table 6.12.

Table 6.12 – Interoperability Factor evaluation

Substation	Overhead line	Total number of lines	Interoperability possibility	Interoperability Factor
Mostar	Mostar 4 - PHE Čapljina (1)	6	NO	4
	Mostar 4 - PHE Čapljina (2)		NO	
	Mostar 4 - RP Mostar 3 (1)		YES	
	Mostar 4 - RP Mostar 3 (2)		YES	
	Mostar 4 - Zakučac (HR)		YES	
	EAL - Mostar 4		YES	
Prijedor	Bihać 1 - Prijedor 2	5	YES	5
	Jajce 2 - Prijedor 2		YES	
	Prijedor 2 - Međurić (HR)		YES	
	Prijedor 2 - Mraclin (HR)		YES	
	Prijedor 2 - RP Kakanj		YES	
Tuzla	TE Tuzla - Đakovo (HR)	5	YES	4
	Gradačac - TE Tuzla		YES	
	TE Tuzla - Tuzla 4 (1)		YES	
	TE Tuzla - Tuzla 4 (2)		YES	
	TE Tuzla (G6) -Tuzla 4 (3)		NO	
Gradačac	TE Tuzla - Đakovo (HR)	2	YES	2
	Gradačac - TE Tuzla		YES	

6.8.6. Double Lines Factor

As more thoroughly described in Chapter 6.5.5.7, a key factor that adds value to the PST installation is the existence of double lines. The main reason for this is the practical functionality of having a power flow controlling device on one circuit when performing maintenance on the other system.

The Double Line Factor is a sum of double circuits that exist within the evaluated substation. Table 6.13 gives the referent evaluation for double line factor, to be used in the final evaluation.

Note that the Double Lines Factor is given with accordance to the substation, not the line.

Table 6.13 – Age Factor evaluation

Substation	Overhead line name	Double lines existance	Double Lines Factor
Mostar	Mostar 4 - PHE Čapljina (1)	YES	2
	Mostar 4 - PHE Čapljina (2)		
	Mostar 4 - RP Mostar 3 (1)	YES	
	Mostar 4 - RP Mostar 3 (2)		
	Mostar 4 - Zakučac (HR)	NO	
	EAL - Mostar 4	NO	
Prijedor	Bihać 1 - Prijedor 2	NO	1
	Jajce 2 - Prijedor 2	NO	
	Prijedor 2 - Međurić (HR)	YES	
	Prijedor 2 - Mraclin (HR)		
	Prijedor 2 - RP Kakanj	NO	
Tuzla	TE Tuzla - Đakovo (HR)	NO	1
	Gradačac - TE Tuzla	NO	

	TE Tuzla - Tuzla 4 (1)	YES	
	TE Tuzla - Tuzla 4 (2)		
	TE Tuzla (G6) -Tuzla 4 (3)	NO	
Gradačac	TE Tuzla - Đakovo (HR)	NO	0
	Gradačac - TE Tuzla	NO	

6.8.7. Interconnector Factor

The interconnector factor quantifies the number of interconnectors in the substation analyzed for PST installation, giving accent to the regional impact, as well as to additional regional interoperability. The factor is compound of a sum of interconnectors in specific substations.

Note that the Interconnector Factor in Table 6.14, is given with accordance to the substation, not the line.

Table 6.14 – Interconnector Factor evaluation

Substation	Overhead line name	Interconnector factor
Mostar	Mostar 4 - PHE Čapljina (1)	1
	Mostar 4 - PHE Čapljina (2)	
	Mostar 4 - RP Mostar 3 (1)	
	Mostar 4 - RP Mostar 3 (2)	
	Mostar 4 - Zakučac (HR)	
	EAL - Mostar 4	
Prijedor	Bihać 1 - Prijedor 2	2
	Jajce 2 - Prijedor 2	
	Prijedor 2 - Međurić (HR)	
	Prijedor 2 - Mraclin (HR)	
	Prijedor 2 - RP Kakanj	
Tuzla	TE Tuzla - Đakovo (HR)	1
	Gradačac - TE Tuzla	
	TE Tuzla - Tuzla 4 (1)	
	TE Tuzla - Tuzla 4 (2)	
	TE Tuzla (G6) -Tuzla 4 (3)	
Gradačac	TE Tuzla - Đakovo (HR)	1
	Gradačac - TE Tuzla	

6.8.8. Throughput Factor

The throughput factor presents a quantification of weak lines in each analyzed substation, as explained in Chapter 6.5.5.9. The ampacity for each line is evaluated, that value is then normalized (first normalization) with regard to the most common conductor used for 220 kV transmission overhead lines – ACSR STARLING (Al/Fe 360/57), with a capacity of 790 A. The ratio values within a substation are then summed and a second normalization is performed in order evaluate meaningful and comparable values, with the following set of formulas:

$$TR = \frac{\sum_{i=1}^{N} \frac{CC_i}{AC}}{\mathrm{N}}$$

$$TCF = \frac{\text{max value (TR)}}{\text{TR}}$$

where:

CC – OHL Current Capacity
AC – Average Capacity (in this analysis AC = 790 A)
N – Total number of lines in a substation
TR – Throughput Ratio
TCF – Throughput Capacity Factor

Therefore, the substation with the weakest set of lines (from the point of view of ampacity) is evaluated with a maximum score. In other words, substations with TCF with the highest rating (in this case Gradačac and Tuzla with 1.67) refers to substations that have the lowest capacity of the lines. Gradačac and Tuzla have only ACSR STARLING lines (790 A Capacity), while Prijedor and Mostar have several lines with higher capacities (1580 and 1290 A). Thus, the aforementioned formulas give a generalized quantification of the weak lines, by prioritizing substation according to the Average Capacity (in this case 790 A).

Note that the Throughput Capacity Factor in Table 6.15, is given in accordance to the substation, not the line.

Table 6.15 – Throughput Capacity Factor evaluation

Substation	**Overhead line name**	**Conductor type**	**Current Capacity *(A)***	**Ratio**	**Sum**	**Throughput Capacity**
Mostar	Mostar 4 - PHE Čapljina (1)	2 x Al/Fe 360/57	1580	2	10.00	1.00
	Mostar 4 - PHE Čapljina (2)	2 x Al/Fe 360/57	1580	2		
	Mostar 4 - RP Mostar 3 (1)	Al/Fe 360/57	790	1		
	Mostar 4 - RP Mostar 3 (2)	2 x Al/Fe 360/57	1580	2		
	Mostar 4 - Zakučac (HR)	Al/Fe 360/57	790	1		
	EAL - Mostar 4	2 x Al/Fe 360/57	1580	2		
Prijedor	Bihać 1 - Prijedor 2	Al/Fe 360/57	790	1	5.63	1.48
	Jajce 2 - Prijedor 2	Al/Fe 360/57	790	1		
	Prijedor 2 - Međurić (HR)	Al/Fe 360/57	790	1		
	Prijedor 2 - Mraclin (HR)	Al/Fe 360/57	790	1		
	Prijedor 2 - RP Kakanj	2 x Al/Fe 240/40	1290	1.63		
Tuzla	TE Tuzla - Đakovo (HR)	Al/Fe 360/57	790	1	5.00	1.67
	Gradačac - TE Tuzla	Al/Fe 360/57	790	1		
	TE Tuzla - Tuzla 4 (1)	Al/Fe 360/57	790	1		
	TE Tuzla - Tuzla 4 (2)	Al/Fe 360/57	790	1		
	TE Tuzla (G6) -Tuzla 4 (3)	Al/Fe 360/57	790	1		
Gradačac	TE Tuzla - Đakovo (HR)	Al/Fe 360/57	790	1	2.00	1.67
	Gradačac - TE Tuzla	Al/Fe 360/57	790	1		

6.8.9. Age Factor

The Age Factor presents a quantification of weak lines in each analyzed substation, as explained in Chapter 6.5.5.9. This parameter accounts for the age of the lines, within the following age groups:

- Age group 1: 0 – 20 years
- Age group 2: 21 – 30 years
- Age group 3: 31 – 40 years
- Age group 4: 40 years and older

In order to highlight the substation with the oldest set of overhead lines, a weighting factor is applied to give more importance to older lines. The following weighting factors are applied to this category (

Table 6.16). The results are presented in Table 6.17.

Table 6.16 – Weighting of Age Factor

Age group categories	Age weighting factor
Age group 1	10 %
Age group 2	20 %
Age group 3	30 %
Age group 4	40 %
Sum	100 %

Note that the Age Evaluation Factor in Table 6.17, is given in accordance to the substation, not the line.

Table 6.17 – Age Factor evaluation

Substation	Overhead line name	Conductor age	Age group 1	Age group 2	Age group 3	Age group 4	Age factor
Mostar	Mostar 4 - PHE Čapljina (1)	40	0	0	3	3	2.1
	Mostar 4 - PHE Čapljina (2)	40					
	Mostar 4 - RP Mostar 3 (1)	42					
	Mostar 4 - RP Mostar 3 (2)	43					
	Mostar 4 - Zakučac (HR)	42					
	EAL - Mostar 4	39					
Prijedor	Bihać 1 - Prijedor 2	41	2	0	0	3	1.4
	Jajce 2 - Prijedor 2	15					
	Prijedor 2 - Međurić (HR)	50					
	Prijedor 2 - Mraclin (HR)	15					
	Prijedor 2 - RP Kakanj	50					
Tuzla	TE Tuzla - Đakovo (HR)	21	2	1	0	2	1.2
	Gradačac - TE Tuzla	16					
	TE Tuzla - Tuzla 4 (1)	19					
	TE Tuzla - Tuzla 4 (2)	48					
	TE Tuzla (G6) -Tuzla 4 (3)	41					
Gradačac	TE Tuzla - Đakovo (HR)	21	1	1	0	0	0.3
	Gradačac - TE Tuzla	16					

6.8.10. Operational Experience

Operational Experience Factor is obtained from facts mentioned in Chapter 6.5.5. Namely, upon the analysis of the realized PST installations in Europe, for the last two decades, it is concluded that the final location was determined by experience. Therefore, a certain degree of pertinence can be given to the experience of operational engineers in charge of running the system.

A questionnaire was given to experienced engineers (including current and former dispatch center operational engineers with extensive knowledge of power systems of Croatia and Bosnia-Herzegovina). Each was asked to rank the five (5) scenarios with 1-5 points (5 points for the best scenario, 1 point for the least favorable). The aggregated values are presented in Table 6.18.

A short explanation was given to the engineers prior to handing the questionnaire, but the results of the performed analyses were not presented to the examinees. A total of [10] experts filled the questionnaire anonymously. The questionnaire form is given in Appendix [F].

Note that the Operational Experience Factor in Table 6.18, is given in accordance to the PST installation scenario, not the substation.

Table 6.18 – Operational Experience Factor evaluation

Scenario	Line	Operational Experience Factor
Scenario 1	PST on OHL 220 kV Mostar - Zakučac	38
Scenario 2	PST on OHL 220 kV Prijedor - Sisak	32
Scenario 3	PST on OHL 220 kV Prijedor - Međurić	34
Scenario 4	PST on OHL 220 kV Gradačac - Đakovo	21
Scenario 5	PST on OHL 220 kV Tuzla - Đakovo	25

6.8.11. Final Assessment of the Analyzed Scenarios

All previously described relative scores for each observed category were placed in the final evaluation matrix, describing the influence of PST installation in each of the selected scenarios.

The evaluation matrix is composed of the following categories:

- Category 1 - Overall Electrical Factor (Chapter 6.8.4),
- Category 2 - Interoperability Factor (Chapter 6.8.5),
- Category 3 - Double Lines Factor (Chapter 6.8.6),
- Category 4 - Interconnector Factor (Chapter 6.8.7),
- Category 5 - Throughput Factor (Chapter 6.8.8),
- Category 6 - Age Factor (Chapter 6.8.9), and
- Category 7 - Operational Experience Factor (Chapter 6.8.10).

In order to mutually compare all topological scenarios and observed categories, relative scores in each category were transposed to a certain number of points (between 0 and 10), by using the following procedure:

- the minimum value of a relative score in each observed category would bring 0 points,
- the maximum value of a relative score in each observed category would bring 10 points,
- scenarios with relative scores between zero and maximum value are awarded points calculated by assuming a linear relationship between zero and maximum relative scores, according to the following expression:

$$Points\ (i,j) = \frac{10}{\max\_value(j) - \min\_value(j)} * rel\_score\ (i,j) - \frac{10 * \min\_value(j)}{\max\_value(j) - \min\_value(j)}$$

where:

i is the number of analyzed topological scenario (i = 1 to 5; topology 1…topology 5),
j is the number of the observed category (j=1 to 7; category 1…category 7),
max_value (j) is maximum value of the relative scores in the observed category j,
min_value (j) is minimum value of the relative scores in the observed category j,
rel_score (i,j) is relative score of the topological scenario i in the observed category j.

Table 6.19 – Evaluation matrix with relative scores

Evaluation Matrix (relative scores)	**Category 1**	**Category 2**	**Category 3**	**Category 4**	**Category 5**	**Category 6**	**Category 7**
Scenario 1	rel_score (1,1)	rel_score (1,2)	rel_score (1,3)	rel_score (1,4)	rel_score (1,5)	rel_score (1,6)	rel_score (1,7)
Scenario 2	rel_score (2,1)	rel_score (2,2)	rel_score (2,3)	rel_score (2,4)	rel_score (2,5)	rel_score (2,6)	rel_score (2,7)
Scenario 3	rel_score (3,1)	rel_score (3,2)	rel_score (3,3)	rel_score (3,4)	rel_score (3,5)	rel_score (3,6)	rel_score (3,7)
Scenario 4	rel_score (4,1)	rel_score (4,2)	rel_score (4,3)	rel_score (4,4)	rel_score (4,5)	rel_score (4,6)	rel_score (4,7)
Scenario 5	rel_score (5,1)	rel_score (5,2)	rel_score (5,3)	rel_score (5,4)	rel_score (5,5)	rel_score (5,6)	rel_score (5,7)
Minimum value	min_value (1)	min_value (2)	min_value (3)	min_value (4)	min_value (5)	min_value (6)	min_value (7)
Maximum value	max_value (1)	max_value (2)	max_value (3)	max_value (4)	max_value (5)	max_value (6)	max_value (7)

The final evaluation matrix is created by transposing the relative scores into the points, as shown in the following figure. By applying the weighting factors which give different significance to each observed category, the overall and final assessment is given as the sum of weighted points for each scenario:

$$Overal\ Assessment\ (i) = \sum_{j=1}^{7} points\ (i,j) * \frac{W_j(\%)}{100}$$

Table 6.20 – Final evaluation matrix with the points

Evaluation Matrix (points)	**Category 1**	**Category 2**	**Category 3**	**Category 4**	**Category 5**	**Category 4**	**Category 5**	**Overall Assessment**
Scenario 1	points (1,1)	points (1,2)	points (1,3)	points (1,4)	points (1,5)	points (1,6)	points (1,7)	Overall Assessment (1)
Scenario 2	points (2,1)	points (2,2)	points (2,3)	points (2,4)	points (2,5)	points (2,6)	points (2,7)	Overall Assessment (2)
Scenario 3	points (3,1)	points (3,2)	points (3,3)	points (3,4)	points (3,5)	points (3,6)	points (3,7)	Overall Assessment (3)
Scenario 4	points (4,1)	points (4,2)	points (4,3)	points (4,4)	points (4,5)	points (4,6)	points (4,7)	Overall Assessment (4)
Scenario 5	points (5,1)	points (5,2)	points (5,3)	points (5,4)	points (5,5)	points (5,6)	points (5,7)	Overall Assessment (5)
Weighting factors (%)	W_1	W_2	W_3	W_4	W_5	W_6	W_7	-

Weighting factors are proposed as follows in Table 6.21:

Table 6.21 – Weighting factor for final assessment

Category	**Weighting factor**
Overall Electrical Factor	60 %
Interoperability Factor	10 %
Double Lines Factor	10 %
Interconnector Factor	5 %
Throughput Factor	5 %
Age Factor	5 %
Operational Experience Factor	5 %

In line with this proposal, the significance is mostly given to the overall electrical factor (60%), while the other six observed factors are equally distributed with a total share of 40%.

Please note that the same set of parameters for Interoperability Factor, Double Lines Factor, Interconnector Factor, Throughput Factor, and Age Factor is given to Scenario 2 and 3 (given in bold in Table 6.22). The reason is that this data set corresponds to substation related factors, and in this case, the substation in question is the same (SS Prijedor).

6.8.12. Final Evaluation Matrix

Concerning the final evaluation matrix, the final relative scores in each observed category for different scenarios are shown in the following table and described in detail in the previous chapters.

Table 6.22 – Relative scores for each analyzed scenario and observed category

Scenario	Overall Electrical impact	Interoperability factor	Double lines factor	Interconnector factor	Throughput factor	Age factor	Operational Experience
Scenario 1	3.80	4	2	1	1	2.1	38
Scenario 2	2.75	**5**	**1**	**2**	**1.48**	**1.4**	32
Scenario 3	5	**5**	**1**	**2**	**1.48**	**1.4**	34
Scenario 4	3.39	2	0	1	1.67	0.3	21
Scenario 5	1	4	1	1	1.67	1.2	25
Minimum value	*1*	*2*	*0*	*1*	*1.00*	*0.3*	*38*
Maximum value	*5*	*5*	*2*	*2*	*1.67*	*2.1*	*21*

The transposition of the relative scores into points by applying weighting factors is presented in the following table.

Table 6.23 – Final evaluation matrix

Scenario	Overall Electrical impact	Interoperability factor	Double lines factor	Interconnector factor	Throughput factor	Age factor	Operational Experience	Overall Assessment	Rank
Scenario 1	7	6.67	10	0	0	10	10	6.86	2
Scenario 2	4.39	10	5	10	7.19	6.11	6.47	5.62	3
Scenario 3	10	10	5	10	7.19	6.11	7.65	9.05	1
Scenario 4	5.97	0	0	0	10	0	0	4.08	4
Scenario 5	0	6.67	5	0	10	5	2.35	2.03	5
Weighting Factor	*60%*	*10%*	*10%*	*5%*	*5%*	*5%*	*5%*	*100%*	

This chapter presents the final result of the performed matrix analysis. It contains the results for 5 scenarios, for a total of seven (7) categories defined in Chapter 6.8.3. Each factor is explained, analyzed and evaluated in Chapters 6.8.4 - 6.8.10, respectively.

Table 6.22 presents the results for each category, where the values are given in normalized form (within each category). However, a second normalization is needed so that appropriate values can be weighted. Therefore, the left part of Table 6.23 presents the final results in normalized form (for each category), while the right part gives the overall (weighted) assessment and rank.

From the rank, it can be observed that the best option is Scenario 3, followed by Scenario 1 and 2. As expected, the Overall Electrical Factor (OEF) has the biggest influence on the final ranking, but when comparing OEF results (Table 6.11) and final results (Table 6.23), it can be seen that the final ranking has changed and that other categories had an impact on the final ranking.

Another important fact is that this methodology allows cross-checking of results. Therefore, if significant differences between similar categories are identified, it can be a signal for re-evaluating the methodology or to introduce new categories (factors).

7. Advanced Conductors Technologies

7.1. Introduction

Aluminum Conductors Steel Reinforced (ACSR) are the most widespread conductors used for overhead lines (OHL). They have been in use for a very long time, have passed extensive testing and finally have proven themselves in electric power systems.

With the deregulation of the electricity markets and open market trade between parties crossing national borders, power lines are becoming more and more loaded in order to transmit the energy from producers to consumers.

At the beginning of the 2000s, two major electricity blackouts happened, one in New York (2003), and another in Germany (2006). In its sequence of events, the New York blackout was caused by a 345 kV transmission line that sagged into trees and tripped.

OHLs have a permissible sag, however when increasing the current, the temperature increases. This causes the conductor to sag below permissible limits, which can be problematic if the vegetation under the overhead line in the corridor is not regularly trimmed, or other objects are in the corridor.

Therefore, engineers started working on High-Temperature Low-Sag (HTLS) conductors that would enable the line to withstand higher temperatures and maintain an allowable sag at the same time.

HTLS conductors are most often used for reconductoring of existing transmission and distribution lines, for use in heavy ice regions, long-span crossing, but also for connecting renewable sources, such as wind power plants.

This chapter consists of a technical overview and comparison of different HTLS conductors and singles out the optimal choice among the presented types. Two specific case studies are then performed, focusing on the previously chosen HTLS conductor type.

7.2. Comparison of Different Types of Conductor Technologies

Generally speaking, OHL conductors can be divided into two categories, the historically older technology, or standard conductors (ACSR), and the advanced technology called High-Temperature Low-Sag (HTLS), which includes [47]:

- Aluminum Conductor Steel Supported (ACSS),
- Gap Aluminum Conductor Steel Reinforced (GACSR),
- Special nickel-iron alloy FeNi36 (Invar),
- Aluminum Conductor Composite Core (ACCC),
- Aluminum Conductor Composite Reinforced (ACCR),
- and others.

Table 7.1 offers an overview of the major differences between the two conductor categories [48].

High-Temperature Low-Sag (HTLS) are conductors capable to withstand high operating temperatures and, therefore, to carry a higher amount of power and/or energy when compared to conventional conductors. The CIGRE Task Force B2.11.03 defines them as conductors designed for applications where continuous operation is about 100°C or as conductors designed to operate in emergency conditions above 150°C [37], [49], [50].

Table 7.1 – Comparison of standard vs. HTLS conductors

	Standard	HTLS
Core	Steel	Reinforced steel Steel alloys Composite materials
Outer Strands	Concentric (round) aluminum wires	Annealed aluminum Aluminum alloys Compact (trapezoid) strand

New composite technology conductors use a core of composite material around which aluminum conductor wires are wrapped. This design results in increased tensile strength and reduced weight. Moreover, together with their higher operating temperatures, composite conductors have reduced sag under high loads [37], [51], [52].

The construction of power lines can be regarded as a multidisciplinary project because of different kinds of tasks that have to be engineered. In this chapter, two comparisons will be made. One can be regarded as electrical, while the second is of a more mechanical nature.

7.2.1. Ampacity vs. Temperature

The key parameter of a conductor is its ampacity. A conductor thermal rating is derived from the ampacity. Thermal ratings relevant for protecting parameters and settings are most usually represented, either in amps (A) or megawatts (MVA).

Different conducting materials tend to have different temperature related properties, thus different ampacity capacities. The mechanical strength of a conductor is of the utmost importance, and material of different structural properties have to be combined in order to get the optimal temperature-to-amps ratio, without compromising mechanical integrity.

Figure 7.1 presents a conductor comparison based on the temperature in function of ampacity. It can be easily concluded that the ACCC conductor achieves the highest ampacity at the coolest operating temperature compared to the other high-temperature capable conductors [53].

Cooler operating temperatures under high load conditions reflect substantial reductions in line losses that can decrease generation requirements, reduce fuel consumption (and associated emissions), and decrease life-cycle costs [53].

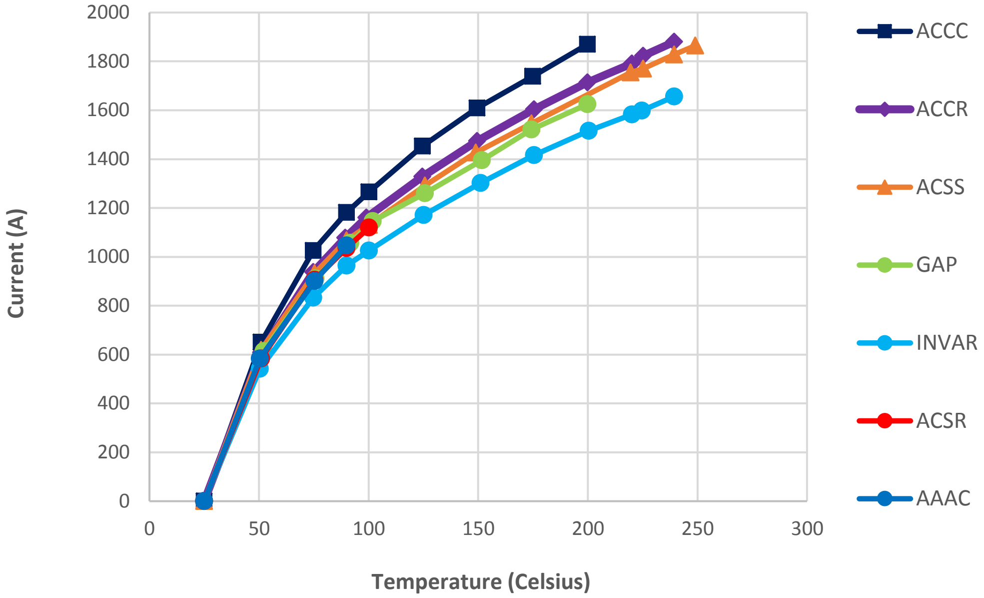


Figure 7.1 – Conductor comparison showing ampacity capabilities [2]

7.2.2. Temperature vs. Sag

A conductor thermal sag comparison (shown in Figure 7.2) was performed, wherein 1600 A of current was run through each conductor type on a 65 meters indoor test span. Note that the ACCC conductor operated at 60° to 80°C was cooler than the other conductors tested under equal load conditions [53], [54].

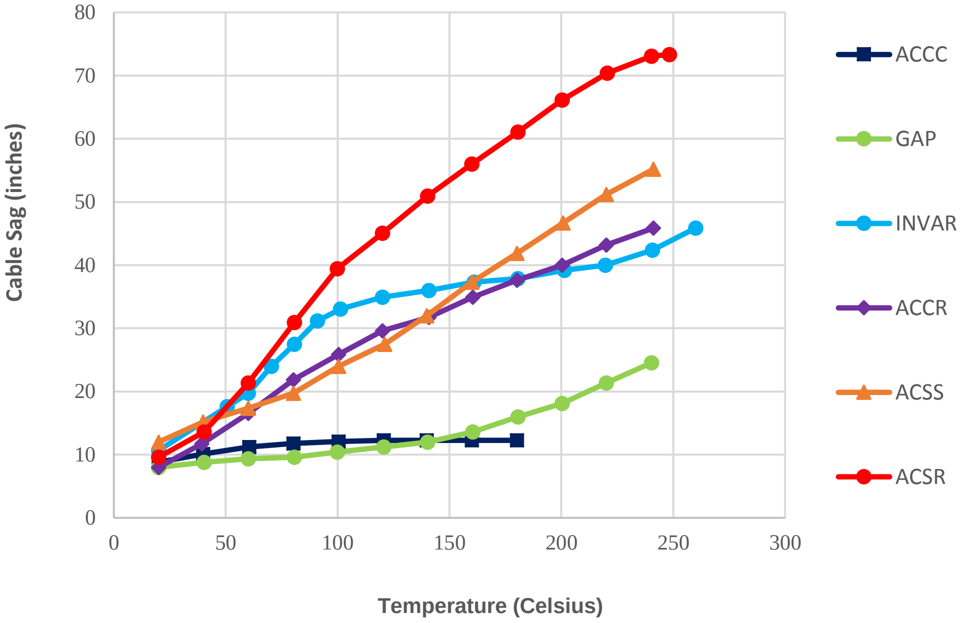


Figure 7.2 – Sag - temperature comparison of several different conductor types [53]

Both ACCC and ACCR are by definition advanced conductor technologies, accomplishing low sag at high temperatures by using composite core technology. The author decided to focus on ACCC, due to better comparisons results, as well as the availability of their manufacturer's (CTC Global) comparison software and compatibility with Siemens PTI's Power System Simulator (PSS-E) database containing the majority of different types of ACCC conductors.

7.2.3. Advantages and Disadvantages of ACCC Technology

This composite strength member provides several advantages [4], [37], [53] [55]:

- It is lighter, the weight saved can be used for more aluminum conductor. ACCC cable uses trapezoidal strands to fit more aluminum into the same cable diameter.
- Softer, fully annealed aluminum can be used for the conductors. ACSR cable uses harder aluminum which contributes to the cable's tensile strength but has about better electrical conductivity.
- It has a much lower coefficient of thermal expansion (CTE) (1.6 ppm/°C) than ACSR (11.6 ppm/°C). This lets the cable be operated at a significantly higher temperature without excessive sag between poles.

The main disadvantages are [4], [37], [53], [55]:

- The primary disadvantage is its cost; ACCC costs 2.5–3 time as much as ACSR cable.
- Although ACCC has significantly less thermal sag than even other HTLS conductor designs, its core is quite elastic and sags more than other designs under ice load, although a higher modulus version is available at a cost premium.
- The conductor has a larger minimum bend radius, requiring extra care during installation.
- The conductor requires special fittings, such as splice and dead-end connections (Figure 7.7).

7.3. Aluminum Conductor Composite Core (ACCC)

Aluminum Conductor Composite Core or ACCC is a type of High-Temperature Low-Sag (HTLS) overhead power line conductor manufactured by more than 20 international conductor manufacturers.

The ACCC conductor consists of a hybrid carbon and glass fiber composite core which utilizes a high-temperature epoxy resin matrix to bind hundreds of thousands of individual fibers into a unified load-bearing tensile member [53].

The composite core is surrounded by aluminum strands to carry electrical current (Figure 7.3). The conductive strands are generally fully annealed aluminum and trapezoidal in shape to provide the greatest conductivity and lowest possible electrical resistance for any given conductor diameter [53].

Figure 7.3 – ACSR (left) and ACCC (right) conductors [5]

ACCCs conductors are rated for continuous operation at up to 180°C (200°C short-term emergency), and operate at a significantly cooler temperature than round wire conductors of similar diameter and weight under equal load conditions. This is due to its increased aluminum content and higher conductivity [3]. Though the ACCC conductor was initially developed as a High-Temperature Low-Sag (HTLS) conductor to increase the capacity of existing transmission and distribution lines with minimal structural changes, its improved conductivity and reduced electrical resistance makes it ideally suited for reducing line losses on new transmission and distribution lines where improved efficiency and reduced upfront capital costs are primary design objectives [55].

7.4. ACCC Investigations

Within the scope of his research of ACCC technology, the author visited the HOPS Regional Office in substation Vrboran, while reconductoring of OHL 110 kV Vrboran – Dujmovača, Vrboran – Meterize and Dujmovača – Meterize was taking place.

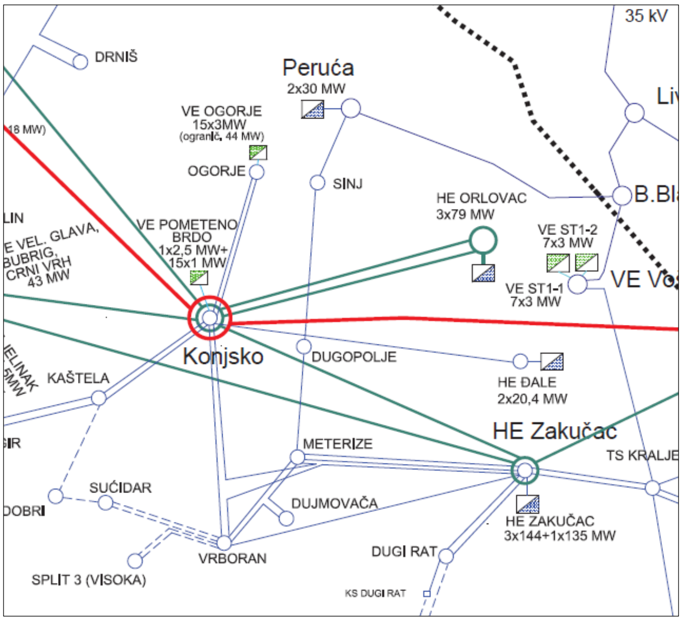


Figure 7.4 – Map of Split region (HOPS network)

While discussing with colleagues from the strategic planning department, as well as operational staff that has been involved with the installation, as well as future use of the new conductor technology, the following experiences were noted:

- The first use of advanced conductor technology in Croatia was on the line Ston – Komolac in 1994. So-called “black conductor” (BTAL / Stalum 154/18) was used in this particular case [56].
- However, with this particular technology, even though the throughput capacity was enhanced, the sag problem remained an issue.
- From that point, extensive research was done about the new technologies available on the market. ACCC emerged as the best solution due to the fact that it has been the most tested in practice.
- Reconductoring of OHL 110 kV Sinj – Meterize – Dugopolje was realized, and the throughput capacity was almost doubled.
- In the case of reconductoring of OHL 110 Vrboran – Dugopolje, the biggest issue was the sag.
- A very important fact that one must not forget is that, in order to increase the throughput capacity of a line, the complete “current path” has to be reinforced. In other words, metering current transformers, bus bars, and circuit breakers have to be reinforced as well, if necessary.
- By the courtesy of the staff and workers on site, the author was given two pieces of the conductors, the old one (ACSR) and the new one (ACCC). As the pieces were long and roughly cut, the author undertook the steps to cut it to a more manageable length. While cutting the pieces by hand, he noticed one interesting fact: even though the diameter was the same, the cut on ACCC required far less time and effort. The reason for that is the fact that aluminum used in ACCC is softer, fully annealed aluminum (as stated in Chapter 7.2.3). This gives ACCC greater electrical conductivity.

Note: More detailed reports made during the visits to substation Vrboran can be found in Appendix [C].

Figure 7.5 – Reconductoring project on OHL 110 kV Vrboran - Dujmovača (HOPS, Croatia).

Figure 7.6 – Reconductoring project on OHL 110 kV Vrboran - Dujmovača (HOPS, Croatia).

Figure 7.7 – Special fittings used for securing the cable ends

7.5. Case Study: Impact of Gradually Replacement of Old Transmission Lines with Advanced Composite Conductors

7.5.1. Introduction

Grid investments are performed by transmission system operators (TSO), and are funded by different sources of incomes, such as tariffs and capacity allocation. It's in their responsibility to present long term network development plans that are then approved by higher bodies, such as regulators. National development plans have to take into account the regional aspirations for a growing need for interconnectors. Very often, in that process the revitalization of old lines is delayed or forgotten.

This case study addresses the issues of equipment aging and proposes a replacement strategy for a cost-effective transition to a modernized power system functioning at improved performance.

After a thorough statistical analysis of [24], and [57], it can be concluded that the transmission grid of Bosnia and Herzegovina (BIH) consist of 279 conductor elements, of which seven 110 kV underground cables.

The majority of 400 kV lines were constructed in the 1970s and 1980s, and accounts for 15 lines. All lines are using 2 bundle ACSR CARDINAL (Al/Fe 490/65 mm2) that can carry 1920 A. Most conductors are in the 10 – 20 age group.

As for the 220 kV voltage level, a total of 41 overhead lines has been constructed mainly in the 1960s and 1970s. Almost 80% of 220 kV conductors are ACSR STARLING (Al/Fe 360/57 mm2), and another 12 % use the same materials, but as two bundles per phase. The permissible currents are 790 A and 1580 A, respectively. The average age is 33 years, and the majority of conductors are in two age groups, 10 – 20, and 40 – 50, respectively. After the first installation in 1957, 20 conductors have been subject to repair, reconstruction or restoration.

For the 110 kV voltage level, a total of 216 overhead lines exist, the greater part built in the period 1950 - 1980 period. Since their initial commissioning, a total of 125 lines have been renovated, some more than 4 times. Roughly 20 lines were restored in such a way what two conductors of different parameters were connected, therefore limiting the throughput capacity of the whole line to the value of the smaller conductor. As it can be observed from Fig. 5, about 50% of lines have surpassed a 30 year lifespan.

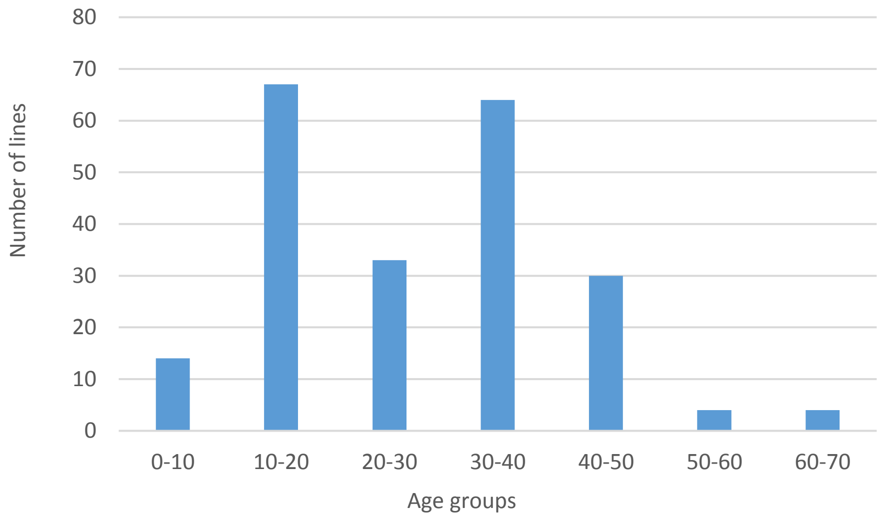


Figure 7.8 – Number of lines per age group for 110 kV

During high load periods, the 110 kV lines can be loaded as high as 85% in normal topology operation. 80% of lines are ACSR HAWK (Al/Fe 240/40 mm2) with a maximum allowed current of 645 A (or 123 MW). Another 15% are ACSR OSTRICH (Al/Fe 150/25 mm2), with an allowed current of 470 A (or 90 MW) [57].

From the statistical data stated above, a conclusion can be made that the 110 kV lines are the oldest ones, and the ones most susceptible to end-of-life failures. Therefore, in the rest of the case study, the attention will be on the replacement and reconductoring of aged 110 kV lines (Figure 7.8).

7.5.2. Line Parameters Comparison

The model will consist of reconductoring all internal 110 kV overhead lines. In other words, cables and interconnectors will not be processed in the modeling of this case study.

All ACSR HAWK lines will be replaced with ACCC LISBON (Table 7.2), while ACSR OSTRICH lines will be reconductored with ACCC OCEANSIDE conductors (see Table 7.3). Due to less perplexing modeling, the remaining 6% of lines which are composed of ACSR FEAL, ACSR WAXWING, 300E-CWC and 250E-CWC will all be replaced with ACCC PASADENA (Table 7.4).

Table 7.2 – Comparison of ACRS HAWK and ACCC LISBON

	ACSR HAWK	**ACCC LISBON**
Diameter (mm)	21.79	21.79
Aluminum area (mm^2)	241.7	315.5
Rated strength (kN)	86.7	103.4
Weight (kg/km)	976	948
AC Resistance at 25°C (ohm/km)	0.1198	0.0910
Ampacity (A)	640	1284
Rating (MVA)	122	244

Table 7.3 – Comparison of ACRS OSTRICH and ACCC OCEANSIDE

	ACSR OSTRICH	**ACCC OCEANSIDE**
Diameter (mm)	17.27	17.27
Aluminum area (mm^2)	152	194.2
Rated strength (kN)	53.8	71.2
Weight (kg/km)	615	590
AC Resistance at 25°C (ohm/km)	0.190	0.1475
Ampacity (A)	490	938
Rating (MVA)	94	178

Table 7.4 – Datasheet for ACCC PASADENA

	ACCC PASADENA
Diameter (mm)	15.64
Aluminum area (mm^2)	154.4
Rated strength (kN)	68.9
Weight (kg/km)	478.1
AC Resistance at 25°C (ohm/km)	0.1929
Ampacity (A)	814
Rating (MVA)	155

The three previous tables present the modeling parameters of the conductors, with characteristic specifications regarding the superiority of ACCC conductors compared to ACSR.

The ACCC conductors used for reconductoring were chosen so that their weight is equal or lower to ACSR conductors, so that it can be supported by existing towers, without the need to invest in new ones.

7.5.3. Parameters of the Analysis

7.5.3.1. Model

The analyses were performed on the merged winter maximum model of South East European transmission systems with moderate transits from east to west. The merged models include transmission grids of Albania, Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Hungary, Macedonia, Montenegro, Romania, Serbia, and Slovenia. This analysis was done using Siemens PSS-E software. The model was created using relevant inputs described in Chapter 3, as well as [24], [9], ENTSO-E Transparency Platform, and ENTSO-E TYNDP Data Set. PSS-E's accompanying software LineProp was used to calculate line parameters for the replaced lines. The Conductor Comparison Program (CPC) database was used for filling necessary LineProp data inputs.

7.5.3.2. Scenarios

Power flows analyses were performed for a total of 8 scenarios:

- **Base Case** - This scenario is the reference case for all further analyses. In this model, all the lines were modeled as ACSR conductors.
- **Scenario 1** - ACSR lines from age group 60-70 were replaced with relevant ACCC conductors.
- **Scenario 2** - ACSR internal overhead lines aged from 50 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 3** - ACSR lines aged from 40 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 4** - ACSR lines aged from 30 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 5** - ACSR lines aged from 20 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 6** - ACSR lines aged from 10 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 7** - ACSR lines aged from 0 to 70 years were replaced with relevant ACCC conductors.

7.5.3.3. Observed parameters

For each scenario, a corresponding data set (positive sequence impedance, admittance, and rating) was updated for each replaced element in the according age groups. A power flow analysis was then performed for each scenario, with a focus on the following results:

- **Lines loadings** – Limit checking reports were evaluated for all modeled 110 kV lines in that scenario.
- **Active power losses** – Area reports were performed and active power losses for the complete power system of Bosnia and Herzegovina were extracted.

7.5.4. Analysis Results

After comparing the differences in input data for appropriate ACSR and ACCC conductors, it can be concluded that only the line resistance is subject to a considerable change. The resistance of ACCC LISBON is 52.5% lower than ACSR HAWK, while the resistance of ACCC OCEANSIDE was 25% lower than ACSR OSTRICH. The reactance and susceptance were not subject of extensive variations, as the geographical disposition of the lines does not change, except for the lower sag.

Due to the fact that the reactance and susceptance remain mostly unchanged, it is important to note that the surge impedance loading (SIL), isn’t subject to change. This can be regarded as an additional advantage, resulting in the fact that the lower loadings will not affect reactive power flows, and therefore will not have an impact on the voltages.

Figure 7.9 shows the observed result of the performed analyses. It presents savings in the average loadings and total losses for each scenario, referenced to the base case.

As more lines get replaced with conductors that have significantly higher throughput capacities, it can be observed that the average loading of the lines, in terms relative to the base case, decreases by 32%.

Also, it should be noted that having decreased lines loadings in regular power flow analyses that were performed in this case study, leads to the conclusion that a significantly lower number of lines will be overloaded when performing contingency analyses.

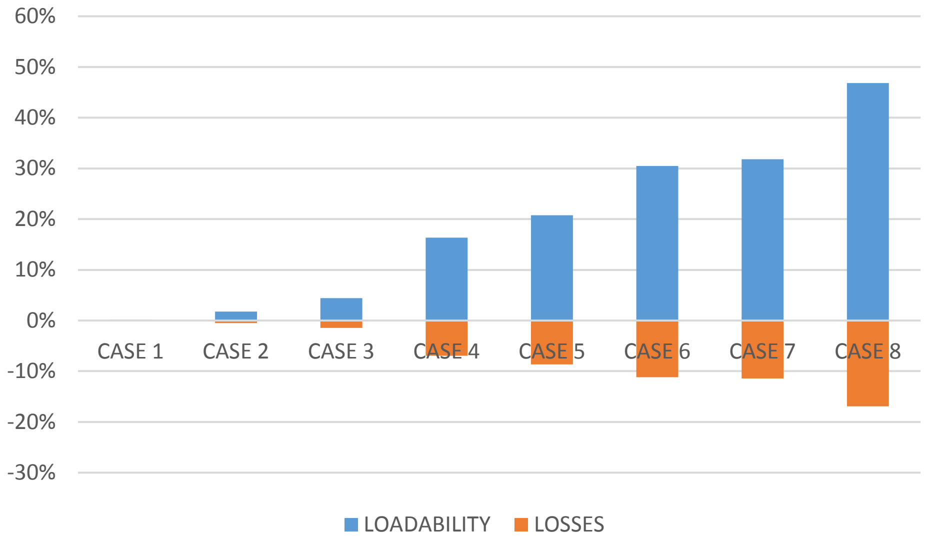


Figure 7.9 – Loadings and losses compared to the base case (accumulated values)

The effect of active power losses reduction can be observed from one scenario to the other, as it can be clearly seen in relative terms (Figure 7.9), as well as in absolute values (Figure 7.10).

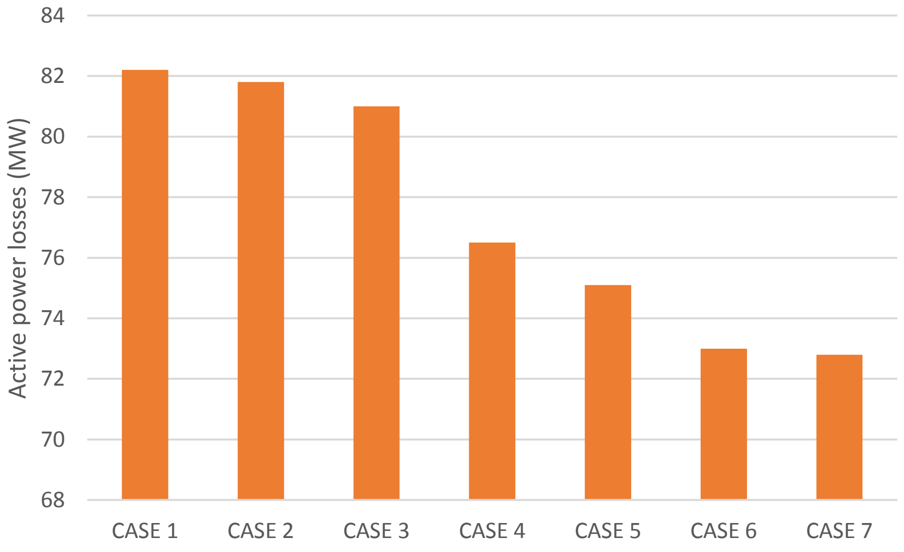


Figure 7.10 – Total active power losses (MW)

In the base case, the total active power losses for the entire transmission system of Bosnia and Herzegovina (composed of 400, 220 and 110 kV) elements, amounts to 82 MW. However, by replacing all 110 kV lines with advances ACCC conductors, additional 9.4 MW of active power losses are saved.

7.5.5. Analysis Conclusion

From this system-wide load flow analysis, that doesn’t even take into account the aspect of time correlation, or in other words, energy savings (MWh), it can be concluded the impact of ACCC conductors on power losses is significant. Active power losses are directly related to the resistance parameter of a line. Once the resistance is decreased, the active power losses are also lowered. It’s exactly what HTLS conductors manage to achieve, therefore the financial savings are noticeable.

Besides that, by reconductoring old lines with advanced conductor technology, such as ACCC, the ampacity of the lines is highly increased, leading to optimal use of existing lines with an extended security margin in cases of contingencies. The newly increased throughput capacity of the lines has an important impact of the ever-growing need for integration of renewable sources, that are most often connected at 110 kV voltage level.

Because of the mentioned benefits, asset managers working for transmission system operators should investigate all the possibilities for the implementation of advanced composite core conductors in their networks [58]. In the future, with the aging of transmission lines, more and more reconductoring projects will be happening worldwide. By investing in superior conductor technologies, a value can be added to the power transmission system, improve its efficiency, without affecting commissioning due to lengthy permitting processes.

7.6. Case Study: ACCC as a Solution for Wind Integration

7.6.1. Introduction

After adopting the EU 20-20-20 legislation set, almost immediately the power system could feel its consequences, as the investments in renewable energy were happening in all ENTSO-E systems. The largest share of new investments in renewable energy sources (RES) was in wind power plans, as well as in solar photovoltaic installations. The most significant problem with the mentioned primary energy sources is their unpredictability which results in an increased need for operating reserves. However, an additional important issue is the necessity to invest in power grids needed to evacuate the energy and deliver it to final consumers.

After the liberalization of the electricity markets, investments in transmission grids have been put into the control of transmission system operators (TSO), which are funded by different sources of incomes, such as tariffs and capacity allocation.

Most new wind power plants (WPP) in Bosnia and Herzegovina’s grid are planned to be connected on existing 110 kV overhead lines. All those lines are type ACSR HAWK that has a rating of 122 MVA. Due to the optimal wind properties, important investments in WPP are planned to be built within close proximity to each other, and the average installed power of each wind park is 50 MVA. Therefore, it can be easily concluded that several plants, in parts of the system with weak lines, operating at maximum capacity can create congestions, and lead to an unstable state of the system, affecting the security of supply of connected customers [2].

In this case study, an alternative to constructing new lines is presented. It consists of reconductoring existing lines with advanced composite conductors. That way, the same corridor can be used, the majority of transmission towers can be restated, and perhaps some repaired or reinforced [2].

7.6.2. Wind energy Investments in Bosnia and Herzegovina

After performing several studies with the aim to study the effect of wind power plants in Bosnia and Herzegovina, it was agreed that a total capacity of 350 MW can be installed without extensive investments into the grid and without further impacting ancillary services [59], [5]. However, in the „paper-collecting“ competition that occurs among potential investors and due to the idleness and conflict of jurisdictions for different government entities, a total of 14 wind power plants successfully finished connection studies, therefore determining the optimal connection to the high voltage transmission grid of Bosnia and Herzegovina. Additionally, investors for 7 wind power plants have expressed their interest. In other words, the total amount of investments in WPP is worth 1,210.7 MW, far exceeding the initially established threshold of 350 MW [9].

As can be seen in Figure 7.11, the most prospective area for investments in wind energy is located in the south and south-west of the country. Of the 14 investments with realized connection studies, 11 are located in the nearest vicinity of each other (in the area near Tomislavgrad) with an aggregated installed capacity of 563 MW (Figure 7.12).

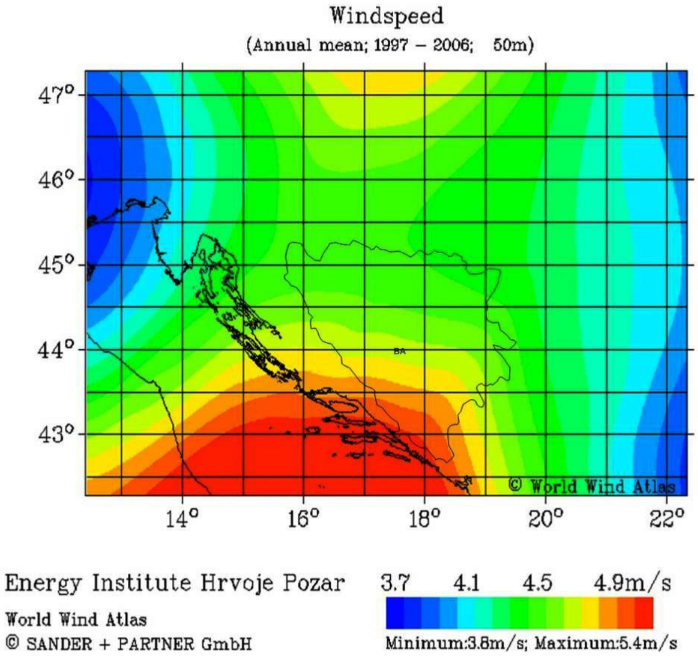


Figure 7.11 – Average wind speeds in Bosnia and Herzegovina [6]

Table 7.5 shows the list of WPPs in the Tomislavgrad area in accordance with the lines there are supposed to be connected to, as a result of appropriate connection studies. The aggregated installed power on lines Tomislavgrad - Livno and Tomislavgrad – Rama far exceeds the installed capacity of the existing lines, making it impossible to realize the investments.

Table 7.5 – List of WPP in Tomislavgrad area in accordance connection study results

WPP	Installed power (∑)	Feeding Line	Type	Capacity
W1, W2	92.2 MVA	Tomislavgrad – Posušje	ACSR HAWK 240/40 mm^2	122 MVA
W3, W4, W5	186.8 MVA	Tomislavgrad – Livno	ACSR HAWK 240/40 mm^2	122 MVA
W6, W7, W8, W9	180 MVA	Tomislavgrad – Rama	ACSR HAWK 240/40 mm^2	122 MVA
W10, W11	104 MVA	Tomislavgrad – Kupres	ACSR HAWK 240/40 mm^2	122 MVA

Therefore, from Table 7.5, Figure 7.11 and Figure 7.12, it can be easily seen and concluded that not all new power plants can be constructed and connected to the existing transmission grid, according to the current state of affairs. Note that W1 – WPP Mesihovina is already constructed and connected on existing line Tomislavgrad – Posušje (See Figure 7.12).

As a conclusion of the connection studies and the proceedings of the connection committee meetings, it is stated that: „based on the status of the previous connections on existing overhead lines, investors might have to perform additional calculations“ (from connection committee reports). In other words, the plans will be subject to changes, depending on the status of WPP investments.

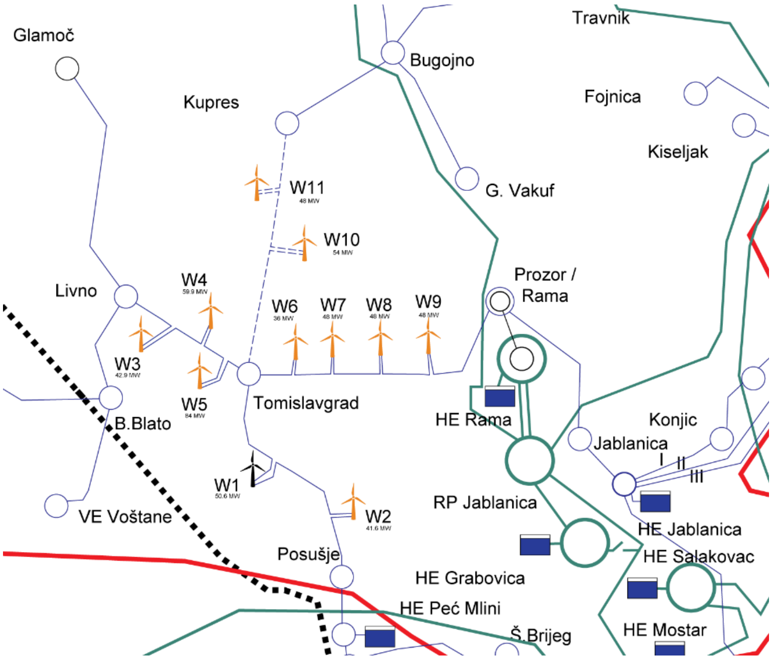


Figure 7.12 – Planned (yellow) wind power plants near Tomislavgrad

However, in this analysis, the author will evaluate the worst possible scenario (i.e. WPP connection according to Table 7.5 and Figure 7.12), in order to analyze the possibility of solving the problem using HLTS conductors.

7.6.3. Parameters of the Analysis

The performed analysis represents one of the worst case scenarios in the future grid of Bosnia and Herzegovina related to the integration of wind energy in the Tomislavgrad area. Namely, the integration of 11 wind power plants with the aggregated installed power of 563 MW is connected on four lines connecting to 110 kV substation Tomislavgrad. Figure 7.13 depicts the relevant elements analyzed in the following model (in accordance with Table 7.5, as well as with Figure 7.12).

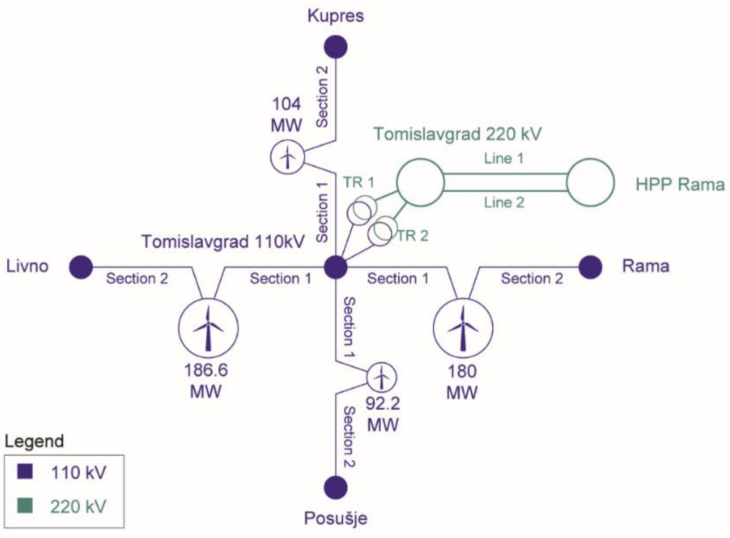


Figure 7.13 – Topology and relevant elements

7.6.3.1. Model

The analysis was performed on the future transmission model of ENTSO-E networks, more specifically, the winter maximum model. This future model comprises of the relevant changes, according to the future development plans submitted by TSOs to ENTSO-E. The model was created using relevant inputs described in Chapter 3, as well as [24], ENTSO-E Transparency Platform, and ENTSO-E TYNDP Data Set. The analysis was performed using Power System Simulator (PSS-E) software. PSS-E's accompanying software LineProp was used to calculate line parameters for the reconductored lines. Conductor Comparison Program (from ACCC's manufacturer) database was used for filling necessary LineProp data inputs.

The following facts and assumptions are taken into account:

- All existing 110 kV lines from Figure 7.12. are type ACSR HAWK.
- In the scenarios including reconductoring, ACSR HAWK is replaced with ACCC LISBON.
- Wind power plants on the four lines are aggregated and represented as one single power source per line, according to values from Table 7.5.
- Hydro power plant Rama is operated at the maximum installed capacity (2 units at 75 MW).

7.6.3.2. Scenarios

The following cases are modeled:

- **Case A** – WPP operating at maximum installed capacity, ACSR conductors in all relevant 110 kV lines.
- **Case B** – WPP operating at maximum installed capacity, ACCC conductors in all relevant 110 kV lines.
- **Case C** – WPP operating at maximum installed capacity, ACSR conductors in 110 kV lines Tomislavgrad – Kupres and Tomislavgrad – Posušje, ACCC conductors in 110 kV lines Tomislavgrad – Livno and Tomislavgrad – Rama.
- **Extension 1** – New single 220 kV ACSR line Tomislavgrad – HPP Rama, with one 110/220 kV power transformer at Tomislavgrad with installed power 150 MVA.
- **Extension 2** – New double 220 kV ACSR line Tomislavgrad – HPP Rama, with two 110/220 kV power transformers at Tomislavgrad with installed power 150 MVA (per transformer).

Cases A - C refers to changes in the 110 kV network, while Extension 1 - 2 refers to modifications in the 220 kV network and its topology.

The following scenarios are subject to analyses and calculations:

- **Base Case** – to determine the flows prior to any changes initialized in the following scenarios,
- **Scenario 1** – Case A,
- **Scenario 2** – Case A + Extension 1,
- **Scenario 3** – Case A + Extension 2,
- **Scenario 4** – Case B,
- **Scenario 5** – Case B + Extension 1,
- **Scenario 6** – Case B + Extension 2,
- **Scenario 7** – Case C,
- **Scenario 8** – Case C + Extension 1,
- **Scenario 9** – Case C + Extension 2.

7.6.4. Analysis Results

Table 7.6 represents the results of the performed analyses, with all scenario results. It gives the loadings of the modeled elements (lines and transformers), according to the above-mentioned cases and scenarios. The term „section“ is introduced and refers to the newly formed lines, from the connection point of the aggregated wind power plants to the existing substations (See Figure 7.12)

The following can be concluded from Table 7.6:

- The result of the base case shows that lines are underloaded prior to wind integration.
- The connection of the WPP on existing lines (Scenario 1) results in overloadings on all the lines. Therefore, as mentioned earlier, this solution would not be possible.
- Scenarios with just one 220/110 kV transformer in Tomislavgrad result in its overloading (Scenario 2, 5, 8), so these solutions would also not be possible.
- The combined scenario (ACCC and ACSR) represented in Scenario 7 also shows overloadings.
- Plausible solutions are scenarios are: Scenario 4, 6 and 9.
- Scenario 4 takes into account the use of existing ACSR lines, with two transformers and two lines. However, it is important to note that some elements are heavily loaded.
- Scenario 6 accounts for reconductoring with ACCC lines, as well as adding two transformers and two lines in Tomislavgrad.
- Scenario 9 accounts for the reconductoring with ACCC conductors of 110 kV lines Tomislavgrad – Livno, and Tomislavgrad – Rama, while using the existing ACSR lines Tomislavgrad – Kupres and Tomislavgrad – Posušje, and at the same time having two 220/110 kV transformers in Tomislavgrad and two 220 kV OHL between Tomislavgrad and HPP Rama.

Table 7.6 – Loadings of analyzed elements
(note: overloadings above 95% are marked as bold)

	OHL 110 kV Tomislavgrad - Posušje		OHL 110 kV Tomislavgrad – Rama		OHL110 kV Tomislavgrad - Kupres		OHL 110 kV Tomislavgrad – Livno		Transformer220/ 110 kV Tomislavgrad		OHL 220 kV Tomislavgrad –HPP Rama	
Element	Section 1	Section 2	Section 1	Section 2	Section 1	Section 2	Section 1	Section 2	Unit 1	Unit 2	Single line	Double line
Base Case	3.1%		14.1%		5.9%		5.4%		/	/	/	/
Scenario 1	23.1%	**97.7%**	13.4%	**132.0%**	18.8%	**103.0%**	31.2%	**112.3%**	/	/	/	/
Scenario 2	26.7%	50.5%	66.2%	74.0%	28.5%	56.0%	88.5%	58.1%	**173.5%**	/	81.5%	/
Scenario 3	26.7%	50.5%	66.2%	74.0%	28.6%	56.0%	88.5%	58.1%	86.8%	86.8%	40.8%	40.8%
Scenario 4	10.5%	48.3%	9.0%	64.7%	14.4%	57.0%	20.1%	55.7%	/	/	/	/
Scenario 5	13.8%	25.2%	34.0%	36.8%	14.0%	29.6%	44.9%	28.7%	**175.5%**	/	82.5%	/
Scenario 6	13.8%	25.2%	34.0%	36.8%	14.0%	29.6%	44.9%	28.7%	87.8%	87.8%	41.3%	41.3%
Scenario 7	22.7%	**98.0%**	6.2%	67.0%	18.4%	**103.0%**	18.3%	57.0%	/	/	/	/
Scenario 8	26.5%	50.6%	33.8%	37.0%	28.4%	56.2%	44.9%	28.8%	**175.5%**	/	82.5%	/
Scenario 9	26.6%	50.6%	33.9%	37.0%	28.4%	56.1%	44.9%	28.7%	87.8%	87.8%	41.3%	41.3%

However, due to the high loadings of specific lines in Scenario 4, the author recommends using either Scenario 6 or 9 in order to perform further analyses.

It is also important to notice the extent to which the cases with ACCC reconductoring projects are positively affecting the loadings of the overhead lines.

7.6.5. Analysis Conclusion

This case study presents some consideration for the implementation of renewable sources in the power system using advanced conductor technologies, based on reconductoring with High-Temperature Low-Sag conductors.

A possible and plausible problem regarding the integration of wind power in Bosnia and Herzegovina in the future transmission grid is presented. The problem is modeled and analyzed, and it comprises of several cases and scenarios that compare the use of existing lines, their reconductoring, as well as adding new elements (transformers and overhead lines). The recommended scenario include reconductoring existing standard lines (ACSR) with High-Temperature Low-Sag conductors of ACCC type. The results show the extent to which ACCC relieves the loading of the lines, by using more aluminum conductor area compared to ACSR conductors. At the same time, ACCC weighs less, therefore allowing the reconductoring project to be realized using the same corridor and towers.

8. Financial Aspects of the Proposed Solutions

8.1. Financial Aspects of PST Technology

In the planning phase, the cost of phase shifting transformers is approximated within the range of 7,000 – 15,000 €/MVA [25]. The range depends on the construction type, as well as the phase angle. The delivery time is 18 – 24 months. The transport costs are in the range of 5-20% of the total investment cost [25]. Table 8.1 gives the comparison of realized PST installations in ELES (Slovenia) and APG (Austria) networks. In the end, the Divača PST was two times more expensive than the maximum range value (mainly due to unfavorable public procurement).

Table 8.1 – Cost comparison of PST in ELES and APG networks

PST	Total price (€)	Total Installed Power (MVA)	€ / MVA
ELES (Divača) (commissioned in 2010)	36,900,000.00	2 x 600 = 1,200	30,750.00
APG PST (Ternitz, Enrsthofen & Tauern) (commissioned in 2006)	30,000,000.00	3 x 600 = 1,800	16,666.67

At the installation site, the foundations need to be excavated and constructed, as well as preparing gantry system for lifting, but also additional buildings usually have to be built. Table 8.2 shows the volume of work in numbers for a typical PST installation, which have to be calculated and added to the final cost [25].

Table 8.2 – Example of volume of work for a typical PST installation [25]

Characteristic		Unit	Quantity
Ground handling	Excavation	m^3	9,200
	Backfilling	m^3	5,200
Concrete		m^3	3,100
Reinforcing bars		kg	200,000
Rails		kg	19,50
Cable trough		m	800
Copper conductors earthing grid		m	5,400
Asphalting		m^2	10,000
LV cables		m	70,000
HV Cables		m	2,400
Metal carpentry		kg	70,000
Man-days		days	4,000

The cost of interoperability as an added functionality also has to be taken into account. In cases when interoperability is important, special steps have to be taken into account in order to achieve it. Interoperability can be realized in a different number of ways. The following picture shows the different setups for PST 400/400 kV Divača – Redipuglia and PST 220/220 kV Padriciano - Divača.

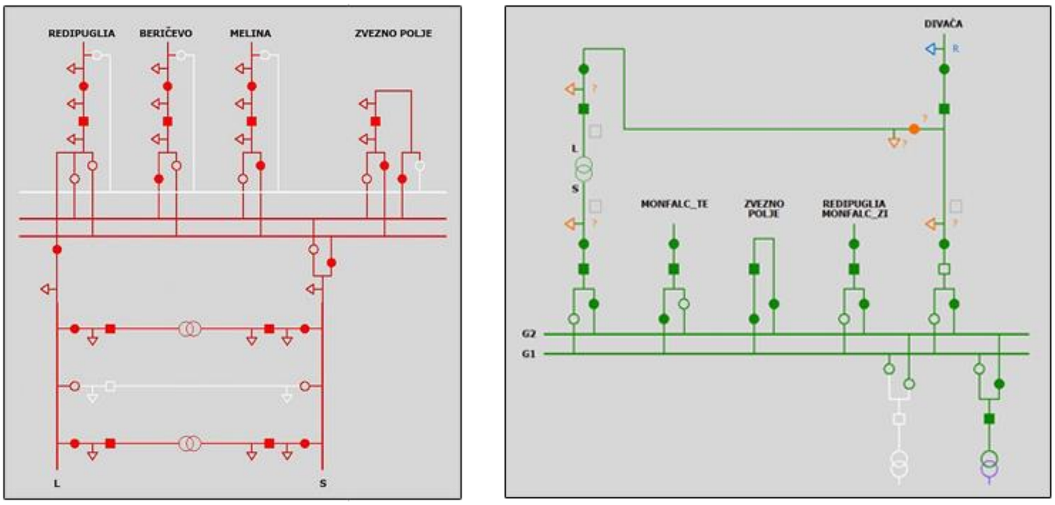


Figure 8.1 – Substation design for Divača – Redipuglia (left) and Divača – Padriciano (right)

It is obvious that the PST setup on Divača – Redipuglia offers several interoperability options, while the other substation design is stiffer, and limits the use of the PST only on the line Padriciano – Divača. Therefore, the interoperability comes at an additional cost.

In order to calculate the investment payback time for a PST installation, detailed market analyses are required. The payback is financed through line losses savings as well as higher revenue from capacity allocation.

8.2. Financial Aspects of ACCC Technology

Financial aspects of ACCC Technology can be divided into the following categories [48], [60], [61]:

- revitalization costs,
- line losses savings,
- financing the revitalization,
- impact on NTC values.

8.2.1. Revitalization Costs

The revitalization or reconductoring of ACSR overhead lines is the process of removing old conductors and equipment, in order to replace it with new HTLS equipment. The revitalization costs can be categorized as:

A) cost of new conductors,
B) cost of dismantling existing conductors,
C) cost of installing new fittings, suspension, and insulators,
D) cost of anti-corrosion protection.

It is important to notice that all of these prices are country-specific and subject to a large number of changes and economic fluctuations. Take for example the price or new HTLS conductors, which are dependent on the wholesale price of aluminum, as well as the stock exchange rate of US Dollars. The manufacture and delivery can take up to 4-6 months, which in the meantime, can affect the final price.

8.2.2. Line Losses Savings

Besides the technical advantages, including the aspect of increasing throughput capacity and having a lower sag, by replacing a line with composite core conductors, another financial advantages are the decreased line losses.

According to line losses formula, $3 \cdot I^2 R$, each line generates losses, depending on the current and the resistance. By using HTLS conductors, and therefore by decreasing the resistance of the line, a decrease of line losses occurs.

The planned lifetime of an overhead line, depending on different factors and evaluation criteria ranges between 30 to 50 years. Consequently, the cumulative line losses savings over a 30 year period, are an important subject when considering the revitalization.

To that end, the financial feasibility of line revitalization is justified by the savings in line losses over the planned lifetime of the line.

8.2.3. Financing the Revitalization

The cost of revitalization can be financed in different ways, from the TSO's own resources, credit funds, or as a combination of the above. In any case, a present discounted analysis has to be performed in order to assess the economic aspects of financing the revitalization.

Present Discounted Value, or simply Present Value (PV) is the value of an expected income stream determined as of the date of valuation. The present value is always less than or equal to the future value because money has interest-earning potential [62].

The present value for the assessment of OHL revitalization has to take account of the following financial parameters:

- interest rate,
- repayment period,
- annuities,
- discount rate,
- grace period.

8.2.4. Impact on NTC Values

Net Transfer Capacity (NTC) is the capacity available for commercial transactions. The NTC value is calculated as follows [63]:

$$NTC = TTC - TRM$$

where,

TTC – Total Transfer Capacity
TRM – Transmission Reliability Margin

In other words, NTC is the maximum allowed transaction possible between two neighboring countries. The capacity varies based on the period of the year, production and consumption, but also on the grid's infrastructure. The maintenance of grid elements, affecting the topology of the grid, can lead to a decreased NTC value, while the investments in expanding the grid, such as new power lines, or reconductoring with new technologies can increase the NTC value.

However, based on experience, an extensive increase of NTC values can only be expected with the revitalization of significant lines on 220 or 400 kV networks.

The funds collected on the account of allocating capacity present a compelling item for budgeting of TSOs. Therefore, the revitalization of significant lines with HTLS conductors can also be justified and financed by NTC funds.

8.2.5. Example

In this chapter, an example of the above financial impacts is given. A cost comparison analysis is given for a 20 km overhead line 110 kV in Bosnia and Herzegovina. In this example, an existing ACSR OSTRICH (Al/Fe 150/25 mm^2) is replaced with a line that has a higher throughput capacity. The two possible options are:

- Building a new line using standard technology ACSR HAWK (Al/Fe 240/40 mm^2) using the existing corridor,
- Revitalizing the existing line, by replacing the conductors and suspension equipment with ACCC ROVINJ.

Table 8.3 – Comparison of conductors

	ACSR OSTRICH	**ACSR HAWK**	**ACCC ROVINJ**
Diameter (mm)	17.27	21.79	17.09
Aluminum area (mm^2)	152	241.7	187.8
Rated strength (kN)	53.8	86.7	71.1
Weight (kg/km)	615	976	576.4
AC Resistance at 25°C (ohm/km)	0.190	0.1198	0.1520
Ampacity (A)	490	640	921

As it can be observed from Table 8.3, ACSR HAWK has a higher weight compared to ACSR OSTRICH, therefore existing towers and suspension equipment can't bear the weight. For that reason, a new line using ACSR HAWK would require new towers, but it would be possible to use the existing corridor.

On the other hand, ACCC ROVINJ has a lower weight than ACSR OSTRICH, allowing it to be used on the existing lines. However, because of ACCC technology, new fittings will have to be installed.

According to [64], the cost of building ACSR HAWK is 97.200 €/km (per three phases), while the dismantling of existing towers, foundations and conductors would cost 25.000 €/km. Therefore, the cost of building a new line using ACSR HAWK would sum up to 2.444.000 €.

The cost of conductor ACCC ROVINJ is 10.000 €/km (per one phase). In order to calculate the total length, one has to account for the following factors:

- geographical length: 3 x 20 km,
- sag,
- reserve.

In practice, the sag and reserve take for 10 % of the geographical length. So, the total length of conductor ACCC ROVINJ would sum up to 66 km. Accordingly, the cost would be 660.000 €.

Besides the mentioned costs of the new conductor, additional costs are given in Table 8.4.

Table 8.4 – Revitalization costs

Conductor	Cost of new conductor	Dismantling existing conductors	Cost of installing new fittings, suspension and insulators	Cost of anti-corrosion protection	TOTAL
	€	€	€	€	€
ACCC ROVINJ	660,000	525,000	180,000	230,000	1,595,000

The costs for both options are given in the following table:

Table 8.5 – Investment costs

Investment	Investment cost
	€
New ACSR HAWK	2,440,000
Revitalization with ACCC ROVINJ	1,595,000

Therefore, it can be seen that the revitalization with HTLS conductors is about 35% cheaper than building a new line, while at the same time increasing the throughput capacity for more than 34 % (according to Table 8.3).

As for the line loss savings, according to the CTC Global Comparison Software, the following load and energy assumptions are used (Table 8.6).

Table 8.6 – Comparison assumptions

Assumption	Value
Line length	20 km
Voltage	110 kV
Total Peak Operating Amps	300 A
Load Factor	20 %
Active Power Losses Price	48.6 €/MWh

It is important to note that the active power losses prices are formed as a market price, based on offer and demand. In this case, the price of 48.6 €/MWh was taken as reference in this example, based on the average losses price for Bosnia and Herzegovina in 2016 [65].

After performing the calculations, the following results are obtained.

Table 8.7 – Comparison results – Yearly

Conductor	Yearly losses		
	MWh	€ *(48.6 € / MWh)*	%
ACSR OSTRICH (Base conductor)	648	31,492.8	100
ACSR HAWK (Option 1)	401	19,488.6	61.9
ACCC ROVINJ (Option 2)	514	24,980.4	79.3

Table 8.8 – Comparison results – 30 Years

Conductor	**30 Years losses**	
	MWh	**Price** ***(48.6 € / MWh)***
	consumption growth = 0.9%	**Interest rate = 6%**
ACSR OSTRICH (Base conductor)	25,512.40	558,998.10
ACSR HAWK (Option 1)	15,787.77	345,923.20
ACCC ROVINJ (Option 2)	20,236.69	443,402.81

In other words, over a 30 year period, compared to the base conductor, ACSR HAWK would earn savings in the amount of 345,923.20 €, while the savings for ACCC ROVINJ would amount to 443,402.81€.

By taking into account the investment costs from Table 8.5 and the calculated 30-years savings, it can be observed that ACCC ROVINJ is the most profitable option.

Table 8.9 – Final Comparison results

Option	**Conductor**	**Investment cost**	**30-years savings**	**Total cost**
		€	**€**	**€**
1	ACSR HAWK	2,440,000	345,923.20	2,094,076.8
2	ACCC ROVINJ	1,595,000	443,402.81	1,151,597.2

8.2.6. Conclusion

The focus of these results is to present, summarize and categorize the financial aspects related to the reconductoring of standard OHL with technologically advanced composite core conductors. The financial impacts are divided into several categories, including; revitalization costs, line losses savings, financing the revitalization, and finally the impact on NTC values. Within the revitalization costs, the most common expenditures are given for reconductoring projects. An important expense for the TSOs are line losses, and it is explained how HTLS conductors can help create savings caused by improved line losses. The financing aspects of the reconductoring are also explained and at the end, it is explained how revitalization with HTLS conductors can potentially help increase the capacity for commercial transactions.

Finally, a detailed example of a reconductoring project is given, defining all relevant costs and items needed to replace an existing ACSR OSTRICH line with the adequate ACCC conductor. An extensive cost comparison is given, proving and justifying the need to invest in the advanced ACCC technology.

9. Development Policies Recommendations

In this chapter, the author gives recommendations to relevant energy-related institution, authorities, and companies in Bosnia and Herzegovina as a group (including ministries, regulators, grid owners, system operator, etc.).

With regard to phase shifting transformers, on the basis of the scope of work undertaken in this thesis, the following recommendation to relevant authorities can be made:

- Prior to committing to PST investments, authorities should investigate the possibility of using topology changes when specific congestions reoccur, as explained in Chapter 6.3.
- The topology changes can be:
  - Redirecting flows by changing the switching state of lines,
  - Redirecting flows by changing the switching state of transformers.
- Drafting specific guidelines (for use in national dispatch center) with regard to the analyzed topology changes.
- When submitting the questionnaire from Appendix [F] to the examinees, an introduction was made and was usually followed by a conversation on the topic of controlling power flows. Several experienced colleagues suggested to analyze and assess the possibility of replacing current power transformers (at the end of their lifetime) with combined autotransformer – phase shifting transformer (like the one in Žerjavinec substation – See Appendix [C]). Namely, the cost is 20-30% higher compared to a normal power transformer, but it gives added value to the stability of the transmission system grid.
- Given the result of the Case Study in Chapter 6.8, it could be said that PST installation can only be justified for preventive control strategies. However, the lines are generally underloaded and given future national and regional development plans, from a financial point of view, the cost of PST installation cannot be easily justified. However, the key factors, as well as the evaluation methodology presented in Chapter 6.7, are generalized and can be used for any PST installation in the system.
- When performing an evaluation methodology of a PST installation, given the specifics of the envisioned scenarios, additional categories can be added in order to fully assess the issue from all the relevant points.

With regard to advanced conductors, more specifically the use of ACCC, the author gives the following facts and recommendations:

- Asset managers are slow to make decisions to replace mature technology with new innovative technology. Usually, assessing the risks of the new technology can be problematic and additional considerations regarding the balance of benefits has to be made. These issues are the topic of [58], which the author recommends as an input to relevant decision makers.
- The revitalization process of old lines is often delayed or forgotten. Relevant institutions should pay special attention to such revitalizations, and regard it as long life assets (40 years plus).
- Performing revitalization of old lines, instead of reconductoring with the same conductor type, the use of advanced conductoring technologies has to be evaluated.
- The integration of renewable energy, especially wind power plants (WPP) in Bosnia and Herzegovina is halted due to: insufficient transmission grid capacity and the required additional regulation reserve funds. The transmission grid near Tomislavgrad will not be able to evacuate the energy produced by all the planned wind turbines. ACCC can be used (at least

in several lines) in order to diminish the issue, but as it explained in the Case study in Chapter 7.6, additional transformation (220/110 kV or 400/110 kV) will have to be introduced.

Regarding increased voltages in the high voltage transmission grid of Bosnia and Herzegovina, the author remarks the following facts:

- Increased voltages are not only a local problem but a regional one.
- Future plans (MONITA cable, Sincro.grid project, consumption growth, etc.) will have a positive impact on the present voltage situation in Bosnia and Herzegovina.
- It could be said that those plans are realistic (with regard to estimated commissioning), but in the case of their failure, the problem remains.
- Therefore, the author urges the authorities to proceed with investments of planned compensation devices in SS Mostar and SS Banja Luka on the 400 kV voltage level.
- Also, the author recommends the installation of Q-U compensation devices in the terminals of newly planned interconnectors: Banja Luka – Lika, as well as the terminal points of the Transbalkan Corridor.

With regard to the financial aspects of the new technologies presented in the thesis, the following remarks and recommendations can be made:

- This thesis presents the key aspects of the proposed innovative technologies, and it gives their initial costs.
- Financial aspects of interest are covered in Chapter 8 and should serve as the basis for further and more detailed analyses.
- In order to determine the financial impacts of PST, detailed regional market analyses have to be performed.
- In order to determine the financial impacts for the use of ACCC, simpler analyses performed on a national level should suffice.

10. Summary

This thesis assesses the resilience of the transmission grid of Bosnia and Herzegovina. In the beginning, a motivation and introduction are given, followed by the research methodology, the research questions and a list of published papers within the scope of performed work.

Details about the current situation in Bosnia-Herzegovina and the region are given. On the basis of those insights, the three following resilience issues are identified:

- increased voltage operating conditions,
- future power flows, and
- wind energy integration.

The details from Chapters 3 and 4 are the basic input for the creation of referent transmission systems models for the examples and case studies in the later stages of the thesis.

In the Chapter "Focusing point for improvement", it is decided to focus on the possible implementations of two advanced transmission technologies: phase shifting transformers (PST) and advanced conductors.

Phase shifting transformers are power flow control devices that can facilitate or block flows. In recent times, a large number is being integrated into the transmission system of ENTSO-E and worldwide. The main advantage of PST technology is that it can affect the power flows on a regional level while being strategically placed in one substation. Thus, the PST technology is further researched, singling out the key factors for the optimal positioning of a PST. The key factors are given from several perspectives: prerequisites for the installation, substation level, and system-wise.

In order to analyze the optimal positioning of a PST installation, an evaluation methodology with weighting factors is proposed. The evaluation methodology is general and quantifies the key factors that were previously identified. This methodology can be used for ranking several scenarios with different PST locations and determining the optimal choice based on selected categories.

A case study is performed, putting the evaluation methodology to the test, on the example of the transmission system of Bosnia and Herzegovina and evaluates five (5) scenarios in a total of sixty (60) analyses.

With regard to advanced conductor technologies, an overview of existing High-Temperature Low-Sag conductors is given, and the optimal technology based on comparison is chosen. Therefore, two additional case studies are then performed with the conductor type - Aluminum Conductor Composite Core (ACCC). The first focuses on the impacts of the revitalization of old transmission lines with ACCC, while the other assesses the impacts of ACCC on the integration of wind energy.

The results of the two independent case studies, performed on the example of Bosnia and Herzegovina, shows that great advantages can be achieved by strategically planning revitalization of lines and that ACCC can make wind integration possible.

The economic aspects of the proposed technologies (PST and ACCC) are summarized, analyzed and presented through examples.

The lessons learned through results and conclusions from the examples and case studies, but also from the proposed evaluation methodology, technology comparison results, visits to realized PST and ACCC projects across the region, results of questionnaire, were then translated into recommendations to relevant entities in charge of drafting, reviewing, and adoption of relevant energy policies.

11. Bibliography

[1] S. Hadžimuratović and L. Fickert, "Determination of Critical Factors for Optimal Positioning of Phase-Shift Transformers in Interconnected Systems," in *Electric Power Engineering Conference*, Brno, May 2018.

[2] S. Hadžimuratović and L. Fickert, "Impact of gradually replacing old transmission lines with advanced composite conductors," in *IEEE PES Innovative Smart Grid Technologies Conference Europe*, 2018.

[3] S. Hadžimuratović, "High-Temperature Low Sag Conductors as a Solution for Increasing Renewable Energy Sources Penetration," in *13th Power Systems Symposium CIGRE Croatian Section*, Rovinj, November 2018.

[4] S. Hadžimuratović, "Financial Impacts of Replacing Old Transmission Lines with Aluminum Composite Core Conductors," in *The International Symposium on Advanced Electrical Power Systems*, 2018.

[5] ECA, KMPG, EIHP,, "Bosnia and Herzegovina: Power Network Analysis for Wind Power Integration and Market Rules Advice," December 2011.

[6] "Law on Transmission of Electric Power, Regulator and System Operator of Bosnia and Herzegovina," Official Gazette BiH, 2002.

[7] "Law Establishing an Independent System Operator for the Transmission System of Bosnia and Herzegovina," Official Gazette BiH, 2004.

[8] "Law Establishing the Company for the Transmission of Electric Power in Bosnia and Herzegovina," Official Gazette BiH, 2004.

[9] Independent System Operator in Bosnia and Herzegovina, "Indicative Generation Development Plan 2019-2028," March 2018.

[10] Independent System Operator in Bosnia and Herzegovina, "Indicative Generation Development Plan 2015-2024," 2014.

[11] Independent System Operator in Bosnia and Herzegovina, "Report on power flows in BiH in 2017," 2018.

[12] Independent System Operator in Bosnia and Herzegovina, "Grid Code," 2016.

[13] "Bosnia and Herzegovina's Action Plan for Renewable Energy," 2017.

[14] Independent System Operator in Bosnia and Herzegovina, "Integration of wind power sources from the aspect of regulation," 2017.

[15] Independent System Operator in Bosnia and Herzegovina, "Integration of wind and solar power sources from the aspect of regulation," 2018.

[16] Parsons Brinckerhoff, "The influence of solar power plants on transmission network," 2014.

[17] State Energy Regulatory Agency, "Connection Rules," 2010.

[18] ENTSO-E, "Ten-year Network Development Plan 2040," ENTSO-E, 2016.

[19] M. Rebolini, G. Lavechia, L. Guizzo and F. Perda, "Submarine cables HV DC&AC in the Mediterranean sea Terna experience," in *First South East European Regional CIGRÉ Conference*, Portoroz, 2016.

[20] M. Ostojic and M. Calasan, "Magnetic Field of the Bipolar HVDS Cable Italy-Montenegro In The See and in The Land Section," in *First South East European Regional CIGRÉ Conference*, Portoroz, 2016.

[21] ELES, HOPS, "Sincro.grid Project," ELES, HOPS, [Online]. Available: https://www.eles.si/en/sincro-grid-project/background.

[22] Independent System Operator in Bosnia and Herzegovina, "Study - Identification of high voltages on the transmission network," 2010.

[23] Energy Institute Hrvoje Požar, "Techno-economic aspects of voltage regulation," 2012.

[24] Elektroprenos BiH, "Bosnia and Herzegovina Ten-year Network Development Plan 2017-2026," 2016.

[25] ENTSO-E, "Workshop on Phase Shifting Transformer Coordination Proceedings," December 2015.

[26] W. Seitlinger, "Phase Shifting Transformers Discussion of Specific Characteristics," in *CIGRE Session 12-306*, 1998.

[27] R. Sweeney, G. Stewart, P. O'Donoghue and P. Gaffney, "he Specification and Control of the Phase Shifting Transformers For The Enhanced Interconnection Between Northern Ireland and The Republic of Ireland," in *CIGRE Session 11-118*, 2002..

[28] IEEE Std C57.135 – 2011, *IEEE Guide for the Application, Specification and Testing of Phase-Shifting Transformers,* IEEE.

[29] T. Overbye and J. W. K. Patten, "Analysis and Visualization of Market Power in Electric Power Systems," in *32nd Hawaii International Conference on System Sciences*, 1999.

[30] A. Polajner, M. Hrast, D. Škamperle and M. Pezdirc, "Installation of Phase shifting transformer in SS Divača," in *CIGRE Slovenia A2-02,*, Ljubljana 2011., 2011.

[31] W. Kling and e. al, "Phase shifting transformers installed in the Netherlands in order to increase available international transmission capacity," in *CIGRE Session C2-207,*, 2004.

[32] J. Rimez, R. V. D. Planken and e. al, "Grid implementation of a 400MVA 220/150kV –15°/+3° phase shifting transformer for power flow control in the Belgian network: specification and operational considerations," in *CIGRE Session A2-202*, 2006.

[33] P. Hurlet, J.-C. Riboud, J. Margoloff and A. Tanguy, "French Experience In Phase-Shifting Transformers," in *CIGRE Session A2-204*, 2006.

[34] E. Carlini, G. Manduzio and D. Bonmann, "Power Flow Control on the Italian network by means of phase-shifting transformers," in *CIGRE Session A2-206*, 2006.

[35] J. Ptacek, P. Modlitba, S. Vnoucek and J. Cermak, "Possibilities Of Applying Phase Shifting Transformers In The Electric Power System Of The Czech Republic," in *CIGRE Session C2-203*, 2006..

[36] M. Eremia, C. Liu and A. Edris, Advanced Solutions in Power Systems, HVDC, FACTS, and Artificial Intelligence, John Wiley & Sons (IEEE Press Series on Power Engineering), 2016.

[37] G. Migliavacca, Advanced Technologies for Future Transmission Grids, 2013: Springer.

[38] S. Curlin and A. Andric, "Power System Losses Optimization with Angle Regulation on TR 400/220 kV in Substation Žerjavinec," in *10th Power Systems Symposium CIGRE Croatian Section*, Opatija, 2012.

[39] I. Ivankovic, B. Filipovic-Grcic and Z. Gajic, "Protection Concept for Combined Autotransformer-Phase Shifting Transformer in Žerjavinec Substation," in *CIGRE B5-05*, Cavtat, 2003.

[40] T. Kelemen, B. Cucic and M. Corak, "Phase Shifting Autotransformer 400 MVA 400/231/(10.5) kV for Substation Žerjavinec," in *CIGRE A2-06*, Cavtat, 2003.

[41] T. Štrumbelj, D. Lenarčič and M. Hrast, "Installing of Phase Shifting Transformers in SS Divača," in *CIGRE Slovenia B3-01*, Ljubljana, 2011.

[42] R. Korab and R. Owczarek, "Application of phase shifting transformers in the tie-lines of interconnected power systems," *Przegląd Elektrotechniczny (ISSN 0033-2097),* vol. 91, no. 8, 2015.

[43] P. Paterni, S. Vitet, M. Bena and A. Yokoyama, "Optimal Location of Phase Shifters in the French Network by Genetic Algorithm," *IEEE Transactions of Power Systems,* vol. 14, no. 1, February 1999.

[44] Energy Institute Hrvoje Požar, "Feasibility Study, Including Social and Environmental Assessment Study, for Strengthening of Main Croatian Transmission North-South Axis Enabling New Interconnection Development - Delivreable 3," Zagreb, 2018.

[45] D. Bajs, " Methods and Criteria in the Revitalization of Power Transmission Networks, PhD Thesis," University of Split, FESB, Split, 2007.

[46] HOPS, "Croatia Ten-year Network Development Plan 2018-2027," 2017.

[47] A. Alawar, E. Bosze and S. R. Nutt, "A Composite Core Conductor for Low Sag at High Temperatures," *IEEE Transactions On Power Delivery,* vol. 20, no. 3, 2005.

[48] Energovod, "Techno-economic analysis of the application of the ACCC conductor on the 110 kV OHL Sinj - Dugopolje – Meterize," 2014.

[49] CIGRE, "Considerations relating to the use of high temperature conductors, Technical Brochure 331," CIGRE , 2007.

[50] CIGRE, "Results of the questionnaire concerning high temperature conductor fittings, Task Force B2.11.032004," CIGRE.

[51] S. Cole, W. V. Hertem and L. Meeus, "Technical Developments for the Future Grid," in *Proceedings of International Conference on Future Power*, November 2005.

[52] Southwire Company, "Southwire Overhead Conductor Manual - Introduction to bare overhead conductors OCM (Overhead Conductor Manual)".

[53] CTC Global Corporation, "ACCC Engineering Manual," 2011.

[54] A. Goel, A. Kamarudin and C. Pon, "New High Temperature Low Sag Conductors," in *NATD Conference & Expo*, May 2005.

[55] A. Kenge, S. V. Dusane and J. Sarkar, "Statistical Analysis & Comparison of HTLS Conductor with Conventional ACSR Conductor," in *International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 2016.

[56] D. Mihalic, V. Ilijanic and I. Pavic, "Revitalization of Old Transmission Lines Using the Conductors of New Technologies," in *First South East European Regional CIGRÉ Conference*, Portoroz, 2016.

[57] Independent System Operator for Bosnia and Herzegovina, "Calculation of electrical parameters for overhead lines," November 2007.

[58] A. Hill and C. FIET, "How do asset managers with long life assets (40 years plus) decide to replace mature technology with new innovative technology? How do they assess the risks and rewards? A case study.".

[59] M. Jonsson, "Firm wind generation hosting capacity in the Bosnia and Herzegovina transmission network," STRI, January 2009.

[60] Energy Institute Hrvoje Požar & Dalekovod Project Zagreb, "Techno-economic analysis of the selection of conductors on OHL 110 kV Obrovac - Zadar," April 2016.

[61] Energy Institute Hrvoje Požar & Dalekovod Project Zagreb, "Techno-economic analysis of the selection of conductors on OHL 2x110 kV Meterize – Dujmovača – Vrboran," January 2016. .

[62] C. Sekhar, Capital Budgeting Decision methods: Payback period, Discounted payback period, Average rate of return, Net present value, Profitability index, IRR and Modified IRR, ISBN 1980203458, , February 2018.

[63] M. Kosarac, A. Carsimamovic, H. Turajlic and C. Vujovic, "A Practical Example of Increasing Net Transfer Capacity (NTC) by Modifying the Power System Topology," CIGRE Cavtat Conference, 2014.

[64] Elektroprenos BiH, "Prices of goods, works, services and normative standards," 2019.

[65] Independent System Operator in Bosnia and Herzegovina, "Report on Auxillary Services and Balance Market Report in Bosnia and Herzegovina for 2016," 2017.

12. List of Figures

13. List of Tables

APPENDIX A
Published Papers

Determination of Critical Factors for Optimal Positioning of Phase-Shift Transformers in Interconnected Systems

Semir Hadzimuratovic
Operational Planning Department
Independent System Operator in Bosnia and Herzegovina (ISO B&H)
Sarajevo, Bosnia and Herzegovina
s.hadzimuratovic@nosbih.ba

Prof. Lothar Fickert
Institute of Electrical Power Systems
Technical University Graz (TU Graz)
Graz, Austria
lothar.fickert@tugraz.at

***Abstract*— Phase-Shifting Transformers (PST) are installed in order to block or facilitate certain power flows. The installation of a single device affects power flows in a wider geographical area. Therefore, determining the optimal location for the Phase Shift transformer is of the utmost importance.**

Firstly, this paper presents summarizes the key factors for the installation of Phase Shift Transformers. Secondly, it give the prerequisites for the installation and finally, and thirdly it determines the deduced critical factors which have to be analyzed from the local (substation level), and global (system-wise) perspective.

Given the necessity for regional approach when determining optimal PST location, this paper focuses on selected results of possibilities for active power flow control using PSTs in the South Eastern Europe (SEE) transmission grid. At the end, in the form a a power flow anaylsis, such an example is presented.

Keywords—Power Shifting Transformer (PST), power flows, optimal positioning

I. INTRODUCTION

The interconnected power system of Europe, operated by European Network of Transmission System Operators for Electricity (ENTSO-E), is probably the biggest man-made system in the world. The entire network consists of 43 electricity transmission system operators (TSO) from 36 countries across Europe, thus extending beyond EU borders.

After the liberalization of the electricity markets, trade has been made possible between countries. However, trade has to comply with physical (technical) limitation of the system and equipment. Due to trade, as well as unplanned activities in the network related to malfunctions in power plants, lines or other elements, significant congestions can occur, that threaten to the stability of the entire system. In the worst case, a major blackout can occur, affecting the power supply of hundred thousands of customers around Europe.

There are various ways to address and retaliate congestions. Most often congestions occur on the interconnecting lines between two different countries or TSOs. The reason for this is the fact that building new interconnectors has become a complex process because of the following reasons:

- In today's society, permitting process is very complicated.
- New corridors are difficult to find.
- Construction takes a long time.
- Costs are very high.
- Process has to be coordinated between neighbors.

The alternative to constructing new lines, is to install active power flow control devices. The most common choice is to install phase shift transformers.

II. PURPOSE, FUNCTION AND TYPES OF PHASE SHIFTING TRANSFORMERS

Basically, a phase shifting transformer (PST) creates a phase shift between the primary (source) and the secondary (load) side [1]. Except for very specific applications, the purpose of this phase shift is usually the control of power flow in a complex network [1].

The equivalent circuit for a PST is given in Fig. 1 and the associated phasor diagram in Fig. 2 [2-3].

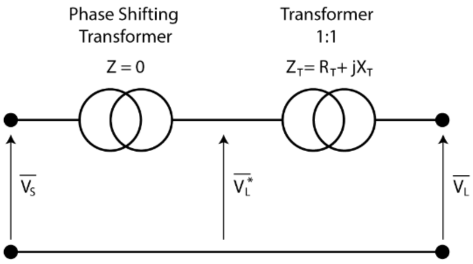


Fig. 1. PST Equivalent Scheme

Where;

$\overline{V_L}^*$ = Load Voltage (No Load)
$\overline{V_L}$ = Load Voltge (Loaded)
Z_T = Transformer Impedance
$\overline{I_L}$ = Load Current
$\overline{V_{S(a)}}$ = Source Voltage (advanced)

$\overline{V_{S(r)}}$ = Source Voltage (retarded)
β = Transformer Load Angle
α = Phase Shift Angle (No Load)
+ Advanced (Leading)
- Retard (Lagging)
α^* = Phase Shift Angle (Loaded)

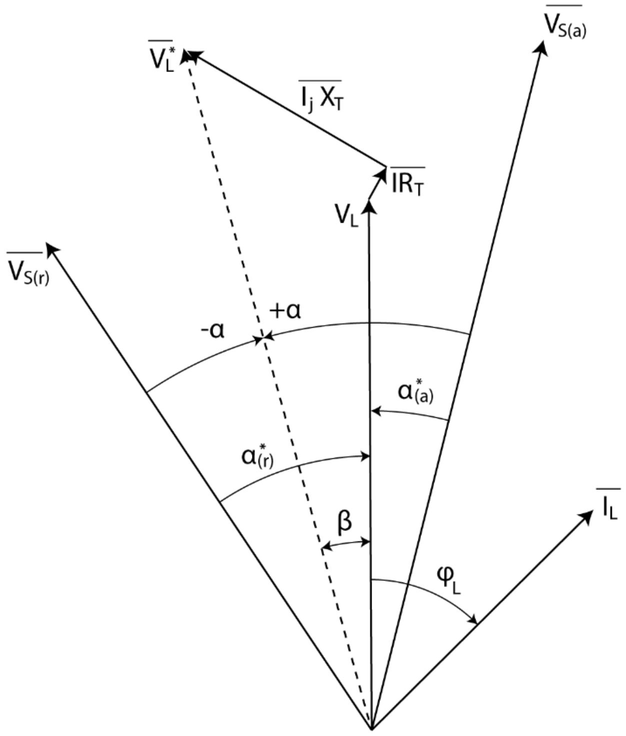


Fig. 2. PST Phasor Diagram

Phase shifting transformers can be classified from different points of view. A phase shifting transformer can be symmetric or non-symmetric, it can be a quadrature or a non-quadrature type, with a single or a dual core design, and finally with a single tank or a dual tank design [1, 3].

Please note that the determination of phase shifting transformer specifications is not the subject of this paper, and therefore will not be addressed any further.

III. PTDF ANALYSIS

Power Transfer Distribution Factors (PTDF) indicate the incremental change in real power that occurs on transmission lines due to real power transfers between two regions [4].

Table I shows the power flow percentage achieved directly between two neighboring control areas for a transaction of 100 MW, for different months in the year. It can be concluded that a significant percentage of power flows, ranging from 25 to 60%, are achieved through surrounding third-part areas, which are unwantingly loaded. The results of PTDF analyses have to be interpreted with regard to the specifics of the network, number of interconnectors, etc… It is important to note that due to unscheduled or unplanned works, these percentages can be subject to further changes.

TABLE I. POWER FLOW PERCENTAGE FOR PTDF CALCULATIONS

	SHB[a]-SMM[b]	**DE-AT**	**DE-FR**	**PL-CZ**	**CZ-AT**
	%	%	%	%	%
January	73.8	39.4	39.1	52.1	45.8
March	77.4	38.3	39.5	45.7	48.8
May	79.2	46.3	40.8	49.4	49.3
July	72.2	46.3	37.6	47.8	38.3
September	75.6	43.4	40	49.5	49.2
November	73.8	39.4	39.1	52.1	45.8
Average	**75.3**	**42.2**	**39.4**	**49.4**	**46.2**

[a] SHB is the control block composed of Slovenia, Croatia, and Bosnia and Herzegovina

[b] SMM is the control block composed of Serbia, Montenegro and Macedonia

Thus, it needs to be said that poor PST location can lead to a further increase of the aforementioned percentages. Poor PST design can also lead to an increasing number of unwanted flows, and create additional loop flows. Also, by taking into account the increasing number of PST installation in the interconnected power system of Europe (ENTSO-E), special caution has to be taken in the harmonization procedure in regional groups prior to the installation.

IV. KEY FACTORS FOR INSTALLATION OF PST

The major reasons for a phase shifting transformer investment, from the point of view of modern transmissions system operator, can be summarized as follows, [4 - 12]:

- To increase efficiency of the existing transmission system.
- To avoid overloading of grid elements.
- To take advantage of existing margins on the network.
- To make interconnections more secure.
- To increase transmission network operation reliability in the electric transmission system.
- To reduce large uncontrolled electric power transit over the electric transmission system.
- To enable larger and controlled electric power flows between the electric transmission system of neighboring systems.
- To reduce the losses in the system resulting from too large and uncontrolled electric power transits.
- To enable greater income from free cross border transfer capacity lease.
- To enable faster and controlled restoration of the network after its potential collapse.

In principle the main control strategies are the following [8]:

- **Curative:** The PST is operated with a small phase shift in normal operating conditions. In case of a sudden line outage, the phase shift is automatically controlled in order to reduce the power flow on the overloaded lines and to avoid a tripping out.
- **Preventive:** The PST is operated with a permanent phase shift which redistributes the power flows in normal operating conditions and avoids stresses on the network in case of a line outage.

V. PREREQUISITES FOR OPTIMAL LOCATION OF PST

When determining the optimal location for a PST, it is necessary to analyze spacious plans from a narrowed selection of substations. Namely, the Phase Shift Transformers require quite a lot of space, especially the dual tank design. Therefore, planners have to take into account that fact, and choose a location according to these results.

Even though it is complicated to generalize the size of a PST, as well as the total area needed for it, with the following example, the authors gives an estimation. For example, the 400 kV, 1200 MVA Phase Shift Transformers located in Divača, for use on the Overhead Line (OHL) 400 kV Divača (SLO) – Redipuglia (ITA) was built on a plateau measuring 115 x 130 m, for a total of 15.000 m^2. The PST in Divača is composed of two units of 600 MW, (each with a dual tank design), and each unit measures 25 x 10 m [13]. The remaining space of the plateau was used to build accompanying buses, as well as to house control, protection, measurement and power equipment.

Fig. 3. Graphical Representation of PST on OHL Divača - Redipuglia

VI. OPTIMAL LOCATION IN A SUBSTATION

Even though the PSTs are represented on geographical representations as if they are located at the end/beginning of a line (Fig. 3), whereas in reality they are located elsewhere (usually behind the bus bars – Fig. 4), mainly because of three reasons:

- **Existing line bays** – Namely, PST are installed historically after the lines. In most cases, line bays are the last entity before the substation fence. So it would be very complicated and ill-advised to install them as they are usually shown on maps (Fig. 3).
- **Space** – As explained in the previous chapter, the first prerequisite for PST is that they are PSTs located where there is enough space. They are then connected galvanically to form an optimal configuration.

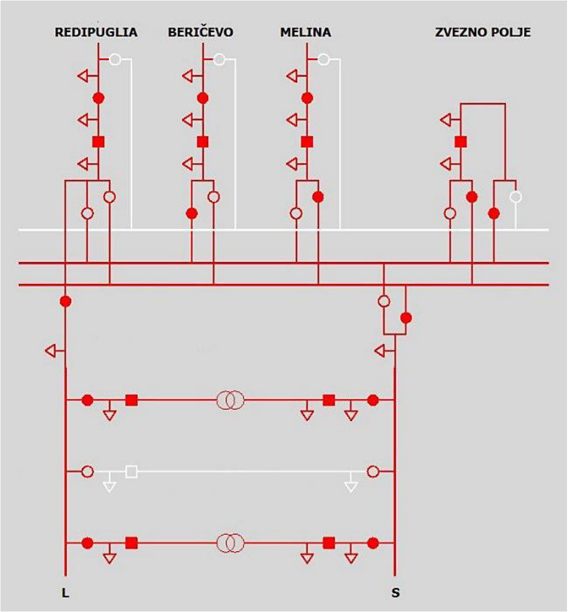


Fig. 4. Single Line Diagram of PST in Substation Divača

- **Interoperability** – Through different switching states, PST can be used for different purposes. For example to help restore the system after a major blackout, or to restrict the flows upon the maintenance of surrounding lines. If PST were located as on the geographical maps, there would be no such possibility. Therefore, by strategically installing the PST "behind" the bus bars (Fig. 4), it is possible to use it on other lines, when such necessity occurs.

In other words, interoperability means that the PST is used with the designated line for most of the time. Nonetheless, on occasions when the flows on that line are not critical (such as night time, or specific period during the year, winter-summer), or in other cases (either preventive or curative), the PST has the possibility to be used to perform other tasks.

VII. OPTIMAL LOCATION IN A POWER SYSTEM

Upon analyzing the installations of European Phase Shifting Transformers in the last two decades [4 - 12, 14], it can be concluded that the final location for the vast majority of devices was determined by experience.

Below are listed the most common criteria that leads to the determination of the optimal location of Phase Shifting Transformers in interconnected systems according to [4 - 12, 14]:

A. *Determination of Network Loadability*

Before committing to the investment of a PST, it is necessary to analyze the loadability of all lines, for different time periods (day, night, winter, summer, maximum, minimum, etc…). Determining this factor should justify following steps for investment in PST.

B. *Determination of Bottlenecks*

Bottlenecks have to be singled out by various power flow analyses, including contingency analyses, Net Transfer Capacity (NTC) analyses, etc…

A simple approach is to insert a phase shifter on each bottleneck line, in order to reduce the flow on these lines. But this “one constraint-one phase shifter” approach is not sufficient, because it leads to creating constraints on new lines, [15]. Therefore, a more detailed analysis is recommended.

C. *Future Network Developments Plans*

Network development plans have to be analyzed in order to check impact of future investments on present bottlenecks. National and regional plans should be taken into account.

D. *Alternative Solutions*

Alternative solutions for present bottlenecks should be analyzed. A possible solution could be the construction of a new line, or replacement of weak lines using new conductor technologies, such as Aluminum Composite Core Conductor (ACCC).

E. *Financial Factors*

Different financial factors should be analyzed at this point. What would be the savings from re-dispatching, capacity allocation, and what would be the pay-off time of such an investment?

F. *Regional Impact*

By their purpose and definition, effects of Phase Shift Transformers go beyond national borders, especially if installed on interconnectors. It is necessary to perform analyses on neighboring systems, as well as to get the project approved by all affected parties.

Other minor factors that can lead to a more efficient usage of Phase Shifting Transformers:

G. *Existance of Double Lines*

Installation of a PST on buses connected to double lines can always be observed as added value. In case of maintenance of one line, using a PST, the flows on the other line can be limited to allowed values.

H. *Increasing PST Capacity*

Experiences from several transmission system operators indicate that increasing PST capacity by up to 5-10% compared to the calculated values, has had a positive effect on future operation and also added value to the system when confronted with severe overloading of lines.

I. *Determination of Weak Spots*

Recommendations from transmission system operators also indicate that it is preferable and beneficial to allocate a PST in a location that has more than one weak line.

VIII. ANALYSIS

A. *Model*

The analysis was performed on the merged winter maximum model of South East European transmission systems with high transits from east to west. The merged models include transmission grids of Albania, Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Hungary, Macedonia, Montenegro, Romania, Serbia and Slovenia. The analysis was performed using Siemens PSS-E software.

A generic PST model for was used from the PSS-E Model Library. The PST was modeled as a 220/220 kV two-winding transformer with a Control Mode set to Active Power (Symmetric design). The throughput capacity was adjusted with regard to the loadability of the line it was placed on.

B. *Scenarios*

After performing a N-1 contingency analysis of the model, it was determined that upon tripping of OHL 400 kV Mostar – Konjsko, OHL 220 kV Mostar – Zakučac becomes overloaded.

Therefore, three more detailed scenarios were analyzed;

- Reference case (Fig. 5)

  Before tripping of OHL 400 kV Mostar – Konjsko.

- Contingency case

  After tripping of OHL 400 kV Mostar – Konjsko.

- Remedial case (Fig. 6)

  After tripping of OHL 400 kV Mostar – Konjsko, a Phase Shifting Transformer is installed on OHL 220 kV Mostar – Zakučac. The permitted flow through the PST is adjusted to 92 % of existing line thermal rating.

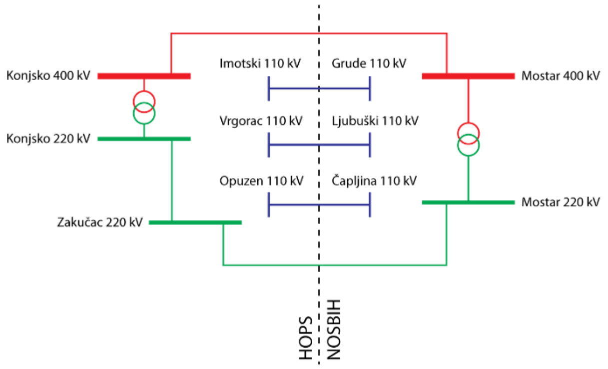


Fig. 5. Reference Case

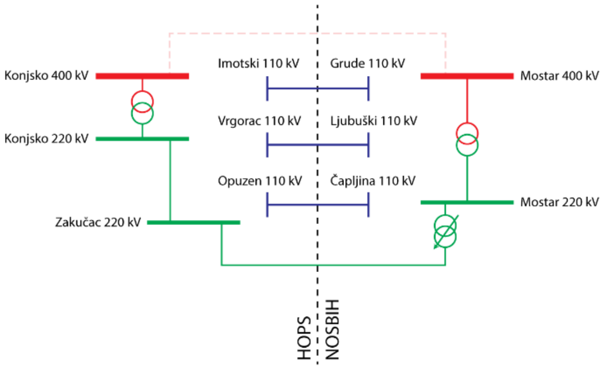


Fig. 6. Remedial Case (with PST)

C. *Results*

Table II shows the loading of relevant lines for all three scenarios.

TABLE II. LOADINGS OF LINES ACCORDING TO SCENARIOS

	Reference	**Contingency**	**Remedial**
OHL 400 kV Konjsko - Mostar	43.64%	N/A	N/A
OHL 220 kV Mostar - Zakučac	36.78%	**116.57%**	92.80%
OHL 220 kV Zakučac - Konjsko	19.96%	84.93%	71%
OHL 110 kV Imotski - Grude	34.54%	81.75%	91.78%
OHL 110 kV Vrgorac - Ljubuški	18.31%	37.52%	41.12%
OHL 110 kV Opuzen - Čapljina	8.91%	19.08%	20.47%

D. *Analysis Conclusion*

It can be concluded that after the tripping of OHL 400 kV Konjsko – Mostar, OHL 220 kV Mostar - Zakučac becomes overloaded with 116.57% of the allowed line thermal rating. After a PST is introduced on the overloaded line, the unwanted flows are restrained within allowed limits. It is important to notice that the flows on 110 kV lines have increased in the remedial scenario.

IX. GENERAL CONSLUSION

Phase Shift Transformers are a plausible solution to a number of issues in the electric power system. By defining objectives and by combining different factors, PSTs add value to the system and help increase system operation safety and stability, and generally speaking, the system's efficiency.

As a result of a detailed study of major investments in Phase Shifting Transformers, this paper summarizes and defines the key factors for the optimal location of phase shifters in interconnected systems, based on experiences around the world and most specifically ENTSO-E, with regard to prerequisites, location in a substation, and finally, location in a wider electric power system.

The term "interoperability" is introduced to give merit to the possibility of using the Phase Shifting Transformer for a wider range of applications as well as for extending topology by using multiple switching states.

At the end, a short analysis is performed, showing the effects of installation of a Phase Shifting Transformer in the electric power system of Bosnia and Herzegovina, by taking into account the surrounding grids of the South East European (SEE) Region.

ACKNOWLEDGMENT

We would like to thank the Security Coordination Center in Belgrade for conceding the results of the PTDF Analysis that they performed on behalf of ENTSO-E.

We would also like to thank colleagues from Slovenian TSO (ELES), Franc Kropec, Blaž Traven, Matjaž Dolinar, Aleksander Polajner and Matej Bratić, who welcomed the authors and made the visit to PST in substation Divača possible.

We would also like to show our gratitude to colleagues from Austrian TSO (APG), Michael Weixelbraun, Mika Gunter, Andrea Dummer and Tarik Bukarić who welcomed the authors in APG premises, as well as for the visit to PST in substation Ternitz.

We thank prof. Herwig Renner from TU Graz, for his inputs and experiences with PST design and installations in European power systems.

REFERENCES

[1] W. Seitlinger, "Phase Shifting Transformers Discussion of Specific Characteristics", CIGRE Session 12-306, 1998.

[2] R. Sweeney, G. Stewart, P. O'Donoghue, P. Gaffney, "The Specification and Control of the Phase Shifting Transformers For The Enhanced Interconnection Between Northern Ireland and The Republic of Ireland", CIGRE Session 11-118, 2002.

[3] IEEE Std C57.135 – 2011, IEEE Guide for the Application, Specification and Testing of Phase-Shifting Transformers

[4] T.J. Overbye, J. D. Weber, K. J. Patten, "Analysis and Visualization of Market Power in Electric Power Systems", Proceedings of the 32nd Hawaii International Conference on System Sciences, 1999.

[5] A. Polajner, M. Hrast, D. Škamperle, M. Pezdirc, "Installation of Phase shifting transformer in SS Divača", CIGRE Slovenia A2-02, Ljubljana 2011.

[6] W.L. Kling and others, "Phase shifting transformers installed in the Netherlands in order to increase available international transmission capacity", CIGRE Session C2-207, 2004.

[7] J. Rimez, R. Van Der Planken and others, "Grid implementation of a 400MVA 220/150kV –15°/+3° phase shifting transformer for power flow control in the Belgian network: specification and operational considerations", CIGRE Session A2-202, 2006.

[8] P. Hurlet, J-C. Riboud, J. Margoloff, A. Tanguy, "French Experience In Phase-Shifting Transformers", CIGRE Session A2-204, 2006.

[9] E.M. Carlini, G. Manduzio, D. Bonmann, "Power Flow Control on the Italian network by means of phase-shifting transformers", CIGRE Session A2-206, 2006.

[10] J. Ptacek, P. Modlitba, S. Vnoucek, J. Cermak, “Possibilities Of Applying Phase Shifting Transformers In The Electric Power System Of The Czech Republic”, CIGRE Session C2-203, 2006.

[11] M. Eremia, C. Liu, A. Edris, “Advanced Solutions in Power Systems, HVDC, FACTS, and Artificial Intelligence”, IEEE Press Series on Power Engineering, John Wiley & Sons, 2016.

[12] G. Migliavacca, Advances Technologies for Future Transmission Grids, Springer, 2013.

[13] T. Štrumbelj, D. Lenarčič, M. Hrast, “Installing of Phase Shifting Transformers in S/S Divača”, CIGRE Slovenia B3-01, Ljubljana 2011.

[14] R.Korab, R.Owczarek, “Application of phase shifting transformers in the tie-lines of interconnected power systems”, Przegląd Elektrotechniczny, ISSN 0033-2097, R. 91 NR 8/2015.

[15] P. Paterni. S. Vitet, M. Bena , A. Yokoyama, “Optimal Location of Phase Shifters in the French Network by Genetic Algorithm”, IEEE Transactions of Power Systems, Vol 14, No. 1, February 1999.

Impact of gradually replacing old transmission lines with advanced composite conductors

Semir Hadzimuratovic
Operational Planning Department
Independent System Operator for Bosnia and Herzegovina (ISO B&H)
Sarajevo, Bosnia and Herzegovina
s.hadzimuratovic@nosbih.ba

Prof. Lothar Fickert
Institute of Electrical Power Systems
Technical University Graz (TU Graz)
Graz, Austria
lothar.fickert@tugraz.at

***Abstract*— Driven by higher energy demand, the complications of finding new corridors, construction, and slow commissioning procedures for transmission lines, an advanced technology has been innovated to adapt to the modern power system's needs.**

A new type of overhead conductor with a polymer composite core (ACCC) have a greater ampacity, lower sag, and are lighter than traditional ACSR conductors. Therefore, it is this innovative technology is optimal choice when the decommissioning of old lines takes place.

This paper analyzes the impact of the gradual replacement of old transmission lines with all the benefits and disadvantages. It addresses the issues of equipment aging and proposes a replacement strategy for a cost-effective transition to a modernized power system functioning at improved performance.

Calculations and analyses are performed on a real interconnected system, composed of several South East European (SEE) transmission grids.

Keywords—ACSR conductor, ACCC conductor, HTLS, sag, ampacity, power flow

I. NOMENCLATURE

AAAC	All Aluminum Alloy Conductor.
ACSR	Aluminum Conductor Steel Reinforced.
ACSS	Aluminum Conductor Steel Supported.
GACSR	Gap Type ACSR
INVAR	Special nickel-iron alloy FeNi36
ACCC	Aluminum Conductor Composite Core.
ACCR	Aluminum Conductor Composite Reinforced.
HTLS	High Temperature Low Sag Conductor.
OHL	Overhead Line
TSO	Transmission System Operator
WPP	Wind Power plants

II. INTRODUCTION

After the liberalization of the electricity markets, investments of grid have been put into the control of transmission system operators (TSO), which are funded by different sources of incomes, such as tariffs and capacity allocation. It’s in their responsibility to present long term network developments plan that are then approved by higher bodies, such as regulators. National developments plans have to take into account the regional aspirations for a growing need for interconnectors. Very often, in that process the revitalization of old lines is delayed or forgotten.

Another problem that has risen is the investment in renewable energy sources (RES), especially hydro, wind and solar. These sorts of plants are connected to existing lines, which can be very old and located in remote areas without appropriate capacity.

For example, most new wind power plants (WPP) in Bosnia and Herzegovina’s grid are planned to be connected on existing 110 kV OHL with 240/40 mm^2 Aluminum Conductor Steel Reinforced (ACSR) technology, that has a rating of 122 MVA. Due to the optimal wind properties, all WPP are planned to be built within close proximity to each other, and the average installed power is 50 MVA. Therefore, it can be easily concluded that several plants, in parts of the system with weak lines, operating at maximum capacity can create congestions, and lead to an unstable state of the system, affecting the security of supply of connected customers.

There are various ways to address and retaliate congestions. Most often congestions occur on the interconnecting lines between two different countries or TSOs. The reason for this is the fact that building new lines has become a complex process because of the following reasons:

- Lengthy permitting process,
- New corridors are difficult to find,
- Construction takes a long time,
- Costs are very high,

In this case, the alternative to constructing new lines is to replace old transmission line with advanced composite conductors. That way, the same corridor can be used, the majority of transmission towers can be restated, perhaps some repaired or reinforced.

III. COMPARISON OF DIFFERENT TYPES OF CONDUCTOR TECHNOLOGIES

Generally speaking, OHL conductors can be divided into two categories, the historically older technology, or standard conductors (ACSR), and the advanced technology, called High Temperature Low Sag (HTLS), which include: ACSS, GACSR, Invar, ACCC, ACCR [1]. Table I offers an overview of major differences between the two conductor categories [2].

978-1-5386-4505-5/18/$31.00 ©2018 IEEE

TABLE I. COMPARISON OF STANDARD VS. HTLS CONDUCTORS

	Standard	HTLS
Core	Steel	Reinforced steel Steel alloys Composite materials
Outer Strands	Concentric (Round) aluminum wires	Annealed aluminum Aluminum alloys Compact (Trapezoid) Strand

Construction of power lines can be regarded as a multidisciplinary project because of different kinds of tasks that have to be engineered. In this chapter, two comparisons will be made. One can be regarded as electrical, while the second is of a more mechanical nature.

A. Temp

The key parameter of a conductor is its ampacity. A conductor thermal rating is derived from the ampacity. Thermal ratings relevant for protecting parameters and settings are most usually represented, either in amps (A) or megawatts (MW).

Different conducting materials tend have different temperature related properties, thus different ampacity capacities. Mechanical strength of a conductor is of the utmost importance, and material of different structural properties have to be combined in order to get the optimal temperature-to-amps ratio, without compromising mechanical integrity.

Fig. 1 present conductor comparison based on temperature in function of ampacity. It can be easily concluded that the ACCC conductor achieves the highest ampacity at the coolest operating temperature compared to the other high temperature capable conductors, as shown in Fig. 1 [3].

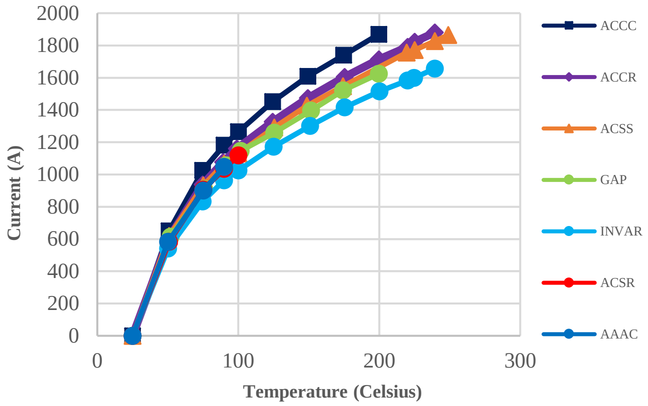


Fig. 1. Conductor comparison showing ampacity capabilities [2]

Cooler operating temperatures under high load conditions reflect substantial reductions in line losses (Fig 3.) that can decrease generation requirements, reduce fuel consumption (and associated emissions), and decrease lifecycle costs [3].

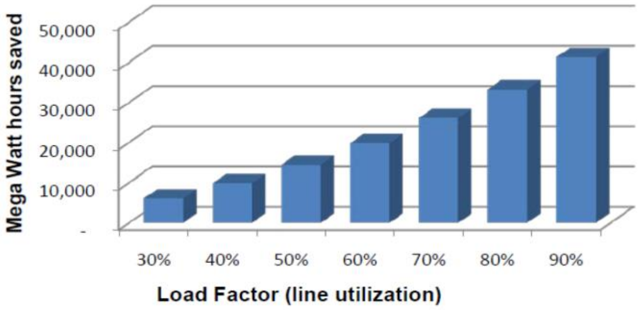


Fig. 2. Line loss Reduction using ACCC compared to ACSR (yearly basis) [2]

B. Temperature vs. Sag

A conductor thermal sag comparison (shown in Fig. 3) was performed, wherein 1600 A of current was run through each conductor type on a 65 meter indoor test span. Note that the ACCC conductor operated at 60° to 80°C cooler than the other conductors tested under equal load conditions [3], [4].

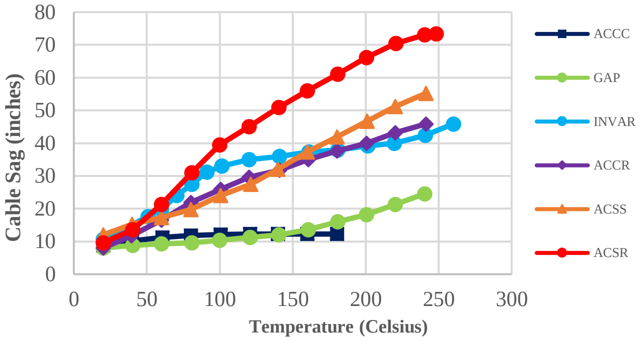


Fig. 3. Sag - temperature comparison of several [2]

Both ACCC and ACCR, are by definition advanced conductor technologies, accomplishing low sag at high temperatures by using composite core technology. The authors decided to focus on ACCC, due to better comparisons results, as well as the availability of their manufacturer's (CTC Global) comparison software and compatibility with Siemens PTI's Power System Simulator (PSS-E) database containing the majority of different types of ACCC conductors.

IV. ADVANCED CONDUCTOR TECHNOLOGIES

Aluminum Conductor Composite Core or ACCC is a type of "high-temperature low-sag" (HTLS) overhead power line conductor manufactured by more than 20 international conductor manufacturers.

The ACCC conductor consists of a hybrid carbon and glass fiber composite core which utilizes a high-temperature epoxy resin matrix to bind hundreds of thousands of individual fibers into a unified load-bearing tensile member [3].

The composite core is surrounded by aluminum strands to carry electrical current (Fig. 4). The conductive strands are generally fully annealed aluminum and trapezoidal in shape to provide the greatest conductivity and lowest possible electrical resistance for any given conductor diameter [3].

Fig. 4. ACSR (left) and ACCC (right) conductors [5]

The ACCC conductor is rated for continuous operation at up to 180°C (200°C short-term emergency), and operates significantly cooler than round wire conductors of similar diameter and weight under equal load conditions due to its increased aluminum content and the higher conductivity [3]. Though the ACCC conductor was initially developed as a "High-Temperature, Low-Sag" (HTLS) conductor to increase the capacity of existing transmission and distribution lines with minimal structural changes, its improved conductivity and reduced electrical resistance makes it ideally suited for reducing line losses on new transmission and distribution lines where improved efficiency and reduced upfront capital costs are primary design objectives [5].

V. TRANSMISSION SYSTEM OF BOSNIA AND HERZEGOVINA

After a thorough statistical analysis of [6], and [7], it can be concluded that the transmission grid of Bosnia and Herzegovina (B&H) consist of 279 conductor elements, of which seven 110 kV underground cables.

The majority of 400 kV lines were constructed in the 1970's and 1980's, and is composed of 15 lines. All lines are using 2 bundle ACSR Cardinal (Al/Fe 490/65 mm^2) that can carry 1920 A. Most conductors are in the 10 – 20 age group.

As for 220 kV voltage level, a total of 41 overhead lines has been constructed mainly in the 1960's and 1970's. Almost 80% of 220 kV conductors are ACSR Starling (Al/Fe 360/57 mm^2), and another 12 % use the same materials, but as two bundles per phase. The permissible currents are 790 A and 1580 A, respectively. The average age is 33 years, and the majority of conductors are in two age groups, 10 – 20, and 40 – 50, respectively. After the first installation in 1957, 20 conductors have been subject to repair, reconstruction or restoration.

For 110 kV voltage level, a total of 216 overhead lines exist, the greater part built in the 1950-1980 period. Since their initial commissioning, a total of 125 lines have been renovated, some more than 4 times. Roughly 20 lines were restored in such a way what two conductors of different parameters were connected, therefore limiting the throughput capacity of the whole line to the value of the smaller conductor. As it can be observed from Fig. 5, about 50% of lines have surpassed a 30 year lifespan.

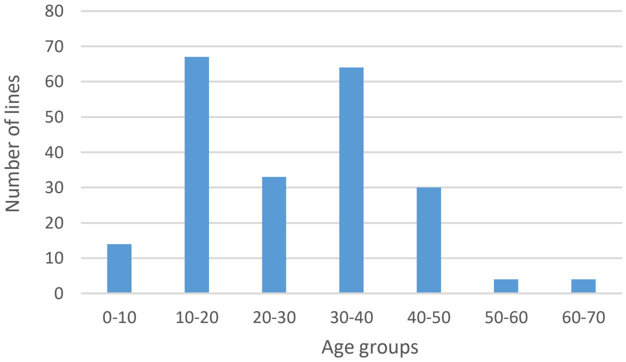


Fig. 5. Number of lines per age group for 110 kV

During high load periods, the 110 kV lines can be loaded as high as 85% in normal topology operation. 80% of lines are ACSR HAWK (Al/Fe 240/40 mm^2) with maximum allowed current of 645 A, or 123 MW. Another 15% are ACSR OSTRICH (Al/Fe 150/25 mm^2), with an allowed current of 470 A, or 90 MW [7].

From the statistical data stated above, a conclusion can be made that the 110 kV lines are the oldest ones, and the ones most susceptible to end-of-life failures. Therefore, in the rest of the paper, the attention will be on the replacement and reconducturing of aged 110 kV lines.

VI. LINE PARAMETERS COMPARISON

The model will consist of reconducturing all internal 110 kV overhead lines. In other words, cables and interconnectors will not be processed in the modelling of this paper.

All ACSR HAWK lines will be replaced with ACCC LISBON (see Table II), while ACSR OSTRICH lines will be reconductored with ACCC OCEANSIDE conductors (see Table III). Due to a less perplexing modeling, the remaining 6% of lines which are composed of ACSR FEAL, ACSR WAXWING, 300E-CWC and 250E-CWC will all be replaced with ACCC PASADENA (sea Table IV).

TABLE II. COMPARISON OF ACRS HAWK AND ACCC LISBON

	ACSR HAWK	**ACCC LISBON**
Diameter (mm)	21.79	21.79
Aluminum area (mm^2)	241.7	315.5
Rated strength (kN)	86.7	103.4
Weight (kg/km)	976	948
AC Resistance at 25°C (ohm/km)	0.1198	0.0910
Ampacity (A)	640	1284
Rating (MVA)	122	244

TABLE III. COMPARISON OF ACRS HAWK AND ACCC LISBON

	ACSR OSTRICH	**ACCC OCEANSIDE**
Diameter (mm)	17.27	17.27
Aluminum area (mm^2)	152	194.2
Rated strength (kN)	53,8	71.2
Weight (kg/km)	615	590
AC Resistance at 25°C (ohm/km)	0.190	0.1475
Ampacity (A)	490	938
Rating (MVA)	94	178

TABLE IV. DATASHEET FOR ACCC PASADENA

	ACCC PASADENA
Diameter (mm)	15.64
Aluminum area (mm^2)	154.4
Rated strength (kN)	68.9
Weight (kg/km)	478.1
AC Resistance at 25°C (ohm/km)	0.1929
Ampacity (A)	814
Rating (MVA)	155

Tables II, III and IV present the modeling parameters of the conductors, with characteristic specifications regarding the superiority of ACCC conductors compared to ACSR.

The ACCC conductors used for reconducturing were chosen so that their weight is equal or lower to ACSR conductor, therefore it can be supported by existing towers, without the need to invest in new ones.

VII. ANALYSIS INPUTS

A. *Model*

The analyses were performed on the merged winter maximum model of South East European transmission systems with moderate transits from east to west. The merged models include transmission grids of Albania, Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Hungary, Macedonia, Montenegro, Romania, Serbia and Slovenia. The analysis was done using Siemens PSS-E software. PSS-E's accompanying software LineProp was used to calculate line parameters for the replaced lines. Conductor Comparison Program (CPC) database was used for filling necessary LineProp data inputs.

B. *Scenarios*

Power flows analyses were performed for a total of 8 scenarios:

- **Base Case** - This scenario is the reference case for all further analyses. In this model, all the lines were modeled as ACSR conductors.
- **Scenario 1** - ACSR lines from age group 60-70 were replaced with relevant ACCC conductors.
- **Scenario 2** - ACSR internal overhead lines aged from 50 to 70 years are replaced with relevant ACCC conductors.
- **Scenario 3** - ACSR lines aged from 40 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 4** - ACSR lines aged from 30 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 5** - ACSR lines aged from 20 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 6** - ACSR lines aged from 10 to 70 years were replaced with relevant ACCC conductors.
- **Scenario 7** - ACSR lines aged from 0 to 70 years were replaced with relevant ACCC conductors.

C. *Observed parameters*

For each scenario, a corresponding data set (positive sequence impedance, admittance and rating) was updated for each replaced element in the according age group. A power flow analysis was then performed for each scenario, with focus on following results:

- **Lines loadings** – Limit checking reports were evaluated for all modeled 110 kV lines in that scenario.
- **Active power losses** – Area reports were performed and active power losses for the complete power system of Bosnia and Herzegovina were extracted.

VIII. ANALYSIS RESULTS

After comparing the differences in input data for appropriate ACSR and ACCC conductors it can be concluded that only the line resistance is subject to a considerable change. The resistance or ACCC LISBON is 52.5% lower than ACSR HAWK, while the resistance of ACCC OCEANSIDE was 25% lower than ACSR OSTRICH. The reactance and susceptance were not subject of extensive variations, as the geographical disposition of the lines do not change, except for the lower sag.

Due to the fact that the reactance and susceptance remain mostly unchanged, it is important to note that the Surge Impedance Loading (SIL), isn't subject to change. This can be regarded as an additional advantage, resulting in the fact that the lower loadings will not affect reactive power flows, and therefore will not have an impact on the voltages.

Fig. 6 shows the observed result of the performed analyses. It presents savings in the average loadability and total losses for each scenario, referenced to the base case.

As more lines get replaced with conductors that have significantly higher throughput capacities, it can be observed that the average loading of the lines, in terms relative to the base case, decreases by 32%.

Also, it should be noted that having decreased lines loadings in regular power flow analyses that were performed in this paper, leads to the conclusion that a significantly lower number of lines will be overloaded when performing contingency analyses.

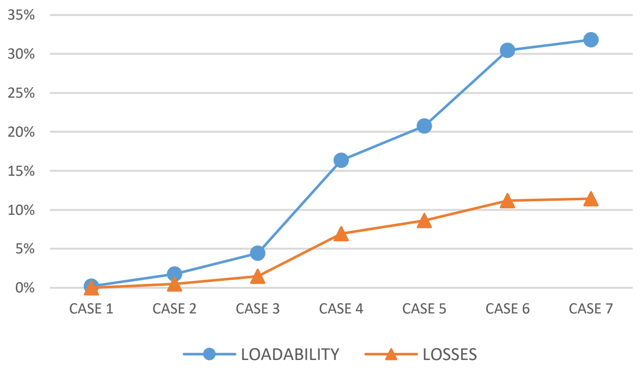


Fig. 6. Loadability and losses compared to the base case (accumulated values)

The effect of active power losses reduction can be observed from one scenario to the other, as it can be clearly seen in relative terms (Fig. 6.), as well as in absolute values (Fig. 7.).

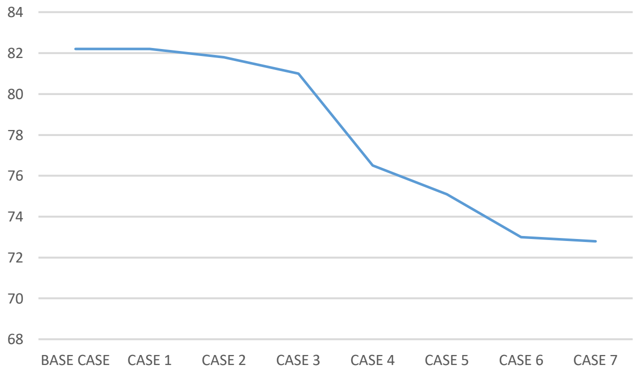


Fig. 7. Total active power losses (MW)

In the base case, the total active power losses for the entire transmission system of Bosnia and Herzegovina (composed of 400, 220 and 110 kV) elements, amounts to 82 MW, however, by replacing all 110 kV lines with advances ACCC conductors, additional 9.4 MW of active power losses are saved.

IX. GENERAL CONSLUSION

From this system-wide load flow analysis, that doesn’t even take into account the aspect of time correlation, or in other words, energy savings (MWh), it can be concluded the impact of ACCC conductors on power losses is significant. Active power losses are directly related to the resistance parameter of a line. Once the resistance is decreased, the active power losses are also lowered. It’s exactly what HTLS conductors manage to achieve, therefore the financial savings are noticeable.

Besides that, by reconducturing old lines with advanced conductor technology, such as ACCC, the ampacity of the lines is highly increased, leading to optimal usage of existing lines with an extended security margin in cases of contingencies. The newly increased throughput capacity of the lines have an important impact of the ever-growing need for integration of renewable sources, that are most often connected at 110 kV voltage level.

Because of the mentioned benefits, asset managers working for transmission system operators should investigate all the possibilities for the implementation of advanced composite core conductors in their networks, [8]. In the future, with the ageing of transmission lines, more and more reconductor projects will be happening worldwide. By investing in superior conductor technologies, value can be added to the power transmission system, improve its efficiency, without affecting commissioning due to lengthy permitting processes.

ACKNOWLEDGMENT

We would like to thank CTC Global for providing the Conductor Comparison Program (CPC) Software for calculation purposes in this paper.

REFERENCES

[1] A. Alawar, E.J. Bosze, S. R. Nutt, “A Composite Core Conductor for Low Sag at High Temperatures”, IEEE Transactions On Power Delivery, Vol. 20, No. 3, July 2005

[2] “Techno-economic analysis of the application of the ACCC conductor on the 110 kV OHL Sinj - Dugopolje – Meterize”, Energovod, 2014

[3] “ACCC Engineering Manual, CTC Global Corporation, 2011

[4] Goel, A., Kamarudin, A., Pon, C. “New High Temperature Low Sag Conductors”, NATD Conference & Expo May 2005

[5] A.V. Kenge, S. V. Dusane, J. Sarkar, “Statistical Analysis & Comparison of HTLS Conductor with Conventional ACSR Conductor”, International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT) – 2016

[6] “Long-Term Development Plan Of The Transmission Networks 2017 – 2026”, Elektroprenos BiH, 2016

[7] “Calculation of line parameters for the transmission system of Bosnia and Herzegovina”, NOSBIH, 2007.

[8] A.R.Hill, C.E. FIET, “How do asset managers with long life assets (40 years plus) decide to replace mature technology with new innovative technology? How do they assess the risks and rewards? A case study.”,

HRVATSKI OGRANAK MEĐUNARODNOG VIJEĆA
ZA VELIKE ELEKTROENERGETSKE SUSTAVE – CIGRÉ
13. simpozij o sustavu vođenja EES-a
Rovinj, 5. – 7. studenoga 2018.

1-30

Semir Hadžimuratović[1]
Independent System Operator in Bosnia and Herzegovina / Technische Universitat Graz
s.hadzimuratovic@nosbih.ba

VISOKOTEMPERATURNI NISKOPROVJESNI VODIČI KAO POTENCIJALNO RJEŠENJE ZA POVEĆANJE UDJELA OBNOVLJIVIH IZVORA

SAŽETAK

U današnje vrijeme, nadzemni vodovi se koriste, više nego ikad sa sve većim opterećenjima. Sa deregulacijom elektroenergetskog sektora, nadzemni vodovi kao suštinska imovina u vlasništvu prenosnog sistema su zanemareni. Zbog rastućih troškova rada i održavanja, rekonstrukcija nadzemnih vodova nije prioritetizirana na odgovarajući način.

Ovo utječe na ulaganja trećih strana u obnovljive izvore energije, s obzirom na to da se te vrste elektrana često agregiraju i nalaze u udaljenim područjima bez lokalne potrošnje i nadzemnih vodova adekvatnog propusnog kapaciteta.

U ovom radu je riječ o načinu iskorištenja novih generacija vodiči, također poznatih kao visokotemperaturni niskoprovjesni vodiči (HTLS), te kako oni mogu poslužiti kao rješenje za taj problem. Na kraju, predstavljena je kratka studija o prenosnom sistemu Bosne i Hercegovine, u kojem se planira izgradnja nekoliko vjetroelektrana u neposrednoj blizini, u dijelu sistema koji ima ograničene mogućnosti za prihvat energije vjetra.

Ključne riječi: Visokotemperaturni niskoprovjersni vodiči, nadzemni vodovi, vjetroelektrane.

HIGH-TEMPERATURE LOW SAG CONDUCTORS AS A SOLUTION FOR INCREASING RENEWABLE ENERGY SOURCES PENETRATION

SUMMARY

Overhead power lines are nowadays used to transmit more power than ever before. However, with the deregulation of the power sector, power lines as an essential asset are neglected. Due to the increasing costs of operation and maintenance, transmission system operators investments for reconductoring are not prioritized in the appropriate way.

This affects very much the third-parties investments in renewable energy sources, due to the fact that those sorts of power plants are very often aggregated and located in remote areas without local consumption and lines of adequate throughput capacity.

This paper address the issue of how new conductor technologies, also known as High-Temperature Low Sag (HTLS) conductors can mitigate that problem. In the end, a study of Bosnia and Herzegovina's network is presented, where several wind power farms are planned to be built in close proximity of each other, in a part of a system that has limited capabilities.

Key words: High-Temperature Low Sag (HTLS), Overhead Lines, Wind Power Plants.

---

[1] The views expressed in the paper are the personal opinions of the author, they are not binding on the company/institution in which the author is employed and do not necessarily match the official positions of the company/institution. This paper is a part of the author's scientific research for his doctoral thesis.

1. INTRODUCTION

After the liberalization of the electricity markets, investments in transmission grids have been put into the control of transmission system operators (TSO), which are funded by different sources of incomes, such as tariffs and capacity allocation. It's in their responsibility to present long-term network developments plan that are then approved by higher bodies, such as regulators. National developments plans have to take into account the regional aspirations for a growing need for interconnectors. Very often, in that process the revitalization of old lines is delayed or forgotten, [1].

Another problem that has risen is the investment in renewable energy sources (RES), especially hydro, wind and solar. These sorts of plants are connected to existing lines, which can be very old and located in remote areas without appropriate capacity, [1].

For example, most new wind power plants (WPP) in Bosnia and Herzegovina's grid are planned to be connected on existing 110 kV OHL are type ACSR HAWK[2], that has a rating of 122 MVA. Due to the optimal wind properties, important investments in WPP are planned to be built within close proximity to each other, and the average installed power of each wind park is 50 MVA. Therefore, it can be easily concluded that several plants, in parts of the system with weak lines, operating at maximum capacity can create congestions, and lead to an unstable state of the system, affecting the security of supply of connected customers, [1].

In this paper, an alternative to constructing new lines is presented. It consists of reconductoring existing lines with advanced composite conductors. That way, the same corridor can be used, the majority of transmission towers can be restated, perhaps some repaired or reinforced, [1].

2. RENEWABLE ENERGY INVESTMENTS

After adopting the EU 20-20-20 set of legislation, almost immediately the power system could feel its consequences, as the investments in renewable energy were happening in all ENTSO-E systems. The largest share of new investments in renewable energy sources (RES) was in wind power plans, as well as in solar photovoltaic installations. The most significant problem with the mentioned primary energy sources is their unpredictability which results in increased need for operating reserves. However, an additional important issue is the necessity to invest in power grids needed to evacuate the energy and deliver it to final consumers.

2.1. Wind power in Bosnia and Herzegovina

After performing several studies with the aim to study the effect of wind power plants in Bosnia and Herzegovina, it was agreed that a total capacity of 350 MW [2-3], can be installed without extensive investments in the grid and without further impacting ancillary services. However, in the „paper-collecting“ competition that occurs among potential investors and due to the idleness and conflict of jurisdictions for different government entities, a total of 14 wind power plants successfully finished connection studies, therefore determining the optimal connection to the high voltage transmission grid of Bosnia and Herzegovina. Additionally, investors for 7 wind power plants have expressed their interest. In other words, the total amount of investments in WPP is worth 1210.7 MW, far exceeding the initial established threshold of 350 MW, [4].

As it can be seen in Figure 1., the most prospective area for investments in wind energy is located in the south and south-west of the country. Of the 14 investments with realized connection studies, 11 are located in the nearest vicinity of each other (in the area near Tomislavgrad) with an aggregated installed capacity of 563 MW (Figure 4.).

---

[2] At the time of their construction, overhead lines were constructed according to Jugoslav Standard (JUS). However, due to negligible changes, in the widely used models of Bosnia's and Herzegovina's power system, these values have been recalculated according to parameters for standard nomenclatures for ACSR conductors, [5]. Therefore, in this paper, instead of JUS nomenclature, the standard international nomenclature is used.

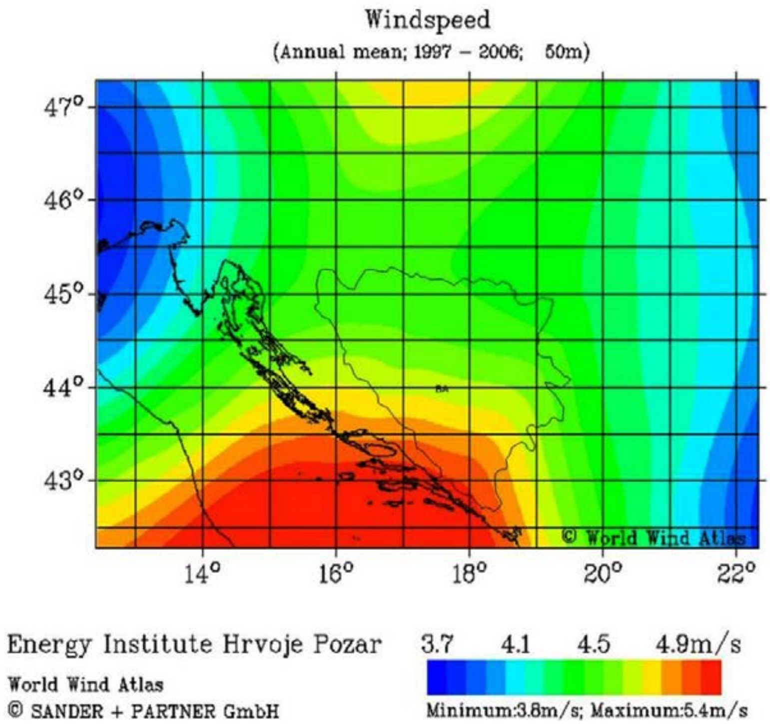


Figure 1. Average wind speeds in Bosnia and Herzegovina [6]

Table I. shows the list of WPPs in the Tomislavgrad area in accordance with the lines there are supposed to be connected, as a result of appropriate connection studies. The aggregated installed power on lines Tomislavgrad - Livno and Tomislavgrad – Rama far exceeds the installed capacity of the existing lines, making it impossible to realize the investments.

Table I. List of WPP in Tomislavgrad area in accordance connection study results

WPP	Installed power (∑)	Line	Type	Capacity
W1, W2	92.2 MVA	Tomislavgrad – Posušje	ACSR HAWK 240/40 mm^2	122 MVA
W3, W4, W5	186.8 MVA	Tomislavgrad – Livno	ACSR HAWK 240/40 mm^2	122 MVA
W6, W7, W8, W9	180 MVA	Tomislavgrad – Rama	ACSR HAWK 240/40 mm^2	122 MVA
W10, W11	104 MVA	Tomislavgrad – Kupres	ACSR HAWK 240/40 mm^2	122 MVA

Therefore, from Table I. and Figure 2., it can be easily seen and understood that not all new power plants can't be constructed and connected to the existing transmission grid, according to the current state of affairs. Note that W1 – WPP Mesihovina is already constructed and connected on existing line Tomislavgrad – Posušje (See Figure 2.).

As a conclusion of the connection studies and the proceedings of the connection committee meetings, it is stated that; „based on the status of the previous connections on existing overhead lines, investors might have to perform additional calculations“. In other words, the plans will be subject to changes, depending on the status of WPP investments.

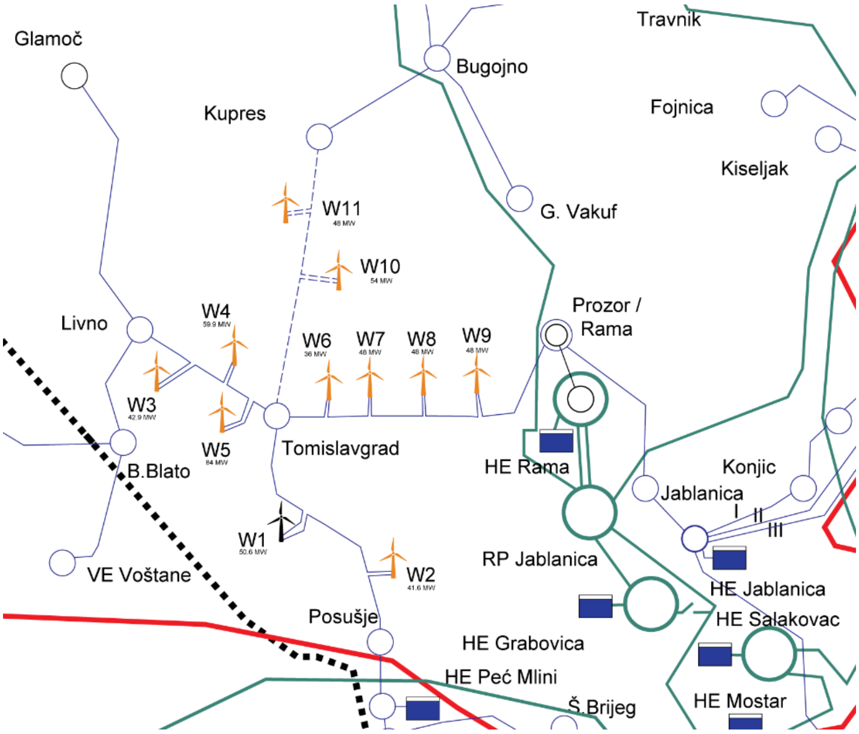


Figure 2. Planned wind power plants near Tomislavgrad

However, in this paper, the author will evaluate the worst possible scenario (i.e. WPP connection according to Table I. and Figure 2.), in order to analyze the possibility of solving the problem using HLTS conductors.

3. CONDUCTOR TECHNOLOGY COMPARISON

Overhead line conductors can be classified into two major categories:

- The historically older technology, or standard conductors, or ACSR
- The advanced technology, or HTLS

All over the years, different HTLS conductors have emerged, some of which are; ACSS, GACSR, ACCC, ACCR. Table II offers the major differences between the two major conductor categories [1, 7].

Aluminum Conductors Steel Reinforced (ACSR) conductors are the most widespread conductors used for overhead lines (OHL). They have been in use for a very long time, have passed extensive testing and finally have proven themselves in electric power systems, [7].

Table II. Comparison of Standard vs. HTLS conductors

	Standard	**HTLS**
Core	Steel	Reinforced steel Steel alloys Composite materials
Outer Strands	Concentric (Round) aluminum wires	Annealed aluminum Aluminum alloys Compact (Trapezoid) Strand

Unlike standard ACSR conductors that can be produced in any major conductor manufacturing facility, HTLS conductors, as a result of a more refined, diverse and complicated manufacturing processes are usually produced in several factories around the world, [7].

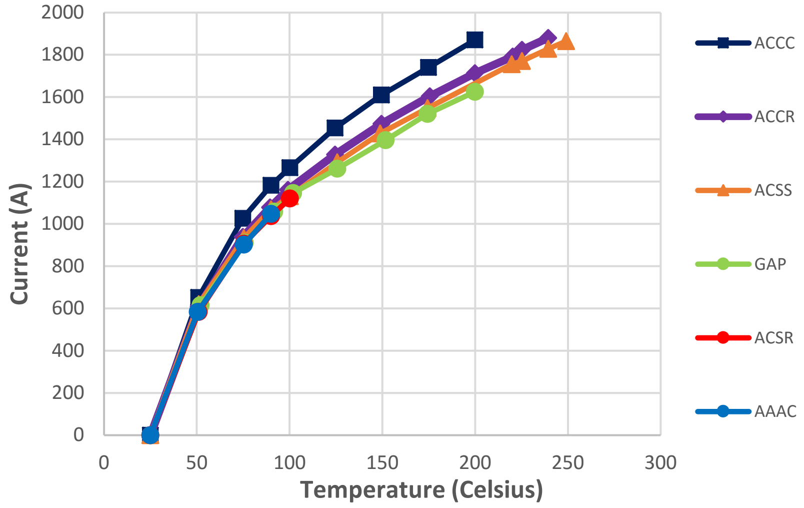


Figure 3. Conductor comparison showing ampacity capabilities [7]

When analyzing ampacity, temperature and sag parameters, Figure 3. and 4., for different HTLS conductor types, it can be concluded that both ACCC and ACCR, accomplish low sag at high temperatures by using composite core technology.

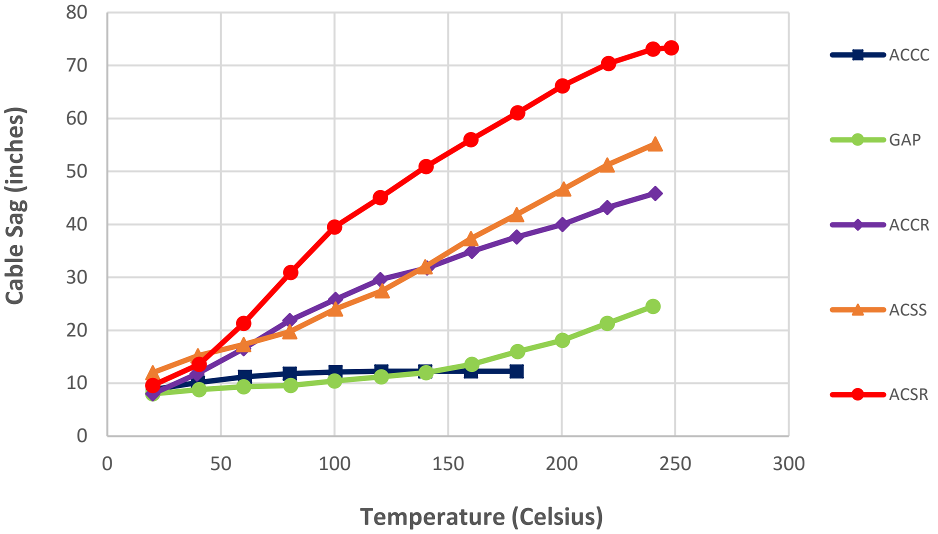


Figure 4. Sag - temperature comparison of several conductors [7]

The author decided to focus on ACCC, due to better comparisons results, as well as the availability of their manufacturer’s comparison software.

3.1. ACCC Conductors

The ACCC conductor (as shown in Figure 5.) is rated for continuous operation at up to 180°C (200°C short-term emergency), and operates significantly cooler than round wire conductors of similar diameter and weight under equal load conditions due to its increased aluminum content and the higher conductivity, [8]. Though the ACCC conductor was initially developed as a “High-Temperature Low-Sag” (HTLS) conductor to increase the capacity of existing transmission and distribution lines with minimal structural changes, its improved conductivity and reduced electrical resistance makes it ideally suited for reducing line losses on new transmission and distribution lines where improved efficiency and reduced upfront capital costs are primary design objectives, [9].


Figure 5. ACSR (left) and ACCC (right) conductors [7]

ACCC conductors are most often used for reconductoring of existing transmission and distribution lines, for use in heavy ice regions, aging structure, long-span crossing, but also for connecting renewable sources, such as wind power plants, [10-12].

Table III. Comparison of ACRS HAWK and ACCC LISBON

	ACSR HAWK	ACCC LISBON
Diameter (mm)	21.79	21.79
Aluminum area (mm^2)	241.7	315.5
Rated strength (kN)	86.7	103.4
Weight (kg/km)	976	948
AC Resistance at 25°C (Ω/km)	0.1198	0.0910
Ampacity (A)	640	1284
Rating (MVA)	122	244

Table III. offers a parameter comparison between ACSR HAWK and ACCC LISBON conductors. Basically, ACCC LISBON has the same diameter, but more aluminum area, which results in increased rating capacity (in this case, doubling the value). The improved rated strength and weight allows reconductoring using the same corridor and towers, but asks for special fittings, such as splice and dead-end connections, making the investment cheaper.

3.2. Advantages and Disadvantages of ACCC Technology

This composite strength member provides several advantages, [6,8-9,13]:

- It is lighter. The weight saved can be used for more aluminum conductor. ACCC cable uses trapezoidal strands to fit more aluminum into the same cable diameter.
- Softer, fully annealed aluminum can be used for the conductors. ACSR cable uses harder aluminum which contributes to the cable's tensile strength but has about 3% less electrical conductivity.
- It has a much lower coefficient of thermal expansion (CTE) (1.6 ppm/°C) than ACSR (11.6 ppm/°C). This lets the cable be operated at a significantly higher temperature without excessive sag between poles.

While the main disadvantages are, [6,8-9,13]:

- The primary disadvantage is its cost; ACCC costs 2.5–3 time as much as ACSR cable.
- Although ACCC has significantly less thermal sag than even other HTLS conductor designs, its core is quite elastic and sags more than other designs under ice load, although a ULS (higher modulus) version is available at a cost premium.
- The conductor has a larger minimum bend radius, requiring extra care during installation.
- The conductor requires special fittings, such as splice and dead-end connections.

4. ANALYSIS

The performed analysis represents one of the worst case scenarios in the future grid of Bosnia and Herzegovina related to the integration of wind energy in the Tomislavgrad area. Namely, the integration of 11 wind power plants with the aggregated installed power of 563 MW is connected on four lines connecting to 110 kV substation Tomislavgrad. Figure 6. depicts the relevant elements analyzed in the following model. Figure 6. is in accordance with Table I., as well as with Figure 2.

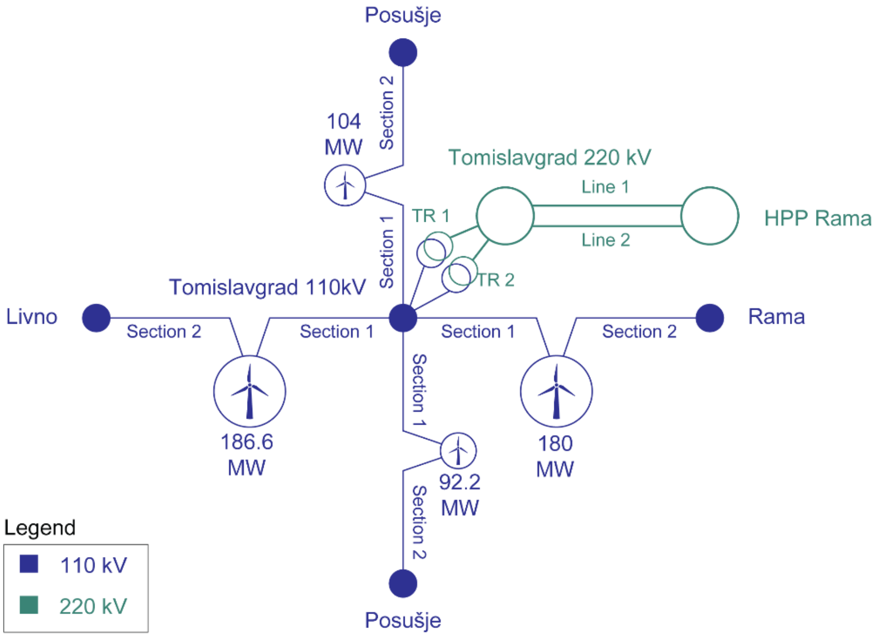


Figure 6. Topology and relevant elements

4.1. Model

The analysis was performed on the future transmission model of ENTSO-E networks, more specifically, winter maximum model. The future model comprises of the relevant changes, according to the future development plans submitted by TSOs to ENTSO-E. The analysis was performed using Power System Simulaltor (PSS-E) software. PSS-E’s accompanying software LineProp was used to calculate line parameters for the reconductored lines. Conductor Comparison Program (from ACCC's manufacturer) database was used for filling necessary LineProp data inputs.

The following facts and assumptions are taken into account:

- All existing 110 kV lines from Figure 6. are type ACSR HAWK.
- In the scenarios including reconductoring, ACSR HAWK is replaced with ACCC LISBON.
- Wind power plants on the four lines are aggregated and represented as one power source per line, according to values from Table I.
- Hydro power plant Rama is operated close to the maximum installed capacity (2 units at 75 MW).

The following cases are modeled:

- **Case A** – WPP operating at maximum installed capacity, ACSR conductors in all relevant 110 kV lines.
- **Case B** – WPP operating at maximum installed capacity, ACCC conductors in all relevant 110 kV lines.
- **Case C** – WPP operating at maximum installed capacity, ACSR conductors in 110 kV lines Tomislavgrad – Kupres and Tomislavgrad – Posušje, ACCC conductors in 110 kV lines Tomislavgrad – Livno and Tomislavgrad – Rama.
- **Case 1** – New single 220 kV ACSR line Tomislavgrad – HPP Rama, with one 110/220 kV power transformer at Tomislavgrad with installed power 150 MVA.
- **Case 2** – New double 220 kV ACSR line Tomislavgrad – HPP Rama, with two 110/220 kV power transformers at Tomislavgrad with installed power 150 MVA (per transformer).

Cases A-C refers to changes in 110 kV network, while Cases 1- 2 refers to modifications in 220 kV network and its topology.

The following scenarios are subject to analyses and calculations:

- **Base Case** – to determine the flows prior to any changes initialized in the following scenarios
- **Scenario 1** – Case A
- **Scenario 2** – Case A + Case 1
- **Scenario 3** – Case A + Case 2
- **Scenario 4** – Case B
- **Scenario 5** – Case B + Case 1
- **Scenario 6** – Case B + Case 2
- **Scenario 7** – Case C
- **Scenario 8** – Case C + Case 1
- **Scenario 9** – Case C + Case 2

4.2. Results

Table IV. represents the results of the performed analyses, with all scenario results. It gives the loadings of the modeled elements (lines and transformers), according to the above-mentioned cases and scenarios. The term „section“ is introduced and refers to the newly formed lines, from the connection point of the aggregated wind power plants to the existing substations (See Figure 6).

The following can be concluded from Table IV.:

- Result of the base case show that lines are underloaded prior to wind integration.
- The connection of the WPP on existing lines (Scenario 1) results in overloadings on all the lines. Therefore, as mentioned earlier, this solution would not be possible.
- Scenarios with just one 220/110 kV transformer in Tomislavgrad result in it's overloading (Scenario 2, 5, 8), so these solutions would also not be possible
- The combined scenario (ACCC and ACSR) represented in Scenario 7 also shows overloadings.
- Plausible solutions are scenarios are: Scenario 4, 6 and 9.
- Scenario 4 takes into account the use of existing ACSR lines, with two transformers and two lines. However, it is important to note that some elements are heavily loaded.
- Scenario 6 accounts for reconductoring with ACCC lines, as well as adding two transformers and two lines in Tomislavgrad.
- Scenario 9 accounts for the reconductoring with ACCC conductors of 110 kV lines Tomislavgrad – Livno, and Tomislavgrad – Rama, while using the existing ACSR lines Tomislavgrad – Kupres and Tomislavgrad – Posušje, and at the same time having two 220/110 kV transformers in Tomislavgrad and two 220 kV OHL between Tomislavgrad and HPP Rama.

Table IV. – Loadings of analyzed elements

	OHL 110 kV Tomislavgrad - Posušje		OHL 110 kV Tomislavgrad – Rama		OHL110 kV Tomislavgrad - Kupres		OHL 110 kV Tomislavgrad – Livno		Transformer 220/110 kV Tomislavgrad		OHL 220 kV Tomislavgrad – HPP Rama	
Element	Section 1	Section 2	Section 1	Section 2	Section 1	Section 2	Section 1	Section 2	Unit 1	Unit 2	Single line	Double line
Base Case	3.1%		14.1%		5.9%		5.4%					
Scenario 1	23.1%	**97.7%**	13.4%	**132.0%**	18.8%	**103.0%**	31.2%	**112.3%**				
Scenario 2	26.7%	50.5%	66.2%	74.0%	28.5%	56.0%	88.5%	58.1%	**173.5%**		81.5%	
Scenario 3	26.7%	50.5%	66.2%	74.0%	28.6%	56.0%	88.5%	58.1%	86.8%	86.8%	40.8%	40.8%
Scenario 4	10.5%	48.3%	9.0%	64.7%	14.4%	57.0%	20.1%	55.7%				
Scenario 5	13.8%	25.2%	34.0%	36.8%	14.0%	29.6%	44.9%	28.7%	**175.5%**		82.5%	
Scenario 6	13.8%	25.2%	34.0%	36.8%	14.0%	29.6%	44.9%	28.7%	87.8%	87.8%	41.3%	41.3%
Scenario 7	22.7%	**98.0%**	6.2%	67.0%	18.4%	**103.0%**	18.3%	57.0%				
Scenario 8	26.5%	50.6%	33.8%	37.0%	28.4%	56.2%	44.9%	28.8%	**175.5%**		82.5%	
Scenario 9	26.6%	50.6%	33.9%	37.0%	28.4%	56.1%	44.9%	28.7%	87.8%	87.8%	41.3%	41.3%

However, as contingency analyses were not performed in this paper, due to the high loadings of specific lines in Scenario 4, the author recommends using either Scenario 6 or 9 in order to perform further analyses.

It is also important to notice the extent to which the cases with ACCC reconductoring projects are positively affecting the loadings of the overhead lines.

4.3. Future Steps

The analysis has also shown slight overloadings on other lines in the galvanic proximity of the relevant analyzed lines. In following analyses, those lines should also be considered for reconductoring.

Due to the high loadings of both new transformers 220 / 110 kV at Tomislavgrad, a scenario comprising of a third transformer could be beneficial for complying with necessary requirements.

For the recommended scenarios (Scenario 6 and 9), contingency analyses should be performed in order to check for the fulfillment of N-1 analyses. Additional analyses could be performed on models with a different generation, consumptions, and transits.

Based on the final scenario, it would also be interesting to determine the maximum installed wind power plants power that could eventually be connected at substation Tomislavgrad, which would comply with the throughput capacity of the lines, as well as for contingency analyses.

In the end, a financial analysis should be performed in order to account for financial impacts for such investments, as well as a cost-benefit analysis.

5. CONCLUSION

This paper presents some consideration for the implementation of renewable sources in the power system using advanced conductor technologies, based on reconductoring with High-Temperature Low Sag conductors.

A possible and plausible problem regarding the integration of wind power in Bosnia and Herzegovina in the future transmission grid is presented. The problem is modeled and analyzed, and it comprises of several cases and scenarios that compare the use of existing lines, their reconductoring, as well as adding new elements (transformers and overhead lines). The recommended scenario include reconductoring existing standard lines (ACSR) with High-Temperature Low Sag conductors of ACCC type. The results show the extent to which ACCC relieves the loading of the lines, by using more aluminum conductor area compared to ACSR conductors. At the same time, ACCC weighs less, therefore allowing the reconductoring project to be realized using the same corridor and towers.

At the end, considerations for further analyses are presented in the last chapter in order to present the author's next steps in his work and field of studies.

6. REFERENCES

[1] S. Hadžimuratović, L. Fickert, “Impact of gradually replacing old transmission lines with advanced composite conductors“, IEEE PES Innovative Smart Grid Technologies Conference Europe 2018.

[2] M. Jonsson, “Firm wind generation hosting capacity in the Bosnia and Herzegovina transmission network“, STRI, January 2009.

[3] ECA, KMPG, EIHP, “Bosnia and Herzegovina: Power Network Analysis for Wind Power Integration and Market Rules Advice“, EBRD, December 2011.

[4] “Indicative Generation Development Plan 2019-2028“, Independent System Operator for Bosnia and Herzegovina, March 2018.

[5] “Calculation of electrical parameters for overhead lines”, Independent System Operator for Bosnia and Herzegovina, November 2007.

[6] S. Hadžimuratović, “Wind Power Integration Analysis - Impact of Wind Power Plant Generation on Power System Reserve Expenses“, Master Thesis, April 2013, 95 pp.

[7] S. Hadžimuratović, “Financial Impacts of Replacing Old Transmission Lines with Aluminum Composite Core Conductors“, The International Symposium on Advanced Electrical Power Systems– ISAPS 2018

[8] “ACCC Engineering Manual“, CTC Global Corporation, 2011

[9] A.V. Kenge, S. V. Dusane, J. Sarkar, “Statistical Analysis & Comparison of HTLS Conductor with Conventional ACSR Conductor”, International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT) – 2016

[10] G. Migliavacca, “Advanced Technologies for Future Transmission Grids“, Springer, 2013.

[11] S. Cole, W. Van Hertem, L. Meeus, “Technical Developments for the Future Grid“, Proceedings of International Conference on Future Power, pp. 6, 16–18 Nov 2005

[12] Southwire Company: Southwire Overhead Conductor Manual- Introduction to bare overhead conductors OCM (Overhead Conductor Manual) Book CP 1–11, available: http://www.southwire.com/

[13] A. Alawar, E.J. Bosze, S. R. Nutt, “A Composite Core Conductor for Low Sag at High Temperatures”, IEEE Transactions On Power Delivery, Vol. 20, No. 3, July 2005

7. NOMENCLATURE

AAAC	All Aluminum Alloy Conductor
ACCC	Aluminum Conductor Composite Core.
ACCR	Aluminum Conductor Composite Reinforced
ACSR	Aluminum Conductor Steel Reinforced
ACSS	Aluminum Conductor Steel Supported
CTE	Coefficient of Thermal Expansion
ENTSO-E	European Network of Transmission System Operators for Electricity
GACSR	Gap Type ACSR
HAWK	Type of conductor (240/40 mm2)
HPP	Hydro Power Plant
HTLS	High-Temperature Low Sag
LISBON	Type of ACCC conductor (diameter 21.79 mm)

OHL	Overhead Line
RES	Renewable Energy Sources
ULS	Advanced (premium) version of ACCC
WPP	Wind Power Plant

FINANCIAL IMPACTS OF REPLACING OLD TRANSMISSION LINES WITH ALUMINUM COMPOSITE CORE CONDUCTORS

Semir HADŽIMURATOVIĆ[1]

[1]Independent System Operator in Bosnia and Herzegovina

Abstract: Driven by the deregulation of power utilities, power lines are nowadays used to send more electric energy through longer distances to end consumers, compared to previous decades. Over the years, there have been various technical proposals for the improvement of old transmission conductors, with a goal of increasing its ampacity, as well as increasing the reliability of the power system as a whole.

Aluminum Conductor Composite Core (ACCC) is the result of an interdisciplinary mission to engineer more efficient lines, using state-of-the-art components that result in significant financial savings for the operators who decide to entrust such a new technology.

This paper deals with a comparative analysis of the financial impacts that advanced conductor technologies represent versus standard conductors. The primary focus of this paper is the reconductoring of existing overhead transmission lines using old corridors, contrary to erecting new lines. In the end, an extensive cost comparison example is given to demonstrate the various aspects of revitalization with ACCC conductors.

1. Introduction

Aluminum Conductors Steel Reinforced (ACSR) are the most widespread conductors used for overhead lines (OHL). They have been in use for a very long time, have passed extensive testing and finally have proven themselves in electric power systems.

With the deregulation of the electricity markets and open market trade between parties crossing national borders, power lines are becoming more and more loaded in order to transmit the energy from producers to consumers.

In the same time, with the economic growth and importance of the energy trade, it is more difficult to build new power corridors, because of, [1]:

- lengthy permitting procedures,
- unavailability of new corridors,
- construction time,
- construction costs.

In the same time period, at the beginning of the 2000's, two major electricity blackouts happened, New York in 2003, and Germany in 2006. In its sequence of events, the New York blackout was caused by a 345 kV transmission line that sagged into a tree and tripped.

OHL have a permissible sag, however when increasing current, the temperature increases, causing the conductor to sag below permissible limits. Which can be problematic if the vegetation under the overhead line in the corridor is not regularly trimmed.

Therefore, engineers started working of High Temperature Low Sag (HTLS) conductors that would enable the line to withstand higher temperatures and maintain an allowable sag at the same time.

High-temperature low sag (HTLS) are conductors capable to withstand high operating temperatures and, therefore, to carry a higher amount of power and/or energy when compared to conventional conductors. The CIGRE Task Force B2.11.03 defines them as conductors designed for applications where continuous operation is about 100°C or as conductors designed to operate in emergency conditions above 150°C, [2-4]

New composite technology conductors use a core of composite material around which aluminium conductor wires are wrapped. This design results in an increased tensile strength and reduced weight. Moreover, together with their higher operating temperatures, composite conductors have reduced sag under high loads [2,5]

The conductivity of aluminium alloy reaches 61% IACS (International Annealed Copper Standard for conductivity). According to other sources [6], the conductivity can be of 63% IACS or even better due to the aluminium strands being “dead soft” (fully annealed). This can translate into higher ratings. Moreover, since the aluminium strands are dead soft, the conductor may be operated at temperatures in excess of 250°C without loss of strength, [2,6].

HTLS Conductors are most often used for reconductoring of existing transmission and distribution lines, for use in heavy ice regions, ageing structure, long-span crossing, but also for connecting renewable sources, such as wind power plants, [2, 5, 6]

2. Conductor comparisons

Overhead line conductors can be classified into two major categories:

- The historically older technology, or standard conductors, or ACSR
- The advanced technology, or HTLS

All over the years, different HTLS conductors have emerged, some of which are; ACSS, GACSR, Invar, ACCC, ACCR. Table 1 offers the major differences between the two major conductor categories [1], [7].

Table 1. Comparison of Standard vs. HTLS conductors

	Standard	HTLS
Core	Steel	Reinforced steel Steel alloys Composite materials
Outer Strands	Concentric (Round) aluminum wires	Annealed aluminum Aluminum alloys Compact (Trapezoid) Strand

Unlike standard ACSR conductors that can be produced in any major conductor manufacturing facility, HTLS conductors, as a result of a more refined, diverse and complicated manufacturing processes are usually produced in several factories around the world.

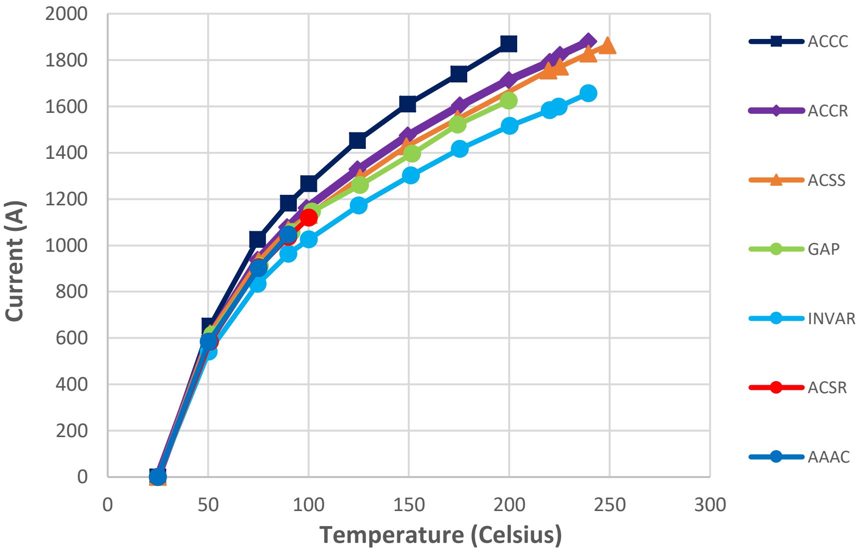


Fig 1. Conductor comparison showing ampacity capabilities [7]

When analyzing ampacity, temperature and sag parameters, Fig 1 and 2, for different HTLS conductor types, it can be concluded that both ACCC and ACCR, accomplish low sag at high temperatures by using composite core technology.

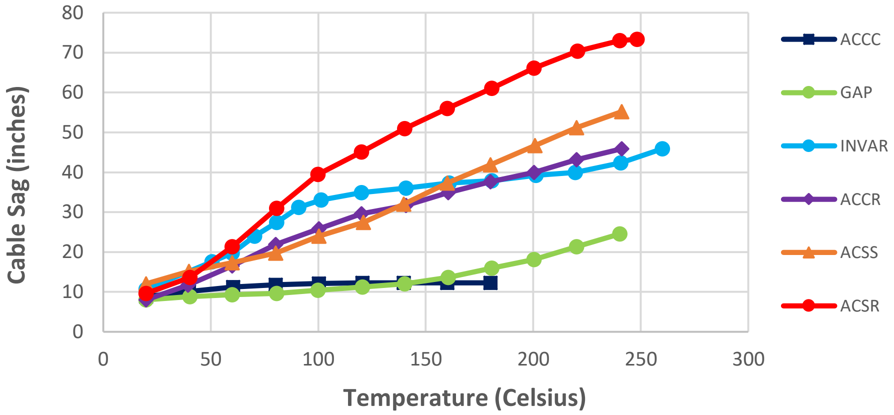


Fig 2. Sag - temperature comparison of several conductors [7]

The author decided to focus on ACCC, due to better comparisons results, as well as the availability of their manufacturer's (CTC Global) comparison software.

3. Aluminum Conductor Composite Core (ACCC)

Aluminum Conductor Composite Core or ACCC is a type of "high-temperature low-sag" (HTLS) overhead power line conductor manufactured by more than 20 international conductor manufacturers.

The ACCC conductor consists of a hybrid carbon and glass fiber composite core which utilizes a high-temperature epoxy resin matrix to bind hundreds of thousands of individual fibers into a unified load-bearing tensile member [8].

The composite core is surrounded by aluminum strands to carry electrical current (Fig. 3). The conductive strands are generally fully annealed aluminum and trapezoidal in shape to provide the greatest conductivity and lowest possible electrical resistance for any given conductor diameter [8].

Fig 3. ACSR (left) and ACCC (right) conductors [8]

The ACCC conductor is rated for continuous operation at up to 180°C (200°C short-term emergency), and operates significantly cooler than round wire conductors of similar diameter and weight under equal load conditions due to its increased aluminum content and the higher conductivity [8]. Though the ACCC conductor was initially developed as a “High-Temperature, Low-Sag” (HTLS) conductor to increase the capacity of existing transmission and distribution lines with minimal structural changes, its improved conductivity and reduced electrical resistance makes it ideally suited for reducing line losses on new transmission and distribution lines where improved efficiency and reduced upfront capital costs are primary design objectives [9].

4. Advantages and disadvantages

This composite strength member provides several advantages, [7-10]:

- It is lighter. The weight saved can be used for more aluminum conductor. ACCC cable uses trapezoidal strands to fit more aluminum into the same cable diameter.
- Softer, fully annealed aluminum can be used for the conductors. ACSR cable uses harder aluminum which contributes to the cable's tensile strength but has about 3% less electrical conductivity.
- It has a much lower coefficient of thermal expansion (CTE) (1.6 ppm/°C) than ACSR (11.6 ppm/°C). This lets the cable be operated at a significantly higher temperature without excessive sag between poles.

While the main disadvantages are:

- The primary disadvantage is its cost; ACCC costs 2.5–3 time as much as ACSR cable.
- Although ACCC has significantly less thermal sag than even other HTLS conductor designs, its core is quite elastic and sags more than other designs under ice load, although a ULS (higher modulus) version is available at a cost premium.
- The conductor has a larger minimum bend radius, requiring extra care during installation.
- The conductor requires special fittings, such as splice and dead-end connections.

5. Financial impacts

Financial aspects can be divided into the following categories, [7, 11, 12]:

- revitalization costs,
- line losses savings,
- financing the revitalization,
- impact on NTC values.

5.1. Revitalization costs

The revitalization or reconductoring of ACSR overhead lines is the process of removing old conductors and equipment, in order to replace it with new HTLS equipment.

A) cost of new conductors,
B) cost of dismantling existing conductors,
C) cost of installing new fittings, suspension and insulators,
D) cost of anti-corrosion protection.

It is important to notice that all of these prices are country-specific and subject to a large number of changes and economic fluctuations. Take for example the price or new HTLS conductors, that are a dependent on the wholesale price of aluminum, as well as the stock exchange rate of US Dollars. The manufacture and delivery can take up to 4-6 months, which in the meantime, affects the final price.

5.2. Line losses savings

Besides the technical advantages, including the aspect of increasing throughput capacity and having a lower sag, by replacing a line with composite core conductors, another financial advantages are the decreased line losses.

According to line losses formula, I^2R, each line generates losses, depending on the current and the resistance. By using HTLS conductors, and therefore by decreasing the resistance of the line, a decrease of line losses occurs.

The planned lifetime of an overhead line, depending on different factors and evaluation criteria ranges between 30 to 50 years. Consequently, the cumulative line losses savings over a 30 year period, are an important subject when considering the revitalization.

To that end, the financial feasibility of line revitalization is justified by the savings in line losses over the planned lifetime of the line.

5.3. Financing the revitalization

The cost of revitalization can be financed in different ways, from the TSO’s own resources, credit funds, or as a combination of the above. In any case, a present discounted analysis has to be performed in order to assess the economic aspects of financing the revitalization.

Present Discounted Value, or simply Present Value (PV) is the value of an expected income stream determined as of the date of valuation. The present value is always less than or equal to the future value because money has interest-earning potential [13].

The present value for the assessment of OHL revitalization has to take account of the following financial parameters:

- interest rate,
- repayment period,
- annuities,
- discount rate,

- grace period.

5.3. Impact on NTC Values

Net Transfer Capacity (NTC) is the capacity available for commercial transactions. The NTC value is calculated as follows [14]:

$$TTC - TRM = NTC \tag{1}$$

where,

TTC – Total Transfer Capacity

TRM – Transmission Reliability Margin

In other words, NTC is the maximum allowed transaction possible between two neighboring countries. The capacity varies based on the period of the year, production, and consumption, but also on grid's infrastructure. The maintenance of grid elements, affecting the topology of the grid, can lead to a decrease of NTC values, while the investments in expanding the grid, such as new power lines, or reconductoring with new technologies can increase the NTC value.

However, based on experience, an extensive increase of NTC values can only be expected with the revitalization of significant lines on 220 or 400 kV networks.

The funds collected on the account of allocating capacity present a compelling item for budgeting of TSOs. Therefore, the revitalization of significant lines with HTLS conductors can also be justified and financed by NTC funds.

6. Example

In this chapter, an example of the above financial impacts is given. A cost comparison analysis is given for a 20 km overhead line 110 kV in Bosnia and Herzegovina. In this example, an existing ACSR OSTRICH (Al/Fe 150/25 mm^2), has to be replaced by line with a higher throughput capacity. Two possible options are:

- Building a new line using standard technology ACSR HAWK (Al/Fe 240/40 mm^2) using the existing corridor,
- Revitalizing the existing line, by replacing the conductors and suspension equipment with ACCC ROVINJ.

Table 2. Comparison of conductors

	ACSR OSTRICH	**ACSR HAWK**	**ACCC ROVINJ**
Diameter (mm)	17.27	21.79	17.09
Aluminum area (mm^2)	152	241.7	187.8
Rated strength (kN)	53,8	86.7	71.1
Weight (kg/km)	615	976	576.4
AC Resistance at 25°C (ohm/km)	0.190	0.1198	0.1520
Ampacity (A)	490	640	921

As it can be observed from Table 2, ACSR HAWK has a higher weight compared to ACSR OSTRICH, therefore existing towers and suspension equipment couldn’t bear the weight. For that reason, a new line using ACSR HAWK would require new towers, but it would be possible to use the existing corridor.

On the other hand, ACCC ROVINJ has a lower weight than ACSR OSTRICH, allowing it to be used on the existing lines. However, because of ACCC technology, new fittings will have to be installed.

According to [15], the cost of building ACSR HAWK is 97.200 €/km (per three phases), while the dismantling of existing towers, foundations and conductors would cost 25.000 €/km. Therefore, the cost of building a new line using ACSR HAWK would sum up to 2.444.000 €.

The cost of conductor ACCC ROVINJ is 10.000 €/km (per one phase). In order to calculate the total length, one has to account for the following factors:

- geographical length: 20 x 3 km,
- sag,
- reserve.

In practice, the sag and reserve take for 10 % of the geographical length. So, the total length of conductor ACCC ROVINJ would sum up to 66 km. Accordingly, the cost would be 660.000 €.

Besides the of the new conductor, additional costs are given in Table 3.

Table 3. Revitalization costs

Conductor	**Cost of new conductor**	**Dismantling existing conductors**	**Cost of installing new fittings, suspension and insulators**	**Cost of anti-corrosion protection**	**TOTAL**
	€	€	€	€	€
ACCC ROVINJ	660.000	525.000	180.000	230.000	1.595.000

In the following table, the costs for both options are given below:

Table 4. Investment costs

Investment	**Investment cost**
	€
New ACSR HAWK	2.440.000
Revitalization with ACCC ROVINJ	1.595.000

Therefore, it can be seen that the revitalization with HTLS conductors is about 35% cheaper than building a new line, while at the same time increasing the throughput capacity for more than 34 % (according to Table 2).

As for the line loss savings, according to the CTC Global Comparison Software, the following load and energy assumptions are used (Table 5).

Table 5. Comparison assumptions

Assumption	**Value**
Line length	20 km
Voltage	110 kV
Total Peak Operating Amps	300 A
Load Factor	20 %
Active Power Losses Price	48,6 €/MWh

It is important to note that the active power losses prices are is formed as a market price, based on offer and demand. In this case, the price of 48,6 € was taken as reference in this example, base on the average losses price for Bosnia and Herzegovina in 2016, [16].

After performing the calculations, the following results are obtained.

Table 6. Comparison results - Yearly

Conductor	**Yearly losses**		
	MWh	**€** ***(48,6 € / MWh)***	**%**
ACSR OSTRICH (Base conductor)	648	31.492,8	100
ACSR HAWK (Option 1)	401	19.488,6	61,9
ACCC ROVINJ (Option 2)	514	24.980,4	79,3

Table 7. Comparison results – 30 Years

Conductor	30 Years losses	
	MWh	€ *(48,6 € / MWh)*
ACSR OSTRICH (Base conductor)	19.440	944.784
ACSR HAWK (Option 1)	12.030	584.658
ACCC ROVINJ (Option 2)	15.420	749.412

In other words, over a 30 year period, compared to the base conductor, ACSR HAWK would earn savings in the amount of 360.126 €, while the savings for ACCC ROVINJ would amount to 195.372 €.

By taking into account the investment costs from Table 4, and the calculated 30 year savings, it can be observed that the most profitable option is ACCC ROVINJ.

Table 8. Final Comparison results

Option	Conductor	Investment cost	30 year savings	Total cost
		€	€	€
1	ACSR HAWK	2.440.000	360.126	2.079.874
2	ACCC ROVINJ	1.595.000	195.372	1.399.628

6. Conclusion

The focus of this paper is to present, summarize and categorize the financial aspects related to the reconductoring of standard OHL with technologically advanced composite core conductors. The financial impacts are divided into several categories, including; revitalization costs, line losses savings, financing the revitalization, and finally the impact on NTC values. Within the revitalization costs, the most common expenditures are given for reconducuring projects. An important expense for the TSOs are line losses, and within the Line Losses Savings chapter, it is explained how HTLS conductors can help create savings cause by line losses. The financing aspects of the reconductoring are explained next and at the end, it is explained how revitalization with HTLS conductors can potentially help increase the capacity for commercial transactions.

In the last chapter, a detailed example of a reconductoring project is given, defining all relevant costs and items needed to replace an existing ACSR OSTRICH line with the adequate ACCC conductor. An extensive cost comparison is given, proving and justifying the need to invest in the advanced ACCC technology.

REFERENCES

[1] S. Hadzimuratovic, L. Fickert, „Impact of gradually replacing old transmission lines with advanced composite conductors“, IEEE ISGT Conference Proceedings, Sarajevo 2018 (unpublished).

[2] G. Migliavacca, „Advanced Technologies for Future Transmission Grids“, Springer, 2013.

[3] CIGRE: Results of the questionnaire concerning high temperature conductor fittings Task Force B2.11.032004

[4] CIGRE: Considerations relating to the use of high temperature conductors Technical Brochure 331 2007

[5] S. Cole, W. Van Hertem, L. Meeus, „Technical Developments for the Future Grid“, Proceedings of International Conference on Future Power, pp. 6, 16–18 Nov 2005

[6] Southwire Company: Southwire Overhead Conductor Manual-Introduction to bare overhead conductors OCM (Overhead Conductor Manual) Book CP 1–11, available: http://www. southwire.com/

[7] “Techno-economic analysis of the application of the ACCC conductor on the 110 kV OHL Sinj - Dugopolje – Meterize”, Energovod, 2014

[8] “ACCC Engineering Manual, CTC Global Corporation, 2011

[9] A.V. Kenge, S. V. Dusane, J. Sarkar, “Statistical Analysis & Comparison of HTLS Conductor with Conventional ACSR Conductor”, International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT) – 2016

[10] A. Alawar, E.J. Bosze, S. R. Nutt, “A Composite Core Conductor for Low Sag at High Temperatures”, IEEE Transactions On Power Delivery, Vol. 20, No. 3, July 2005

[11] “Techno-economic analysis of the selection of conductors on OHL 2x110 kV Meterize – Dujmovača – Vrboran“, Energy Institute Hrvoje Požar & Dalekovod Project Zagreb, January 2016.

[12] “Techno-economic analysis of the selection of conductors on OHL 110 kV Obrovac - Zadar“, Energy Institute Hrvoje Požar & Dalekovod Project Zagreb, April 2016.

[13] C. Sekhar„Capital Budgeting Decision methods: Payback period, Discounted payback period, Average rate of return, Net present value, Profitability index, IRR and Modified IRR“, ISBN 1980203458, February 2018

[14] M. Kosarac, A. Carsimamovic, H. Turajlic, C. Vujovic „A Practical Example of Increasing Net Transfer Capacity (NTC) by Modifying the Power System Topology“, Cavtat Conference 2014.

[15] „Prices of goods, works, services and normative standards“, Elektroprenos BiH.

[16] „Report on Auxillary Services and Balance Market Report in Bosnia and Herzegovina for 2016“, Independent System Operator in Bosnia and Herzegovina, 2017.

NOMENCLATURE

AAAC	All Aluminum Alloy Conductor.
ACSR	Aluminum Conductor Steel Reinforced.
ACSS	Aluminum Conductor Steel Supported.
GACSR	Gap Type ACSR
INVAR	Special nickel-iron alloy FeNi36
ACCC	Aluminum Conductor Composite Core.
ACCR	Aluminum Conductor Composite Reinforced.
HTLS	High Temperature Low Sag Conductor.
OHL	Overhead Line
TSO	Transmission System Operator
WPP	Wind Power plants
TTC	Total Transfer Capacity
TRM	Transmission Reliability Margin
NTC	Net Transfer Capacity

APPENDIX B
Transmission System Maps

Figure B1 – Map of Slovenia and parts of Italy, Austria and Croatia

Figure B2 – Map of Hungary and nothern Croatia

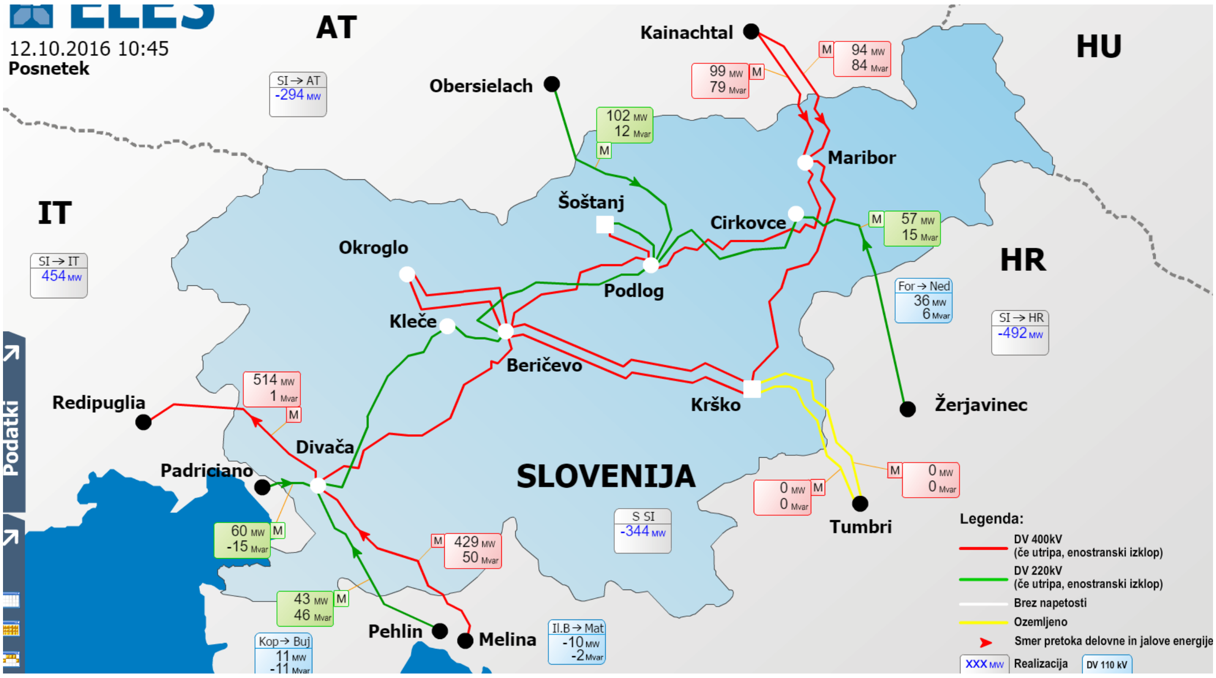
Figure B3 – Map of Italy, Montenegro and MONITA Cable

Figure B4 – Bosnia, and parts of Croatia, Serbia and Montenegro

APPENDIX C
Field Trip Reports

ELES PST @ Divača

Visit Report – 07.11.2016.



Tehnical details

Voltage level: **400 kV**
Rated power: **2 x 600 MVA units = 1200 MVA**
Taps: **65 (neutral ± 32)**
Phase shifting angle: **± 40°**
Total weight: **1760 tons** (two units)
Oil weight: **434 tons** (two units)
Cooling: **ONAN/ONAF – 80/100%**
Dimensions: **25 x 10 m** (one unit)

Tank configuration: **Symmetrical**
$U_k = 20.6\ \%$
$X_0 = 49.23\ \Omega$
$X_+ = 55$ @ 0°C
Total cost: **143.6 mil. €** (36.9 mil. € - PST only)
Factory: **Siemens** Transformers Austria - Weiz
In operation: **15th of December 2010**

Notes

Challenges before investment

- The SLO system was operating on the edge of fulfilling N-1 criterion:
    - **Separation of grid in two parts** (tripping of TL 400 kV Beričevo-Podlog) probably followed by partial black-out
    - **Cascade tripping with influence on the wider area** (tripping of TL 400 kV Beričevo – Podlog and TL 400 kV Divača - Melina)
    - **Endangered operation of neighboring systems** (overloading of SWISSGRID transmission system after tripping of 400 kV Divača – Redipuglia)
- Transient instability was also a major issue because of the threshold on SLO-ITA border set to 1700 MW.
- Low voltage profiles in summer were also an issue.
- Increased losses in transmission grid (operational costs).

Realtime solutions to mentioned issues were:

- Real-time solutions
    - Topology changes in transmission grid
        - Redirecting flows to neighboring TSO (direct connection APG-HEP OPS in SS Podlog)
        - Redirecting flows between voltage levels (disconnection of TR 400/220 kV in SS Podlog)
    - Pentalateral reduction
- Investments
    - Aditional lines (TL 400 Krško – Beričevo - ongoing project for last 20 years)
    - **Instalation of PST**

Purpose of investment

- To increase 400 kV transmission network operation reliability
- To reduce large uncontrolled power transits over Slovenian electric transmission system
- To enable larger and controlled power flows between SLO-ITA
- To reduce losses in the system resulting from too large and uncontrolled transits from East Europe towards Italy
- To enable greater income from free cross-border transfer capacity lease
- To enable faster and controlled restoration of the network after its potential collapse.

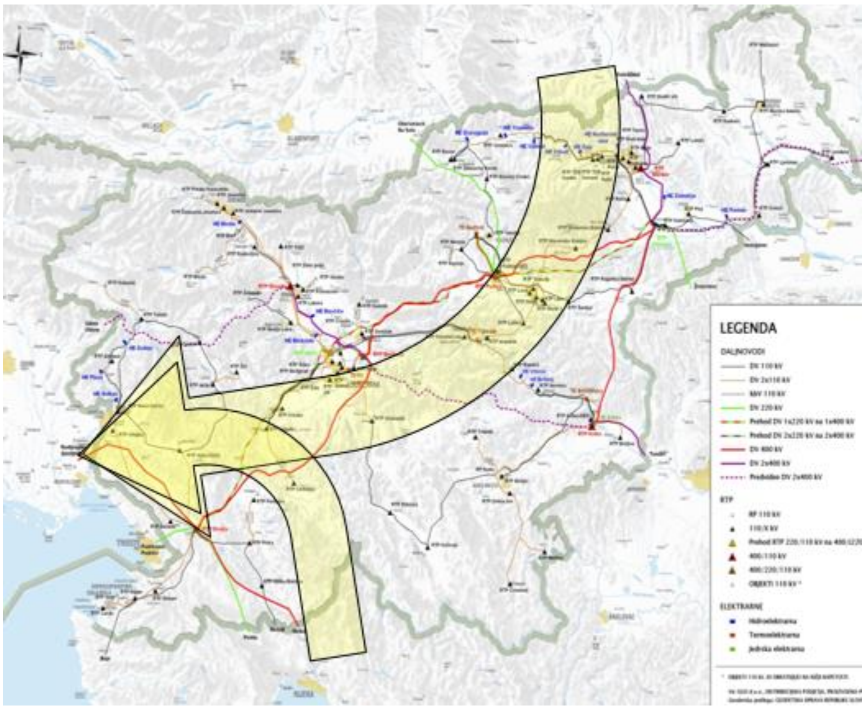


Figure – Flows through Slovenia

There are two PSTs on Italian – Slovenian border:

- 400 kV Redipuglia – **Divača** (on SLO side) – commissioned in 2010.
- 220 kV **Padriciano** – Divača (on ITA side) – commissioned in 2008.

Padriciano PST details
220 kV / ± 40 ° / 33 taps
370 MVA

The Divača PST was planned in 2004/2005, ordered in 2006 (5 years building period), delivered earlier (4 years) and finally commissioned on 15th of December 2010. Analyzes have shown that within 3 years, the PST was payed of (through capacity selling, losses reduction, etc…).
At the time of ordering, factories were full, but ELES experts estimate that now the PST would have been cheaper and could be delivered earlier.
The cost of the whole project was 140 mil. € (PST + bays + OHL + transformer). The cost of the two PST units were 36.8 mil. €, with a total of 46 mil. € including bays and the connection itself.

Flows / Capacity

The capacity of 400kV OHL Redipuglia-Divača is **2700 MW** (3-bundle OHL).
The capacity NTC of SLO-ITA border is calculated to 1500 MW:

- **1200 MW** - 400 kV Redipuglia – Divača, plus
- **300 MW** - 220 kV Padriciano – Divača

Before PST installation, flows were exceeding **1800 MW** on Redipuglia-Divača only.
Analyses have shown that tripping of OHL Redipuglia – Divača with a power flow of more than 1400 MW could cause tripping of NPP Krško. Therefore the threshold of power flows on SLO-ITA border is set to 1700 MW (1500 MW?). Even nowadays, when the PST is turned off, the flow can be 1800 MW.
Power flow influence of one tap is 18 MW. There are 65 taps (±32).

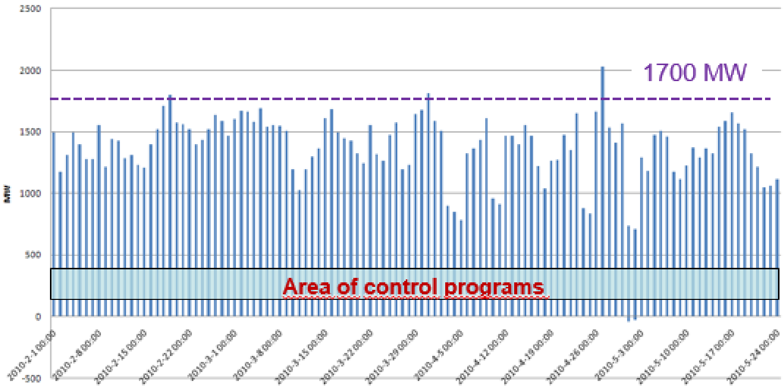


Figure - Power flow on SLO-ITA border in February – May 2010

PST Construction

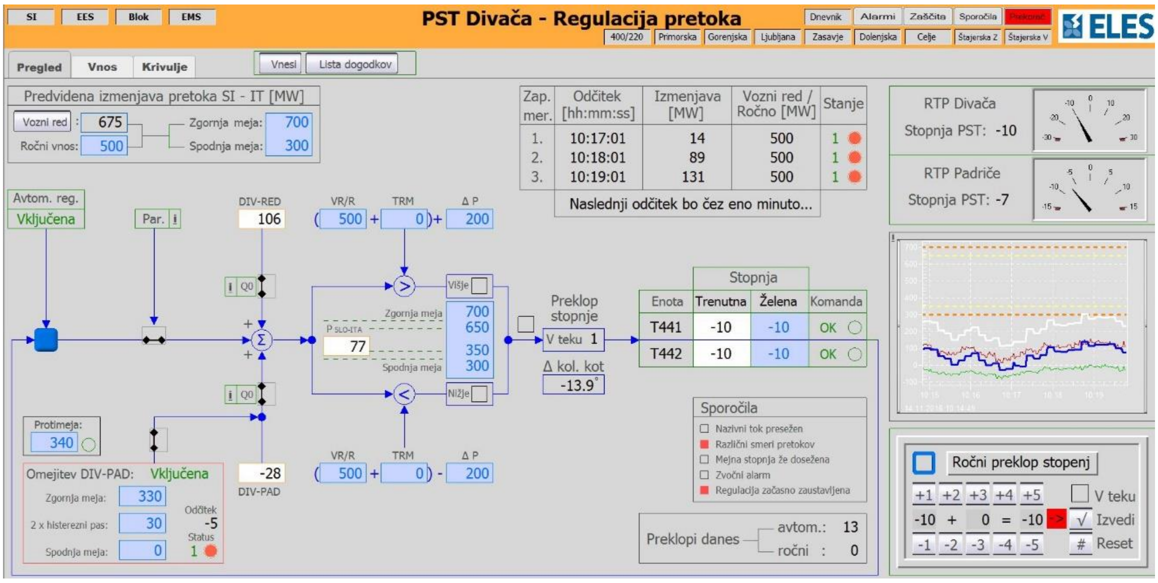
The PST units consist of four parts:

- serial 400 kV winding,
- exciter,
- cooling system for serial winding,
- cooling system for exciter.

The **OLTC** is on the exciter side and consists of 3 one-phase tap changers. Three-phase configuration was not possible because of high currents through tap changer.
On the other hand, the **ADVANCE/RETARD** switch is inside the serial part.
Dimensions of one unit (with cooling system): 25 x 10 m
Weight of one unit: 900 t / 200 t of oil

Operation modes

The controller of the PST in Divača is coordinated with data from PST in Padriciano. The setpoint is at **800 MW (±200),** which means it can go from **600-1000 MW**. There is a **50 MW** threshold in regard to hysteresis.



PST Divača - Regulacija pretoka

Predvidena izmenjava pretoka SI - IT [MW]

Vozni red : 675

Ročni vnos: 500

Zgornja meja: 700

Spodnja meja: 300

Zap. mer.	Odčitek [hh:mm:ss]	Izmenjava [MW]	Vozni red / Ročno [MW]	Stanje
1.	10:17:01	14	500	1 ●
2.	10:18:01	89	500	1 ●
3.	10:19:01	131	500	1 ●

Naslednji odčitek bo čez eno minuto...

RTP Divača
Stopnja PST: -10

RTP Padriče
Stopnja PST: -7

Avtom. reg.: Vključena

DIV-RED 106

VR/R TRM Δ P: (500 + 0)+ 200

Zgornja meja 700 650

P SLO-ITA 77

Spodnja meja 350 300

V teku 1

Δ kol. kot -13.9°

	Stopnja		
Enota	Trenutna	Želena	Komanda
T441	-10	-10	OK ○
T442	-10	-10	OK ○

Protimeja: 340 ○

Omejitev DIV-PAD: Vključena

Zgornja meja: 330

2 x histerezni pas: 30

Spodnja meja: 0

Odčitek -5

Status 1 ●

DIV-PAD -28

VR/R TRM Δ P: (500 + 0) - 200

Sporočila
- ☐ Nazivni tok presežen
- 🟥 Različni smeri pretokov
- ☐ Mejna stopnja že dosežena
- ☐ Zvočni alarm
- 🟥 Regulacija začasno zaustavljena

Preklopi danes
avtom.: 13
ročni : 0

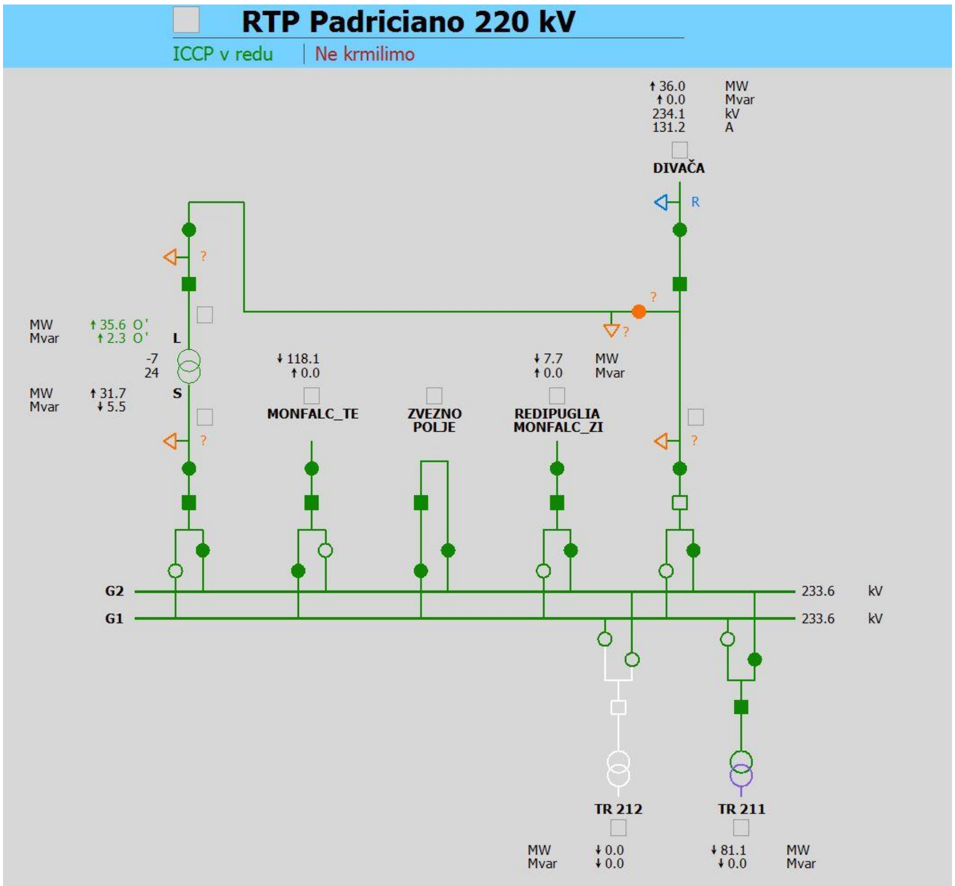
☐ Ročni preklop stopenj

☐ V teku

-10 + 0 = -10 -> √ Izvedi

\# Reset

Figure - PST Divača controller



RTP Padriciano 220 kV

ICCP v redu | Ne krmilimo

Figure – PST Padriciano

The controller calculates flow each two minutes and coordinates the tap of the PST. The PST must be operated with great caution, and with slow OLTC operation. Therefore, after the PST passes the threshold (ex. 1000 MW), the controller waits for two more cycles (2x2 min), and changes the tap until the new operation point is within the limits of 950-650, because of the hysteresis.

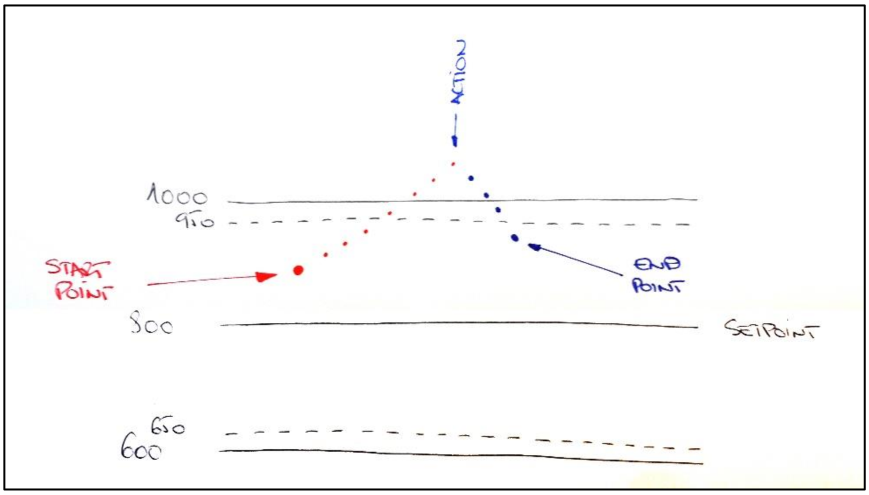
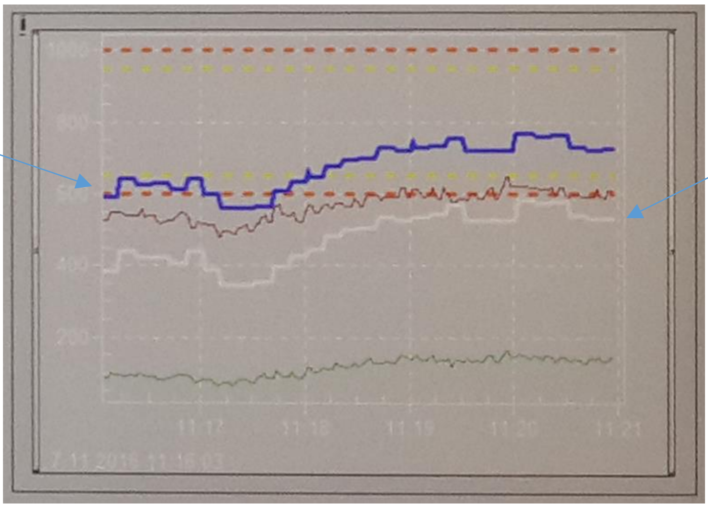


Figure – Operation logic

The PST can also be operated manually, and because of security issues, the use is limited to steps between 1 MW and 5 MW.

The two units are always working in parallel. Even though at specific times, one unit could be turned off in order to reduce the losses, it is never done. There is a specific protection ensuring same tap settings are used on both units in order to protect them from loop flows.



without PST
(blue line)

with PST
(white line)

Figure – Flows with/without PST

Control is mainly based on flows, not on the angle. The angle is being calculated and is not used as a primary reference. However, the angle of the PST is used as a reference when reconnecting systems. If there would be a big angle difference upon reconnection of ITA-SLO border, then angle could be changed in order to reconnect systems (synchro-check function).

PST Location

There was not much of a specific analysis when PST location was determined. The problem was on SLO-ITA border, and there was no calculation regarding finding the optimal location.

It is interesting, that even though the PSTs are represented on geographical representations as if they are located at the end/beginning of a line (between two line bays), in reality they are located somewhere else (usually behind) because of three reasons:

- Existing line bays – Namely PST are installed historically after the lines. So it would be complicated to put them as they are shown on maps.
- Space – PSTs are located where there is enough space. They are then electrically connected in an optimal configuration.
- Interoperability – through different switching states, PST can be used for different purposes. If PST were located as on maps, there would be no such possibility.

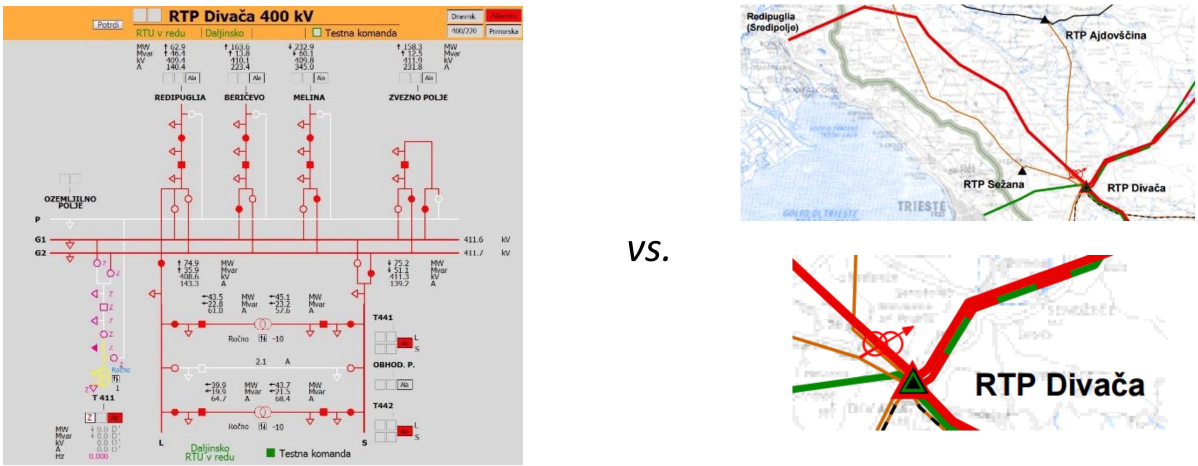


Figure – Map vs. realistic location

Protection and maintenance

The PST is protected by differential protection (set with the help of Zoran Gajc from ABB), but also overvoltage, overcurrent, but also bus bar protection.

As it is shown of Figure/one-phase diagram, Redipuglia and Melina are on the same bus bars (G2), while Beričevo is the other bus bar (G1). Buses G1 and G2 are coupled through the coupling bay.
This is done in order to limit tripping of bus bar protection to a minimum number of elements.

There is "tap changer" protection which ensures that both PST are using same tap settings.
The PST units are maintained once a year, at the same time of the maintenance of Redipuglia – Divača line.

PST Divača interoperability

PST is located "behind" bus bars and connected electrically as shown on following figure. In this way, it is possible to connect it in a number of different ways.

By changing the switching state, it is possible to isolate specific line/lines, or to put the PST between bus bars G1 and G2, which is a great function in case of emergency. But generally speaking, the PST is connected to Redipuglia (Load side).

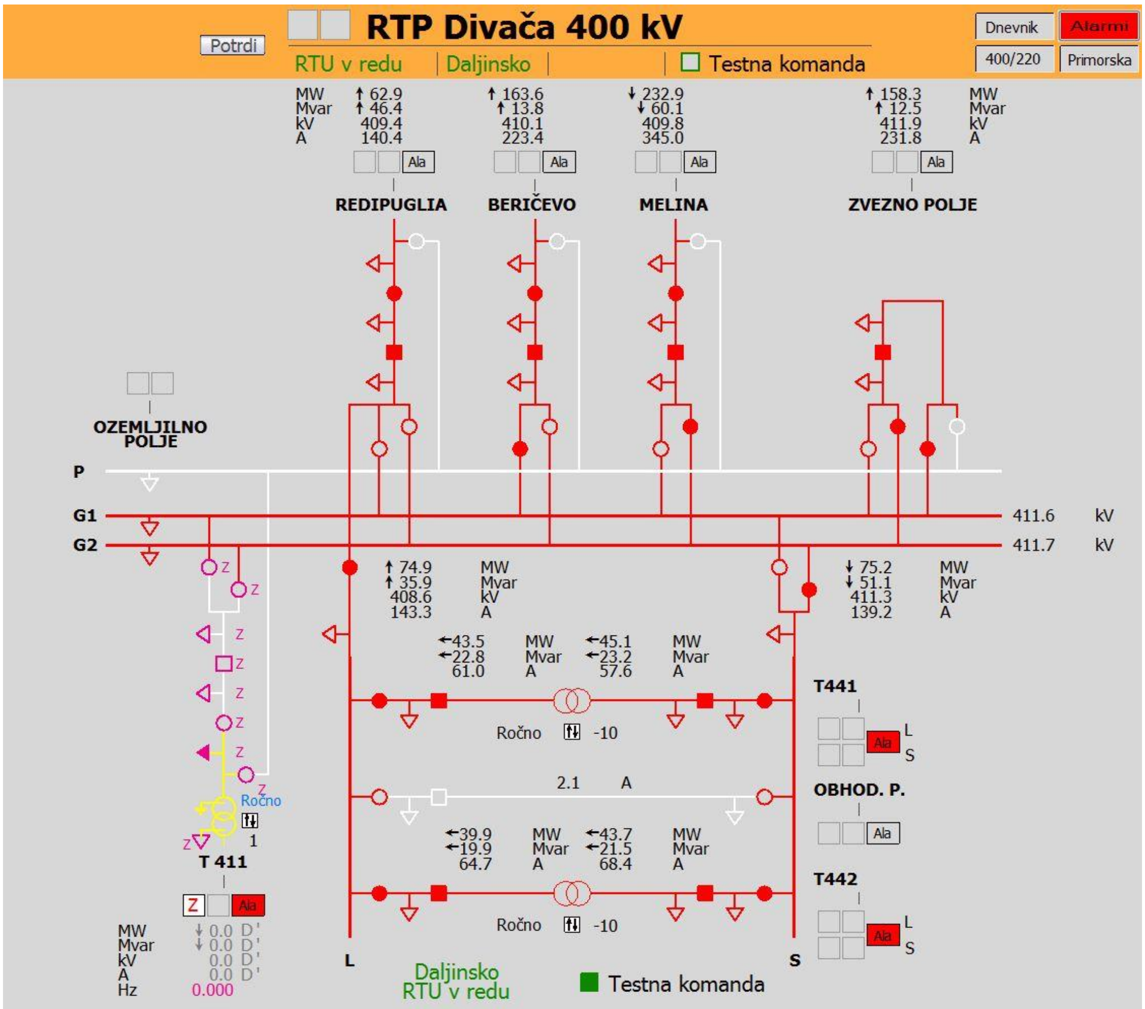


Figure – One-phase diagram of 400 kV substation Divača

Reactive power control

Generally speaking, the PST is a consumer of reactive power. At the moment of the visit, one PST unit loaded with 300 MW was consuming about **38 MVAr** (figure taken from previous figure).

However, it is possible to influence voltages through load flow changes.

- In case of **low voltage scenario** (<400 kV), by **increasing** the load through PST, it is possible to decrease voltages.
- In the case of **high voltage scenario** (>400 kV), by **decreasing** the load through PST, it is possible to increase voltages.

This has to be done with regard to surge impedance load (line natural power) – e.g. for 2xAl-Fe 490/65, SIL = 530 MW (thermal limit = 1330 MW)

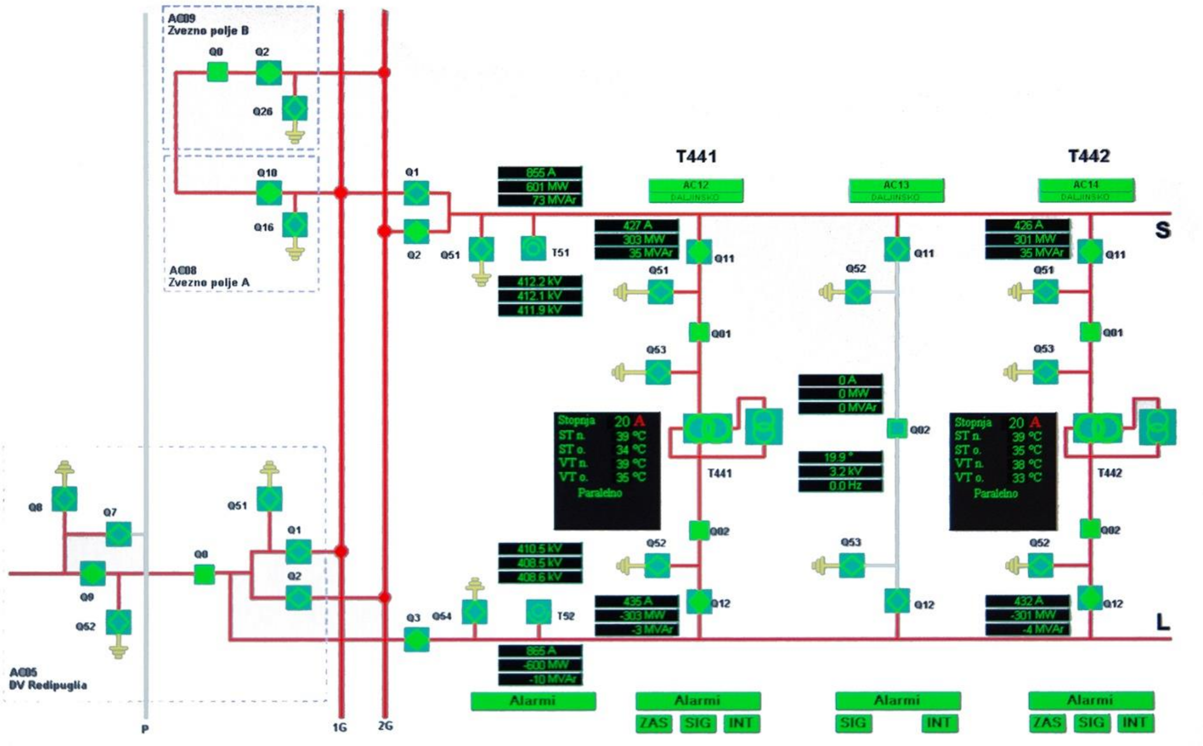


Figure – PST Parameters

Followup

→ ENTSO-E WG “Coordinated System Operation”
→ ELES Questions – NTC/TTC values after/before.
→ APG asymmetrical PST build
→ What if PST would be smaller than regular flows?
→ NTC/TTC research (Zeka?)
→ why is it called quadrature voltage?
→ Advanced Solutions in Power Systems: HVDC, FACTS, and Artificial Intelligence / Mircea Eremia, Chen-Ching Liu, Abdel-Aty Edris
→ Advanced Technologies for Future Transmission Grids / Gianluigi Migliavacca
→ Lienz – Soverzene PST ?
→ prof. Aleksandar Savić, ETF Beograd

Other details

Divača – Ljubljana: 54 km

Contact persons

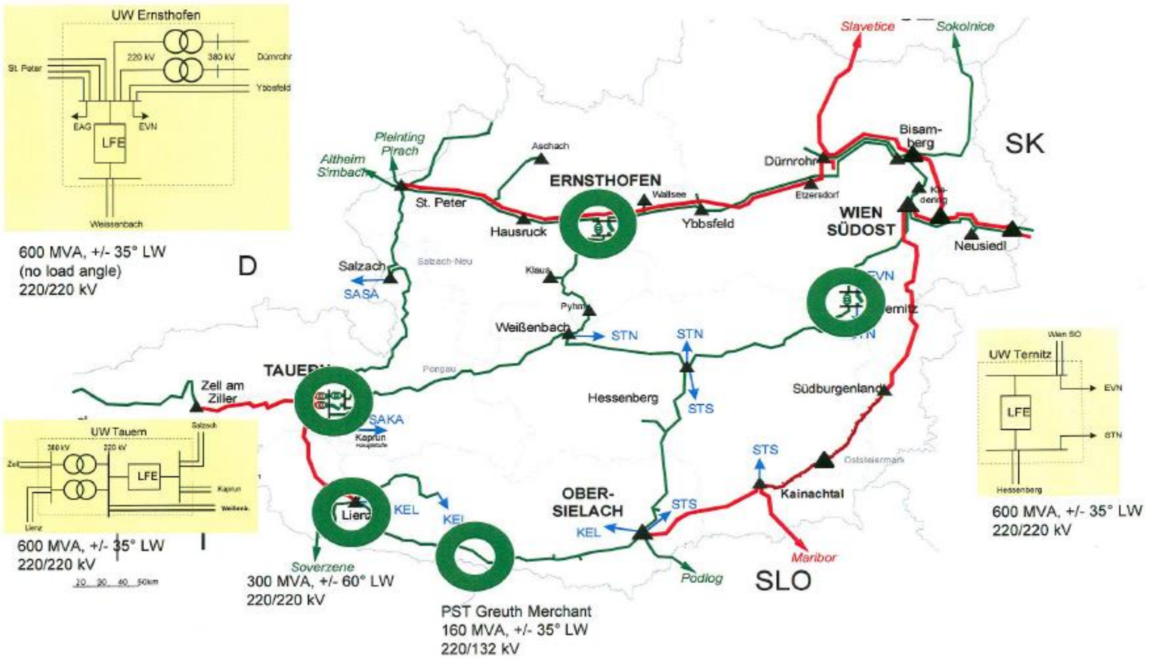
- Franc Kropec, Head of DC, (franc.kropec@eles.si)
- Blaž Traven, Protection, (blaz.traven@eles.si)
- Matjaž Dolinar, Operational Planning, (dolinar.matjaz@eles.si)
- Aleksander Polajner, Asset Management, (aleksander.polajner@eles.si)
- Mater Bratić, (matej.bratic@eles.si /matej.bratic@gmail.com / 041 349 289 / 040 501 077)

Sources/Links:

https://www.ibe.si/en/news/Pages/Novica35.aspx
http://www.eib.org/projects/pipelines/pipeline/20090453
http://www.kolektorautomation.com/index.php?t=referenceNews&l=en&id=68

APG PST Meeting

Visit Report – 11.11.2016.



Tehnical details

North-South PST – Ternitz, Enrsthofen & Tauern)

Voltage level: **220 kV**
Rated power: **600 MVA units**
Phase shifting angle: **± 35°**
Tank configuration: **Symmetrical**
Total cost: **30 mil. €**
Factory: **ABB**
In operation: **2006**

PST Lienz – Soverzene (ITA)

Voltage level: **220 kV**
Rated power: **300 MVA unit**
Phase shifting angle: **± 60°**
Tank configuration: **Symmetrical**
In operation: **2012**

PST Merchant line Greuth – Tavizio (ITA)

Voltage level: **220 / 110 kV**
Rated power: **160 MVA unit**
Phase shifting angle: **± 35°**
Tank configuration: **Asymmetrical**

Notes

Before PSTs

Especially during winter nights, strong loadflow from north to south occurs. This is due to following reasons:

- constant production of hydro power plants along the danube
- high production of thermal power plant in the Vienna region
- high demand due to pumping hydro pump storage plants in the south
- European transit from Germany, Czech republic, Poland to Italy (partly through Slovenia)

Bottlenecks are the 220 kV lines (from west to east):

- St. Peter – Tauern
- Ernsthofen – Weissenbach
- Wien/Südost – Ternitz

Those lines are constructed as double circuit lines with 340/110 mm² aluminum-steel conductors with a thermal rating of 800 A per circuit resp. 300 MVA per circuit. The total transfer capacity from north to south is therefore thermally limited to 6x300=1800 MVA. Considering the N-1 security analysis, there is a limit of 200 MVA per circuit resp.1200 MVA totally. Those 1200 MVA are theoretical, because that assumes an equal loading of all three double-lines, which is normally not given. During last years, N-1 security was hurt quite often and long.

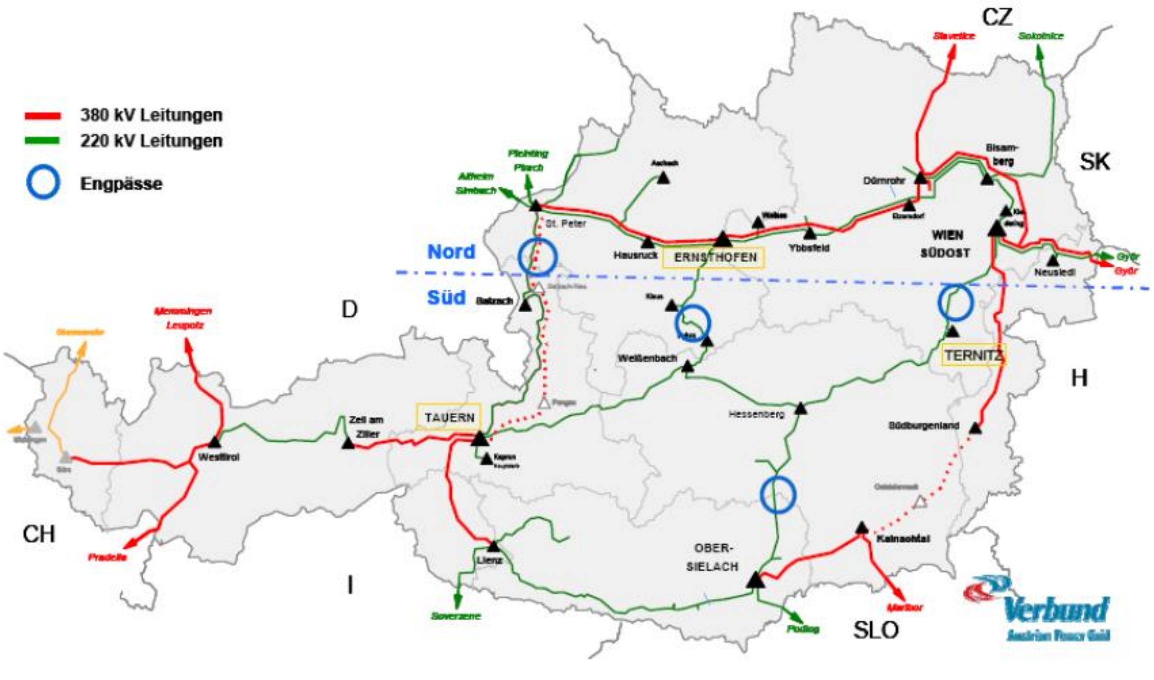


Figure – Map of Austrian Transmission grid

Improvements after PST

Constraints for the placement of the PSTs were given by the available space for enlargement in the existing substations. Furthermore it was necessary, that all transformers feeding into one 110 kV grid must be on the same side of a PST to avoid excessive loadflows through the 110 kV grid. In Austria there are approx. 15 galvanic separated 110 kV grids.

Two alternatives had been investigated:

- One PST in Tauern for St.Peter – Tauern and one PST in Hessenberg for controlling the loadflow on Ernsthofen – Weissenbach and Wien/Südost – Ternitz
- One PST in Tauern for for St.Peter – Tauern, one PST in Ernsthofen for Ernsthofen – Weissenbach and one PST in Ternitz for Wien/Südost – Ternitz

Due to better controllability, the **second alternative** was chosen.
All substations are equipped with minimum 2 busbars.
Controlling one PST means also changing the load flow over the other lines. With loadflow calculations the following control-matrix was generated:

$$\begin{pmatrix} \Delta P_1 \\ \Delta P_2 \\ \Delta P_3 \end{pmatrix} = \begin{pmatrix} -19,2 & 6,2 & 3,0 \\ 5,4 & -24,4 & 6,2 \\ 2,2 & 6,8 & -18,2 \end{pmatrix} [\mathrm{MW}] \cdot \begin{pmatrix} \Delta tap_1 \\ \Delta tap_2 \\ \Delta tap_3 \end{pmatrix}$$

1=Tauern, 2=Ernsthofen, 3=Ternitz, ± 28 taps resp. ± 35° no load angle

Contingency analysis was made for tripping of a single circuit and tripping of both circuits resp. tripping of one PST. It was analyzed, whether the overloading of parallel lines, following an outage, can be handled with the PSTs and how many tap changes are necessary for that. Latter means, how fast a temporary overloading can be removed, assuming that switching from one tap to the next takes 5-6 seconds.

The result was, that the the (N-1)-transfer limit of each double line can be increased to 470 MVA, which gives 1400 MVA (instead of theoretical 1200 MVA before) total in north-south-direction.
The control behaviour of the PSTs is implemented in the Optimal Power Flow-Tool of Verbund Austrian Power Grid.

Planning and implementation:

- Most activities happened during Oct-Nov-Dec 2006
- N-1 was not ok during winter
- Integral software was used, PST was modeled as two asymmetrical units
- First to order (30 mil. € - equipment, bays, cables, PST) – ABB

General information

- PSTs are used even today, when working on parallel lines, to limit flows on the other line.
- Maximum capacility of the line is 400 MVA, with PST it increases to 600 MVA
- What would happen if lower capacity PST was installed → Lowering capacity of PST would lower capacity of line.
- Experience has shown that if you build a weak line to Italy, you need a PST.
- Energizinig transformers → inrush current → current transformer
- Each phase shifter has a specific control strategy
- **Advice is to put PST in a place that has more than one weak line. And to put it bigger.**

PST Specifics

North-South PSTs

600 + 15% overload all time, 150% 30 min (20C), 170% 30 min (-20C)
Heating of lines takes 10-30 minutes
PST Tauern coul be moved to Hessenberg (in the near future)
Symmetrical (35+10/35-10)
Manual control
Automatic protection

PST Lienz - Soverzene

63 deg in Lienz → 300 MVA
Lienz can completely block the flow (0 MVA flow)
Very fast (full flow in 1 minute, 15/20 MW / tap)
Automatic control

PST Greuth – Tavizio

Greuth - Tavizio (merchant line) (220 → 132)
asymmetrical – 150 MVA (35 deg)
Automatic control

Plan about new PSTs

NEW PST → Austria → Czech Republic
NEW PST → 380/220 kV Westtirol – Italy
Czech 1700 in total (2x850)

Financial effects / savings

- Redispatch (pump wanted to pump, but it wasn't allowed)
- 30-70 mil€ for redispatch before PSTs
- No savings concertning capacity for no/so PSTs
- Lienz PST payoff time → 6 years
- APG North/South PST payoff time → 1.5 years
- PST Mikolowa (Poland) payoff time → compensated in months (1200 MVA in series) 20 degree each (40 in total)

APG Reactive compensation

- Shunt reactors on 400/200 kV in 30 kV
- 1200 MVAr of coils in APG network

PST Reactive compensation

- Reactive compensation used but it's not the primary role.
- Augmenting impedance helps but it augments losses

PST experiences from neighboring TSOs:

- Tennet could't use PST because of neighbours. Neighbours were against it, then Tennet bought the neighbouring TSOs.
- Czech TSO are planning huge investment

Follow up activities:

- ENTSO-E PST workshop in Rome 2015
- **Walter Seitlinger** (formely with ELIN, freelancer now)

Contact persons

- Mika Gunter - System support (Guenter.Mika@apg.at)
- Andrea Dummer - Operational management (Planning department in 2006) (Andrea.Dummer@apg.at)

Schemes:

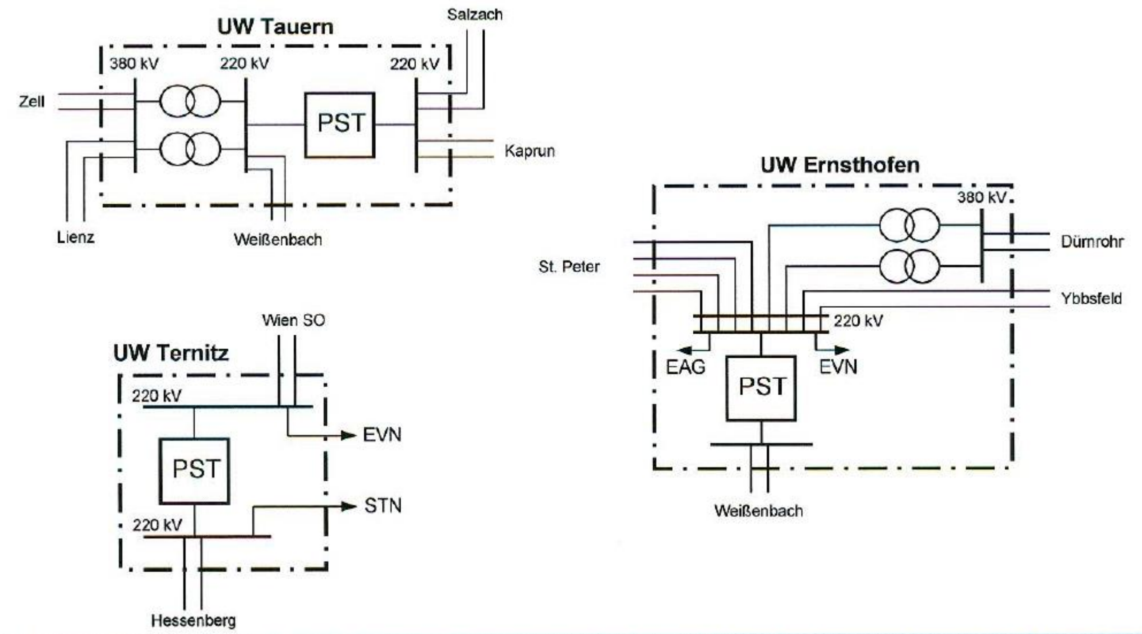


Figure – PST transformer design

ACCC Visit Split

Visit Report – 12.11.2018.

The author visited HOPS regional office in Split, when the reconductoring lines betwen substations Vrboran – Dujmovača – Meterize was taking place.

- First use of advanced conductor technology in Croatia was on line Ston – Komolac in 1994. So-called "black conductor" (BTAL / Stalum 154/18) was used in this particular case.

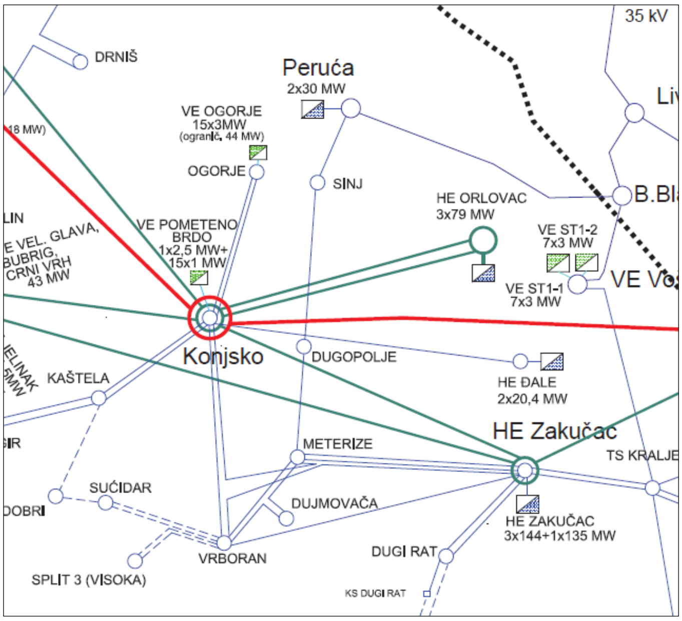


Figure – HOPS Split Map

- Reconductoring of OHL 110 kV Sinj – Meterize – Dugopolje was realized, and the throughput capacity was almost doubled.
- In the case of reconductoring of OHL 110 Vrboran – Dugopolje, the biggest issue was the sag.
- For this reconductoring project (Vrboran-Dujmovača-Meterize), the biggest issue was also the sag, as the OHL passes through the urban areas and roads.
- However, in this case, the issue was also to increase the throughput capacity, due to high loadings.
- In order to increase the throughput capacity of a line, the complete "current path" has to be reinforced. In other words, metering current transformers, bus bars, and circuit breakers have to be reinforced as well, if necessary.
- Given the results, HOPS will continue using ACCC for reconductoring projects. In the near future, the revitalization of OHL 220 kV Konjsko – Zakučac will take place.

Figure – Reconductoring Project in Split network (HOPS, Croatia)

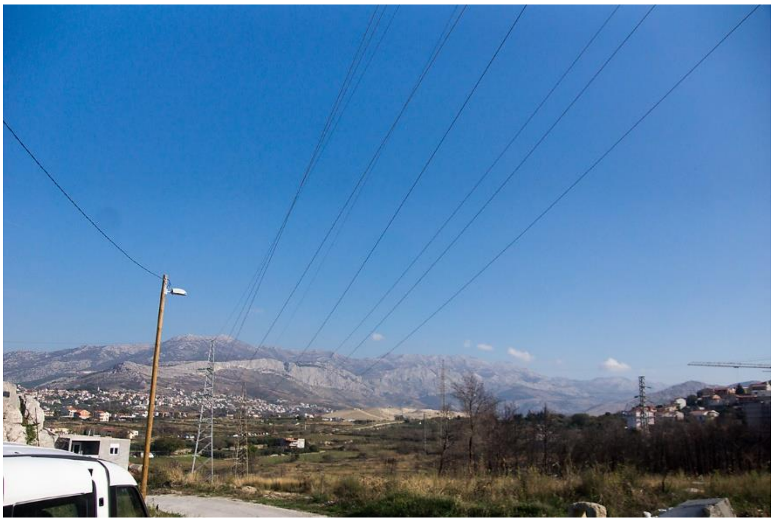


Figure – Reconductoring Project in Split network (HOPS, Croatia)

Figure – Reconductoring Project in Split network (HOPS, Croatia)


GLOBAL LAMIFIL

ACCC™ Conductor

produced by Lamifil nv in Belgium under license from CTC Global Corp

Lamifil nv, Frederic Sheidlaan, B-2620 Hemiksem, Belgium

DRUM : LAM/837

ALUMINIUM CONDUCTOR COMPOSITE

CORE LISBON 325 MM²

STANDARD : EN50182

REQUESTED LENGTH : 2400 m

PRODUCED LENGTH : 2404 m

WEIGHT GROSS : 2752 Kg

WEIGHT TARE : 426 Kg

WEIGHT NET : 2326 Kg

DATE OF MANUFACTURE : 21/09/17

LAMIFIL

ELEKTRO MERKUR D.O.O.

Nett : 2326 Kg
Brut : 2752 Kg
Length : 2404 m

56222565

LAMIFIL 36736/1/3

Client : ELEKTRO MERKUR D.O.O.

Y. ref : 17-020-0077
Project : REECONDUCTORING PROJECT
SPLITREGION

ACCC LISBON
1X7,11C+16X5,04T
EN50182

Brut : 2752 kg Tarra : 426 kg
Nett : 2326 kg Reel : LAM/837
Length : 2404 m (Request. Lgth : 2400 m
Deliv.ref : OHL 110kV D165: TS Dujmovaca - 1 - 4

Figure – Datasheet for ACCC LISBON

Figure – Reconductoring equipment

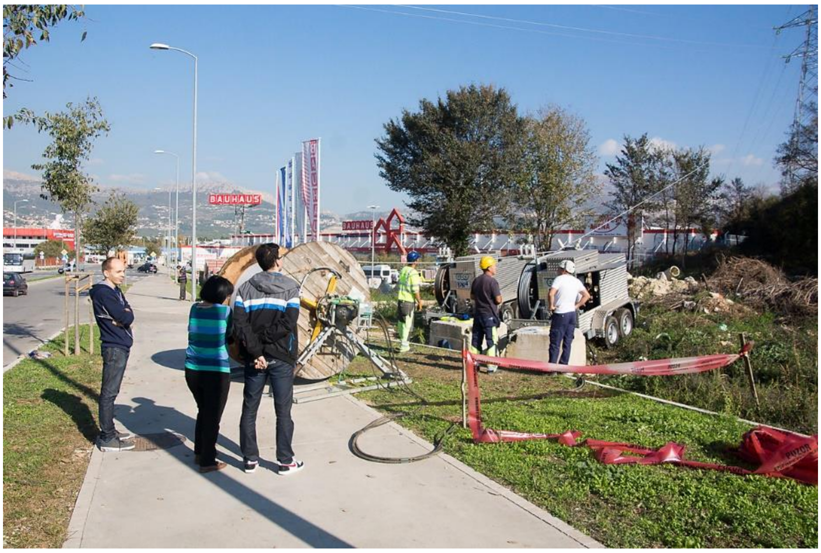


Figure – Reconductoring Project in Split network (HOPS, Croatia)

PST Žerjavinec Visit

Visit Report – 18.11.2018.

Type of transformer: Asymmetric autotransformer
Installed Apparent Power: 400 MVA
Control modes: Voltage and Angle/Power
Voltage level: 400/220 kV
Manufacturer: Končar
Comissioning: 2004

- The transformer can either be operated in Voltage control mode, or in Angle control mode. In order to switch from one to the other control mode, the transformer has to be disconnected off the grid. This process requires several minutes.
- The normal mode is angle control.
- The transformer has 25 taps. The same tap changer is used for both control modes.
- One tap change affects the flows by 20 MW (approximately).
- The cost of this transformer was 20% higher than an ordinary one with voltage control mode only.
- A special protection scheme had to be made for this transformer.
- A similar transformer is installed in HPP Senj.
- In some occasions, the topology is changed on the 220 kV lines connection Obersielach – Podlog – Cirkovce – Žerjavinec. Flows are redirected to neighboring TSOs, by switching the disconnectors on the sectioned 220 kV bus bars in Podlog, thus connecting APG directly to HOPS.

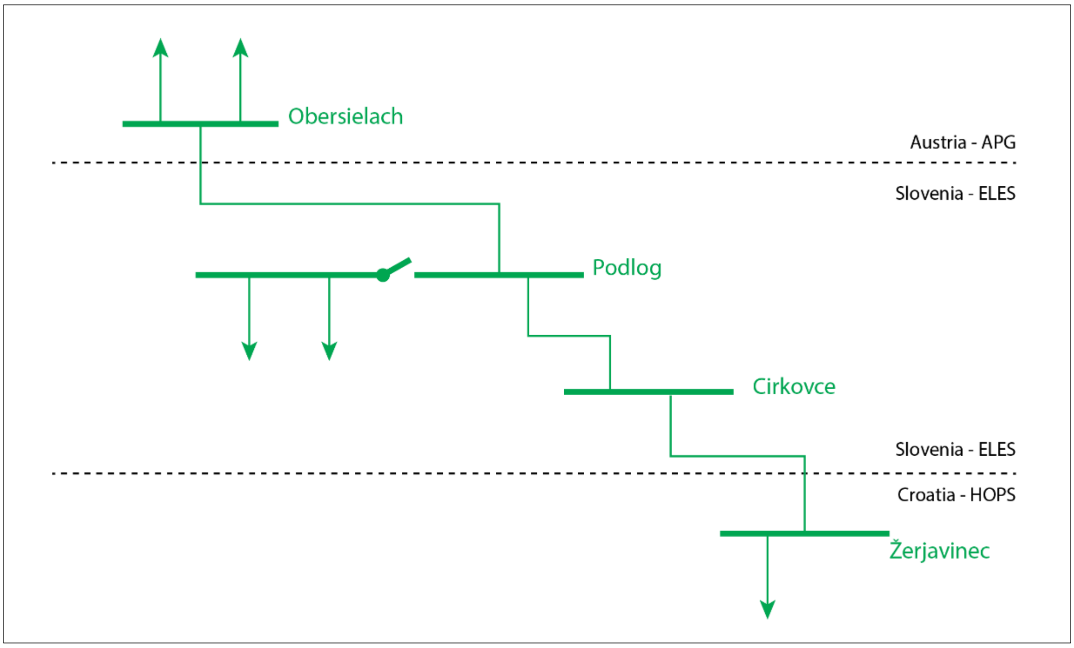


Figure - Modified topology at SS Podlog (ELES, Slovenia)

Figure – PST in SS Žerjavinec (HOPS, Croatia)

APPENDIX D

Code List Matrix

Code List Matrix

Table Ax.1. Code List Matrix for Case Study – Overall Electricity Factor (OEF)

Scenario	Model	Target Year	Contigency Type	Violation Range	Output type
S	**M**	**Y**	**I**	**II**	**III**
A **B** **C** **D** **E**	**SP** for summer peak **WP** tor winter peak	**20** for year 2020 **30** for Year 2030	**N0** for N criterion **N1** for N-1 criterion **N2** for N-2 criterion	**90p** for loadings > 90% **100p** for loadings > 100%	**NS** for non-spreasheet reports **YS** for spreadsheet reports

Scenario list

Scenario A: PST on OHL 220 kV Mostar - Zakučac

Scenario B: PST on OHL 220 kV Prijedor - Sisak

Scenario C: PST on OHL 220 kV Prijedor - Međurić

Scenario D: PST on OHL 220 kV Gradačac - Đakovo

Scenario E: PST on OHL 220 kV Tuzla - Đakovo

Coding Master Key

The coding master key is given in the following table:

Table Ax.2. Coding master key

S	**M**	**Y**	**I**	**II**	**III**

Example

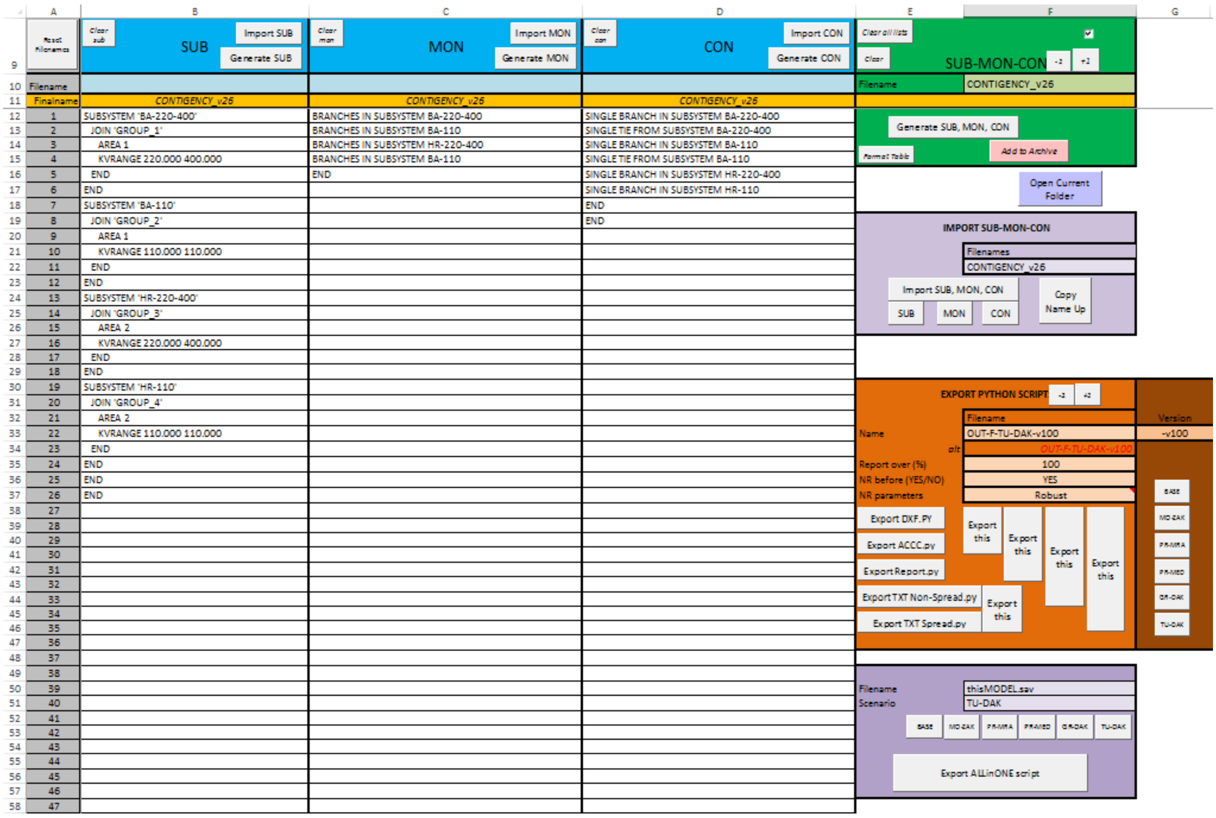
The code **A-SP-30-N2-90p-NS** implies that the scenario is:

- Scenario A – „PST on OHL 220 kV Mostar – Zakučac“
- Model SP – „Summer Peak“,
- Target year 30 - „2030“,
- Contigency type N2 – „N-2 Criterion“
- Violation type 90p – „> 90%“
- Output type NS – „non-spreadsheet“ text output

APPENDIX E
SubMonConPy

SubMonConPy

In order to automate the calculation process, but also to quicken the calculation of the described 60 calculation/analyses, and to eliminate the possibility of human error when changing parameters of the analysis, a separate program called „SubMonConPy“ was created (Figure E1).



	A	B	C	D
9		SUB	MON	CON
10	Filename			
11	Finalname	*CONTIGENCY_v26*	*CONTIGENCY_v26*	*CONTIGENCY_v26*
12	1	SUBSYSTEM 'BA-220-400'	BRANCHES IN SUBSYSTEM BA-220-400	SINGLE BRANCH IN SUBSYSTEM BA-220-400
13	2	JOIN 'GROUP_1'	BRANCHES IN SUBSYSTEM BA-110	SINGLE TIE FROM SUBSYSTEM BA-220-400
14	3	AREA 1	BRANCHES IN SUBSYSTEM HR-220-400	SINGLE BRANCH IN SUBSYSTEM BA-110
15	4	KVRANGE 220.000 400.000	BRANCHES IN SUBSYSTEM BA-110	SINGLE TIE FROM SUBSYSTEM BA-110
16	5	END	END	SINGLE BRANCH IN SUBSYSTEM HR-220-400
17	6	END		SINGLE BRANCH IN SUBSYSTEM HR-110
18	7	SUBSYSTEM 'BA-110'		END
19	8	JOIN 'GROUP_2'		END
20	9	AREA 1		
21	10	KVRANGE 110.000 110.000		
22	11	END		
23	12	END		
24	13	SUBSYSTEM 'HR-220-400'		
25	14	JOIN 'GROUP_3'		
26	15	AREA 2		
27	16	KVRANGE 220.000 400.000		
28	17	END		
29	18	END		
30	19	SUBSYSTEM 'HR-110'		
31	20	JOIN 'GROUP_4'		
32	21	AREA 2		
33	22	KVRANGE 110.000 110.000		
34	23	END		
35	24	END		
36	25	END		
37	26	END		
38	27			
39	28			
40	29			
41	30			
42	31			
43	32			
44	33			
45	34			
46	35			
47	36			
48	37			
49	38			
50	39			
51	40			
52	41			
53	42			
54	43			
55	44			
56	45			
57	46			
58	47			

SUB-MON-CON

Filename: CONTIGENCY_v26

IMPORT SUB-MON-CON

Filenames: CONTIGENCY_v26

EXPORT PYTHON SCRIPT

	Filename	Version
Name	OUT-F-TU-DAK-v100	-v100
alt	*OUT-F-TU-DAK-v100*	
Report over (%)	100	
NR before (YES/NO)	YES	
NR parameters	Robust	

Filename: thisMODEL.sav
Scenario: TU-DAK

Figure E1 – Screenshot of Interface of SubMonConPy

The name of the software refers to SUB, MON, CON and PY files.

- SUB files ares file that define the subsystems for the contigency analysis (areas, or other parts of the system).
- CON files are files that define the type of contingency (N, N-1, N-1-1, N-2, etc...)
- MON files define the element list that will be monitored for overloadings.
- PY files are files in Python programing language used in order to automate the calculation procedure within Siemens PSS-E .

The program „SubMonConPy“ was coded in Visual Basic code within a macro-enabled Excel Macro Workbook, with the aim to perform the following activities;

- Easily create, modify, export and import PSS-E contingency related files – „.sub“/“.mon“/“.con“,
- Create automated PSS-E scripting files in Python programing language to automate the calculation procedure.

The following figure shows the algorithm of SubMonConPy (Figure E2). Namely, the SUB, MON and CON files are created in Microsoft Excel, and can be exported and imported for easier management.

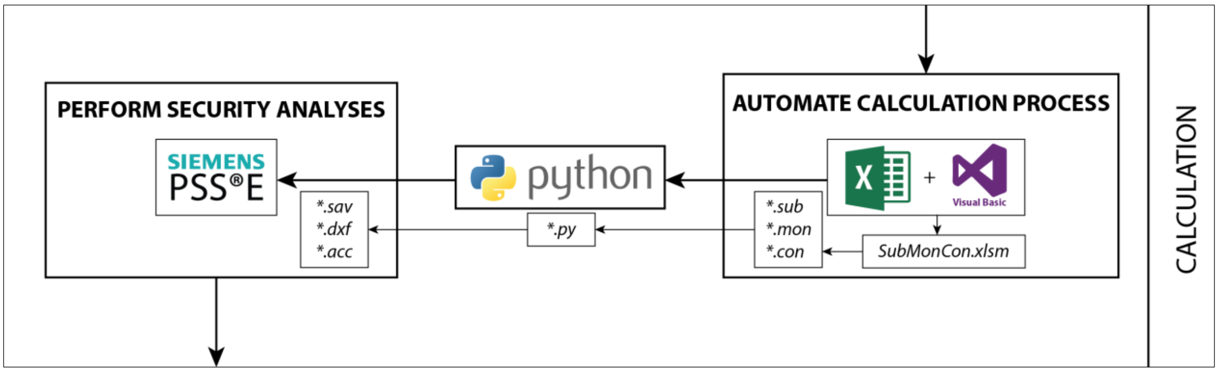
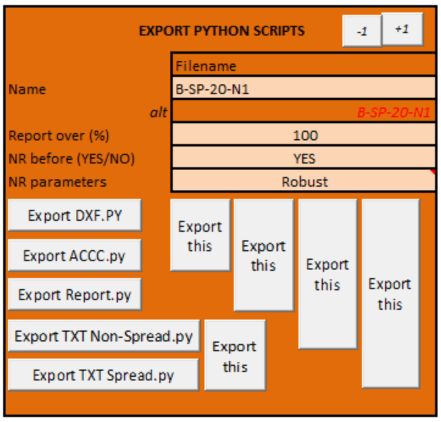


Figure E2 - SubMonConPy algorithm (part of Figure 6.19)

At that stage, SUB, MON and CON files can be used for manual input in PSS-E. However, in order to automate the calculation procedure, but also to eliminate the human error, the program was expanded to export python files. Figure E3 shows the possibility to export different parts of the python code, depending on the scope of work that is being performed. This functionality is extremely useful when drafting and experimenting further analyses that need to be performed.
It allows the following funtionalities:

- Creation of DXF files (on the basis of SUB, MON and CON files),
- Creation of ACCC analyses,
- Automatic power flow calculations with following methods:
    - Newthon-Raphson (NR)
    - fixed Slope NR,
    - robust solution.
- Creation of spreadsheet and non-spreadsheet reports,


EXPORT PYTHON SCRIPTS

	Filename
Name	B-SP-20-N1
alt	B-SP-20-N1
Report over (%)	100
NR before (YES/NO)	YES
NR parameters	Robust

Figure E3 - Python Export Module

As it can be seen from Figure E3, the program is fully compliant with the developed Code List Matrix, (further explained in the previous Appendix [D]).

The program was compiled in a way that adjustments for additional case studies, with different scenarios can be easily made.

In the following pages, the SubMonConPy code is given, as well as the example of a report.

SubMonConPy code:

```
'
'
'   _____  ______  _____ _______ _____  _____ _____ _______ _____ ____  _   _  _____
'  |  __ \|  ____|/ ____|__   __|  __ \|_   _/ ____|__   __|_   _/ __ \| \ | |/ ____|
'  | |__) | |__  | (___    | |  | |__) | | || |       | |    | || |  | |  \| | (___
'  |  _  /|  __|  \___ \   | |  |  _  /  | || |       | |    | || |  | | . ` |\___ \
'  | | \ \| |____ ____) |  | |  | | \ \ _| || |____   | |   _| || |__| | |\  |____) |
'  |_|  \_\______|_____/   |_|  |_|  \_\_____\_____|  |_|  |_____\____/|_| \_|_____/
'
'
'
' EXPORT / GENERATE FUNCTION only has formating for 600 rows, but will only generate rows in between 12 and 600. For more rows, the function has to be changed.
'
'



Private Sub CommandButton28_Click()
Range("F33").Value = "OUT-A-Base" + Range("G33").Value
End Sub

Private Sub CommandButton29_Click()
Range("F33").Value = "OUT-B-MO-ZAK" + Range("G33").Value
End Sub

Private Sub CommandButton30_Click()
Range("F33").Value = "OUT-C-PR_MRA" + Range("G33").Value
End Sub

Private Sub CommandButton31_Click()
Range("F33").Value = "OUT-D-PR_MED" + Range("G33").Value
End Sub

Private Sub CommandButton32_Click()
Range("F33").Value = "OUT-E-GR_DAK" + Range("G33").Value
End Sub

Private Sub CommandButton33_Click()
```

```
Range("F33").Value = "OUT-F-TU-DAK" + Range("G33").Value
End Sub

' __          __     _____  _   _ _____ _   _  _____      __  __ ______  _____ _____         _____ ______
' \ \        / /\   |  __ \| \ | |_   _| \ | |/ ____|    |  \/  |  ____|/ ____/ ____|  /\   / ____|  ____|
'  \ \  /\  / /  \  | |__) |  \| | | | |  \| | |  __     | \  / | |__  | (___| (___   /  \ | |  __| |__
'   \ \/  \/ / /\ \ |  _  /| . ` | | | | . ` | | |_ |    | |\/| |  __|  \___ \\___ \ / /\ \| | |_ |  __|
'    \  /\  / ____ \| | \ \| |\  |_| |_| |\  | |__| |    | |  | | |____ ____) |___) / ____ \ |__| | |____
'     \/  \/_/    \_\_|  \_\_| \_|_____|_| \_|\_____|    |_|  |_|______|_____/_____/_/    \_\_____|______|
'


Private Sub Worksheet_SelectionChange(ByVal Target As Range)
    If Not Intersect(Target, Range("F37")) Is Nothing Then _
        MsgBox "Are you really sure you want to change this?", vbInformation, "Information"
End Sub


'           _____  _____       _______ ____                 _____   _____ _    _ _______      ________
'     /\   |  __ \|  __ \     |__   __/ __ \          /\   |  __ \ / ____| |  | |_   _\ \    / /  ____|
'    /  \  | |  | | |  | |       | | | |  | |        /  \  | |__) | |    | |__| | | |  \ \  / /| |__
'   / /\ \ | |  | | |  | |       | | | |  | |       / /\ \ |  _  /| |    |  __  | | |   \ \/ / |  __|
'  / ____ \| |__| | |__| |       | | | |__| |      / ____ \| | \ \| |____| |  | |_| |_   \  /  | |____
' /_/    \_\_____/|_____/        |_|  \____/      /_/    \_\_|  \_\\_____|_|  |_|_____|   \/   |______|
'
'


Private Sub CB_AddToArchive_Click()
Call BOXIT
Call CopyCells_CP("FILEGEN", Worksheets("FILEGEN").Range("J25").Value, "ARCHIVE", Worksheets("FILEGEN").Range("J32").Value)
End Sub

'   _____ _      ______          _____           _____ ____  _   _ _______ ______ _   _ _______ _____
'  / ____| |    |  ____|   /\   |  __ \         / ____/ __ \| \ | |__   __|  ____| \ | |__   __/ ____|
' | |    | |    | |__     /  \  | |__) |       | |   | |  | |  \| |  | |  | |__  |  \| |  | | | (___
' | |    | |    |  __|   / /\ \ |  _  /        | |   | |  | | . ` |  | |  |  __| | . ` |  | |  \___ \
' | |____| |____| |____ / ____ \| | \ \        | |___| |__| | |\  |  | |  | |____| |\  |  | |  ____) |
'  \_____|______|______/_/    \_\_|  \_\        \_____\____/|_| \_|  |_|  |______|_| \_|  |_| |_____/
'

Private Sub CB_Resetfilenames_Click()
Call Clear_Contents("FILEGEN", "B10:D10")
```

```vb
End Sub

Private Sub CommandButton1_Click()
Call Clear_Contents("FILEGEN", "F10")
End Sub

Private Sub CommandButton2_Click()
Call Clear_Contents("FILEGEN", "B12:B400")
End Sub

Private Sub CommandButton3_Click()
Call Clear_Contents("FILEGEN", "C12:C400")
End Sub

Private Sub CommandButton4_Click()
Call Clear_Contents("FILEGEN", "D12:D400")
End Sub

Private Sub CommandButton5_Click()
Call Clear_Contents("FILEGEN", "B12:B400")
Call Clear_Contents("FILEGEN", "C12:C400")
Call Clear_Contents("FILEGEN", "D12:D400")
End Sub

'
'  _    _ _____ _____  ______       __   _____ _    _  ______          __
' | |  | |_   _|  __ \|  ____|     / /  / ____| |  | |/ __ \ \        / /
' | |__| | | | | |  | | |__       / /  | (___ | |__| | |  | \ \  /\  / /
' |  __  | | | | |  | |  __|     / /    \___ \|  __  | |  | |\ \/  \/ /
' | |  | |_| |_| |__| | |____   / /     ____) | |  | | |__| | \  /\  /
' |_|  |_|_____|_____/|______| /_/     |_____/|_|  |_|\____/   \/  \/
'


Private Sub CheckBox_Hide_Show_Click()
Call CheckBox_HideShow(CheckBox_Hide_Show, "H:XFD", "612:1048576")
End Sub


'
'  _____ __  __ _____   ____  _____ _______              _____ _    _ ____     __  __  ____  _   _      _____ ____  _ _
' |_   _|  \/  |  __ \ / __ \|  __ \__   __|            / ____| |  | |  _ \   |  \/  |/ __ \| \ | |    / ____/ __ \| \ | |
'   | | | \  / | |__) | |  | | |__) | | |              | (___ | |  | | |_) |  | \  / | |  | |  \| |   | |   | |  | |  \| |
'   | | | |\/| |  ___/| |  | |  _  /  | |               \___ \| |  | |  _ <   | |\/| | |  | | . ` |   | |   | |  | | . ` |
'  _| |_| |  | | |    | |__| | | \ \  | |               ____) | |__| | |_) |  | |  | | |__| | |\  |_  | |___| |__| | |\  |
```

```
' |_____|_|  |_|_|     \____/|_|  \_\ |_|       |_____/ \____/|____( ) |_|  |_|\____/|_| \_( )  \_____\____/|_| \_|
'                                                                  |/                      |/

Private Sub CB_IMPORTSUBMONCON_Click()
Call IMPORTSUB
Call IMPORTMON
Call IMPORTCON
End Sub

Private Sub CB_IMPORTSUB_Click()
Call IMPORTSUB
End Sub

Private Sub CB_IMPORTMON_Click()
Call IMPORTMON
End Sub

Private Sub CB_IMPORTCON_Click()
Call IMPORTCON
End Sub

Private Sub CommandButton15_Click()
Call CopyCells_CP("FILEGEN", "F22", "FILEGEN", "F10")
End Sub

    '                _____                           _                                      _ _
    '               |  __ \                         | |                                    | |     | |
    '  ______ ______| |__) | __ ___  _ __ ___  _ __ | |_     ___  ___ _ __   __ _ _ __ __ _| |_ ___| |_ _
    ' |______|______|  ___/ '__/ _ \| '_ ` _ \| '_ \| __|   / __|/ _ \ '_ \ / _` | '__/ _` | __/ _ \ | | | |
    '               | |   | | | (_) | | | | | | |_) | |_    \__ \  __/ |_) | (_| | | | (_| | ||  __/ | |_| |
    '               |_|   |_|  \___/|_| |_| |_| .__/ \__|   |___/\___| .__/ \__,_|_|  \__,_|\__\___|_|\__, |
    '                                         | |                    | |                               __/ |
    '                                         |_|                    |_|                              |___/

Private Sub CB_IMPORTSUB_PROMPT_Click()
Call Accelerate_ON
Call Clear_Contents("FILEGEN", "B12:B600")
Call ImportDataFromExcel_prompt_type(1, "A:A", "FILEGEN", "B12:B600", "SUB files,*.sub")
Call Accelerate_OFF
End Sub

Private Sub CB_IMPORTMON_PROMPT_Click()
Call Accelerate_ON
```

```
Call Clear_Contents("FILEGEN", "C12:C600")
Call ImportDataFromExcel_prompt_type(1, "A:A", "FILEGEN", "C12:C600", "MON files,*.mon")
Call Accelerate_OFF
End Sub

Private Sub CB_IMPORTCON_PROMPT_Click()
Call Accelerate_ON
Call Clear_Contents("FILEGEN", "D12:D600")
Call ImportDataFromExcel_prompt_type(1, "A:A", "FILEGEN", "D12:D600", "CON files,*.con")
Call Accelerate_OFF
End Sub



    '              _____                            _ _
    '             |_   _|                          | |               | |
    '  ______ ______| |  _ __ ___  _ __   ___  _ __| |_     ___ _   _| |__  ___
    ' |______|______| | | '_ ` _ \| '_ \ / _ \| '__| __|   / __| | | | '_ \/ __|
    '              _| |_| | | | | | |_) | (_) | |  | |_    \__ \ |_| | |_) \__ \
    '             |_____|_| |_| |_| .__/ \___/|_|   \__|   |___/\__,_|_.__/|___/
    '                             | |
    '                             |_|


Public Sub IMPORTSUB()
Call Accelerate_ON
Call Clear_Contents("FILEGEN", "B12:B600")
Call ImportTextFile(Worksheets("FILEGEN").Range("F22").Value & ".sub", "FILEGEN", "B12:B600", "A:A")
Call Accelerate_OFF
End Sub

Public Sub IMPORTMON()
Call Accelerate_ON
Call Clear_Contents("FILEGEN", "C12:C600")
Call ImportTextFile(Worksheets("FILEGEN").Range("F22").Value & ".mon", "FILEGEN", "C12:C600", "A:A")
Call Accelerate_OFF
End Sub

Public Sub IMPORTCON()
Call Accelerate_ON
Call Clear_Contents("FILEGEN", "D12:D600")
Call ImportTextFile(Worksheets("FILEGEN").Range("F22").Value & ".con", "FILEGEN", "D12:D600", "A:A")
```

```
Call Accelerate_OFF
End Sub

'
'  _______     _________ _    _  ____  _   _     _____ ______ _   _ ______ _____         _______ ______
' |  __ \ \   / /__   __| |  | |/ __ \| \ | |   / ____|  ____| \ | |  ____|  __ \     /\|__   __|  ____|
' | |__) \ \_/ /   | |  | |__| | |  | |  \| |  | |  __| |__  |  \| | |__  | |__) |   /  \  | |  | |__
' |  ___/ \   /    | |  |  __  | |  | | . ` |  | | |_ |  __| | . ` |  __| |  _  /   / /\ \ | |  |  __|
' | |      | |     | |  | |  | | |__| | |\  |  | |__| | |____| |\  | |____| | \ \  / ____ \| |  | |____
' |_|      |_|     |_|  |_|  |_|\____/|_| \_|   \_____|______|_| \_|______|_|  \_\/_/    \_\_|  |______|
'

'DXF
Private Sub CommandButton7_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("N17").Value, 14, 27, 38)
End Sub

'ACCC
Private Sub CommandButton8_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("N18").Value, 14, 39, 43)
End Sub

'DXF+ACCC
Private Sub CommandButton9_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("N19").Value, 14, 26, 43)
End Sub

'Report
Private Sub CommandButton10_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("N20").Value, 14, 44, 48)
End Sub

'DXF+ACCC+Report
Private Sub CommandButton13_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("N21").Value, 14, 26, 48)
End Sub

'TXT NON-SPREDSHEET
Private Sub CommandButton11_Click()
```

```
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("N22").Value, 14, 49, 61)
End Sub

'DXF+ACCC+Report+TXT NON-SPREDSHEET
Private Sub CommandButton14_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("N23").Value, 14, 26, 61)
End Sub

'TXT SPREADSHEET
Private Sub CommandButton18_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("O22").Value, 14, 63, 75)
End Sub

'DXF+ACCC+Report+TXT NON-SPREADSHEET+TXT SPREADSHEET
Private Sub CommandButton19_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("O23").Value, 14, 26, 75)
End Sub

'TXT SPREADSHEET + TXT NON-SPREADSHEET
Private Sub CommandButton20_Click()
Call This_Workbook_Path("FILEGEN", "N14")
Call ExportToFile(Worksheets("FILEGEN").Range("O25").Value, 14, 49, 75)
End Sub

'   _____ ______ _   _ ______ _____         _______ ______    ____  _    _ _______ _____  _    _ _______   ______ _____ _      ______  _____ 
'  / ____|  ____| \ | |  ____|  __ \     /\|__   __|  ____|  / __ \| |  | |__   __|  __ \| |  | |__   __| |  ____|_   _| |    |  ____|/ ____|
' | |  __| |__  |  \| | |__  | |__) |   /  \  | |  | |__    | |  | | |  | |  | |  | |__) | |  | |  | |    | |__    | | | |    | |__  | (___  
' | | |_ |  __| | . ` |  __| |  _  /   / /\ \ | |  |  __|   | |  | | |  | |  | |  |  ___/| |  | |  | |    |  __|   | | | |    |  __|  \___ \ 
' | |__| | |____| |\  | |____| | \ \  / ____ \| |  | |____  | |__| | |__| |  | |  | |    | |__| |  | |    | |     _| |_| |____| |____ ____) |
'  \_____|______|_| \_|______|_|  \_\/_/    \_\_|  |______|  \____/ \____/   |_|  |_|     \____/   |_|    |_|    |_____|______|______|_____/ 


Private Sub Generate_SUB_Click()
Call ExportToFile(Worksheets("FILEGEN").Range("B11").Value & ".sub", 2, 12, 400)
End Sub

Private Sub Generate_MON_Click()
Call ExportToFile(Worksheets("FILEGEN").Range("B11").Value & ".mon", 3, 12, 400)
End Sub

Private Sub Generate_CON_Click()
```

```
Call ExportToFile(Worksheets("FILEGEN").Range("B11").Value & ".con", 4, 12, 400)
End Sub

Private Sub Generate_SUBMONCON_Click()
Call ExportToFile(Worksheets("FILEGEN").Range("B11").Value & ".sub", 2, 12, 605)
Call ExportToFile(Worksheets("FILEGEN").Range("B11").Value & ".mon", 3, 12, 605)
Call ExportToFile(Worksheets("FILEGEN").Range("B11").Value & ".con", 4, 12, 605)
Call BOXIT
Call CopyCells_CP("FILEGEN", Worksheets("FILEGEN").Range("J25").Value, "ARCHIVE", Worksheets("FILEGEN").Range("J32").Value)
End Sub


'
'  _____  _      _    _  _____         __
' |  __ \| |    | |  | |/ ____|       /_ |
' | |__) | |    | |  | | (___          | |
' |  ___/| |    | |  | |\___ \         | |
' | |    | |____| |__| |____) |        | |
' |_|    |______|\____/|_____/         |_|
'

Private Sub CB_PLUSONE_Click()
Call Plus_one("FILEGEN", "F10")
End Sub

Private Sub CommandButton16_Click()
Call Minus_one("FILEGEN", "F10")
End Sub


Private Sub CommandButton12_Click()
Call Plus_one("FILEGEN", "F33")
End Sub

Private Sub CommandButton17_Click()
Call Minus_one("FILEGEN", "F33")
End Sub



'
'  ______ ____  _____  __  __       _______   _______       ____  _      ______
' |  ____/ __ \|  __ \|  \/  |   /\|__   __| |__   __|/\   |  _ \| |    |  ____|
' | |__ | |  | | |__) | \  / |  /  \  | |       | |  /  \  | |_) | |    | |__
' |  __|| |  | |  _  /| |\/| | / /\ \ | |       | | / /\ \ |  _ <| |    |  __|
```

```
' | |   | |__| | | \ \| |  | |/ ____ \| |       | |/ ____ \| |_) | |____| |____
' |_|    \____/|_|  \_\_|  |_/_/    \_\_|       |_/_/    \_\____/|______|______|
'


Private Sub CommandButton6_Click()
    Range("B12:D12").Select
    Selection.Copy
    Range("B13:D211").Select
    Selection.PasteSpecial Paste:=xlPasteFormats, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
    Application.CutCopyMode = False
End Sub

'   ____  _____  ______ _   _      _____ _    _ _____  _____  ______ _   _ _______     ______ ____  _      _____  ______ _____
'  / __ \|  __ \|  ____| \ | |    / ____| |  | |  __ \|  __ \|  ____| \ | |__   __|   |  ____/ __ \| |    |  __ \|  ____|  __ \
' | |  | | |__) | |__  |  \| |   | |    | |  | | |__) | |__) | |__  |  \| |  | |      | |__ | |  | | |    | |  | | |__  | |__) |
' | |  | |  ___/|  __| | . ` |   | |    | |  | |  _  /|  _  /|  __| | . ` |  | |      |  __|| |  | | |    | |  | |  __| |  _  /
' | |__| | |    | |____| |\  |   | |____| |__| | | \ \| | \ \| |____| |\  |  | |      | |   | |__| | |____| |__| | |____| | \ \
'  \____/|_|    |______|_| \_|    \_____|\____/|_|  \_\_|  \_\______|_| \_|  |_|      |_|    \____/|______|_____/|______|_|  \_\
'

Private Sub CP_OpenCurrentExplorer_Click()
Call GoToThisFolder
End Sub


'  ____   ______   __     _____ _______      ______                _   _
' |  _ \ / __ \ \ / /    |_   _|__   __|    |  ____|              | | (_)
' | |_) | |  | \ V /       | |    | |       | |__ _   _ _ __   ___| |_ _  ___  _ __
' |  _ <| |  | |> <        | |    | |       |  __| | | | '_ \ / __| __| |/ _ \| '_ \
' | |_) | |__| / . \     _| |_   | |       | |  | |_| | | | | (__| |_| | (_) | | | |
' |____/ \____/_/ \_\    |_____|  |_|       |_|   \__,_|_| |_|\___|\__|_|\___/|_| |_|
'


Public Sub BOXIT()
Call Accelerate_ON
Call Activate_Sheet("ARCHIVE")
'Worksheets("ARCHIVE").Range("A55:E65").Select
Worksheets("ARCHIVE").Range(Worksheets("ARCHIVE").Range("I11").Value).Select

    'Selection.Borders(xlDiagonalDown).LineStyle = xlNone
```

```
    'Selection.Borders(xlDiagonalUp).LineStyle = xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlMedium
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlMedium
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlMedium
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlMedium
    End With
Call Activate_Sheet("FILEGEN")
Call Accelerate_OFF
End Sub



'          _      _        _____ _   _    ____  _   _ ______
'    /\   | |    | |      |_   _| \ | |  / __ \| \ | |  ____|
'   /  \  | |    | |        | | |  \| | | |  | |  \| | |__
'  / /\ \ | |    | |        | | | . ` | | |  | | . ` |  __|
' / ____ \| |____| |____   _| |_| |\  | | |__| | |\  | |____
'/_/    \_\______|______| |_____|_| \_|  \____/|_| \_|______|
'

Private Sub CommandButton21_Click()
Call Accelerate_ON
```

```
Call This_Workbook_Path("FILEGEN", "N14")
Call Clear_Contents("FILEGEN", "R25:R55")

If Range("F51").Value = "MO-ZAK" Then Call CopyCells_CP("FILEGEN", "V26:V55", "FILEGEN", "R26:R55")
If Range("F51").Value = "PR-SIS" Then Call CopyCells_CP("FILEGEN", "W26:W55", "FILEGEN", "R26:R55")
If Range("F51").Value = "PR-MED" Then Call CopyCells_CP("FILEGEN", "X26:X55", "FILEGEN", "R26:R55")
If Range("F51").Value = "GR-DAK" Then Call CopyCells_CP("FILEGEN", "Y26:Y55", "FILEGEN", "R26:R55")
If Range("F51").Value = "TU-DAK" Then Call CopyCells_CP("FILEGEN", "Z26:Z55", "FILEGEN", "R26:R55")

Call ExportToFile(Worksheets("FILEGEN").Range("R15").Value, 18, 18, 147)

Call Accelerate_OFF

End Sub

Private Sub CommandButton22_Click()
Range("F51").Value = "Base"
End Sub

Private Sub CommandButton23_Click()
Range("F51").Value = "MO-ZAK"
End Sub

Private Sub CommandButton24_Click()
Range("F51").Value = "PR-SIS"
End Sub

Private Sub CommandButton25_Click()
Range("F51").Value = "PR-MED"
End Sub

Private Sub CommandButton26_Click()
Range("F51").Value = "GR-DAK"
End Sub

Private Sub CommandButton27_Click()
Range("F51").Value = "TU-DAK"
End Sub
```

```
'
'  _____  _           __     _______ _____   ____  _    _ _   _ _____             __  __  ____  _____  _    _ _      ______
' |  __ \| |        /\\ \   / / ____|  __ \ / __ \| |  | | \ | |  __ \           |  \/  |/ __ \|  __ \| |  | | |    |  ____|
' | |__) | |       /  \\ \_/ / |  __| |__) | |  | | |  | |  \| | |  | |          | \  / | |  | | |  | | |  | | |    | |__
' |  ___/| |      / /\ \\   /| | |_ |  _  /| |  | | |  | | . ` | |  | |          | |\/| | |  | | |  | | |  | | |    |  __|
' | |    | |____ / ____ \| | | |__| | | \ \| |__| | |__| | |\  | |__| |          | |  | | |__| | |__| | |__| | |____| |____
' |_|    |______/_/    \_\_|  \_____|_|  \_\\____/ \____/|_| \_|_____/           |_|  |_|\____/|_____/ \____/|______|______|
'
' developed by: Semir Hadzimuratovic (semir.h@gmail.com)
' version: 9
' last update: 2019-01-06
'

Sub ExportToFile(E2F_filename, E2F_y, E2F_n1, E2F_n2)
        Dim y As Integer
        Dim x As Integer
        Open (ThisWorkbook.Path & "\" & E2F_filename) For Output As #1
            y = E2F_y
            n1 = E2F_n1
            n2 = E2F_n2
            For x = n1 To n2
                 Print #1, Cells(x, y)
            Next x
        Close
End Sub
Sub ImportTextFile(H, WBK, R1, R2)
    Dim wb As Workbook, wb2 As Workbook
    Dim ws As Worksheet
    Dim vFile As Variant
    Set wb = ActiveWorkbook
    Workbooks.Open (ThisWorkbook.Path & "\" & H), UpdateLinks:=False
    Set wb2 = ActiveWorkbook
    wb.Worksheets(WBK).Range(R1).Value = wb2.Worksheets(1).Range(R2).Value
    ActiveWorkbook.Close True
End Sub
Sub ImportDataFromExcel(X_Filename, SOURCE_Sheet, SOURCE_Range, DEST_Sheet, DEST_Range)
    Dim wb As Workbook, wb2 As Workbook
    Dim ws As Worksheet
    Dim vFile As Variant
    Set wb = ActiveWorkbook
    Workbooks.Open (ThisWorkbook.Path & "\" & X_Filename), UpdateLinks:=False
    Set wb2 = ActiveWorkbook
    wb.Worksheets(DEST_Sheet).Range(DEST_Range).Value = wb2.Worksheets(SOURCE_Sheet).Range(SOURCE_Range).Value
```

```
    ActiveWorkbook.Close True
End Sub
Sub ImportDataFromExcel_prompt(SOURCE_Sheet, SOURCE_Range, DEST_Sheet, DEST_Range)
    Dim wb As Workbook, wb2 As Workbook
    Dim ws As Worksheet
    Dim vFile As Variant
    OpenPath = ThisWorkbook.Path
    Application.DefaultFilePath = OpenPath
    ChDir OpenPath
    Set wb = ActiveWorkbook
    vFile = Application.GetOpenFilename("Excel-files,*.*", 1, "Select file", , False)
    If TypeName(vFile) = "Boolean" Then Exit Sub
    Workbooks.Open vFile, UpdateLinks:=False
    Set wb2 = ActiveWorkbook
    wb.Worksheets(DEST_Sheet).Range(DEST_Range).Value = wb2.Worksheets(SOURCE_Sheet).Range(SOURCE_Range).Value
    ActiveWorkbook.Close True
End Sub
Sub ImportDataFromExcel_prompt_type(SOURCE_Sheet, SOURCE_Range, DEST_Sheet, DEST_Range, DEST_Filetype)
    Dim wb As Workbook, wb2 As Workbook
    Dim ws As Worksheet
    Dim vFile As Variant
    OpenPath = ThisWorkbook.Path
    Application.DefaultFilePath = OpenPath
    ChDir OpenPath
    Set wb = ActiveWorkbook
    vFile = Application.GetOpenFilename(DEST_Filetype, 1, "Select file", , False)
    If TypeName(vFile) = "Boolean" Then Exit Sub
    Workbooks.Open vFile, UpdateLinks:=False
    Set wb2 = ActiveWorkbook
    wb.Worksheets(DEST_Sheet).Range(DEST_Range).Value = wb2.Worksheets(SOURCE_Sheet).Range(SOURCE_Range).Value
    ActiveWorkbook.Close True
End Sub
Sub CopyCells(SOURCE_Sheet, SOURCE_Range, DEST_Sheet, DEST_Range)
    Worksheets(DEST_Sheet).Range(DEST_Range).Value = Worksheets(SOURCE_Sheet).Range(SOURCE_Range).Value
End Sub
Sub CopyCells_CP(SOURCE_Sheet, SOURCE_Range, DEST_Sheet, DEST_Range)
    Sheets(SOURCE_Sheet).Range(SOURCE_Range).Copy
    Sheets(DEST_Sheet).Range(DEST_Range).PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=False,
Transpose:=False
    Application.CutCopyMode = False
End Sub
Sub GoToWebPage_Cell(R1)
    strPath = Range(R1)
```

```
    ActiveWorkbook.FollowHyperlink strPath
End Sub
Sub GoToWebPage_DirectLink(R1)
    ActiveWorkbook.FollowHyperlink R1
End Sub
Sub Execute_Shell_Script(X_Filename)
    Call Shell(Environ$("COMSPEC") & " /k " & Chr(34) & ThisWorkbook.Path & "\" & X_Filename & Chr(34), vbNormalFocus)
End Sub
Sub Execute_Shell_Script_Full(X_Filename)
    Call Shell(Environ$("COMSPEC") & " /k " & X_Filename, vbNormalFocus)
End Sub
Sub ExportExcelSheet(X_Sheet, X_Filename)
    ThisWorkbook.Sheets(X_Sheet).Copy
    ActiveWorkbook.SaveAs X_Filename, FileFormat:=51
End Sub
Sub PasteValues_ErrorCheck()
    On Error Resume Next
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=False
    If Err Then
       MsgBox "Nothing to paste!"
       Err.Clear
    End If
End Sub
Sub CheckBox_HideShow(X_CheckBox_Element, X_Columns, X_Rows)
    If X_CheckBox_Element.Value = True Then
        Columns(X_Columns).Hidden = True
        Rows(X_Rows).Hidden = True
    Else
        Columns(X_Columns).Hidden = False
        Rows(X_Rows).Hidden = False
    End If
End Sub
Sub Paste_Special()
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=False
End Sub
Sub Clear_Contents(X_Sheet, X_Range)
    Sheets(X_Sheet).Range(X_Range).ClearContents
End Sub
Sub Sort_Table_Ascending(X_Sheet, X_Range, X_Sort_Column)
    Sheets(X_Sheet).Range(X_Range).Select
    ActiveWorkbook.Worksheets(X_Sheet).Sort.SortFields.Clear
    ActiveWorkbook.Worksheets(X_Sheet).Sort.SortFields.Add Key:=Range(X_Sort_Column), SortOn:=xlSortOnValues,
Order:=xlAscending, DataOption:=xlSortNormal
```

```
    With ActiveWorkbook.Worksheets(X_Sheet).Sort
        .SetRange Range(X_Range)
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
End Sub
Sub Sort_Table_Descending(X_Sheet, X_Range, X_Sort_Column)
    Sheets(X_Sheet).Range(X_Range).Select
    ActiveWorkbook.Worksheets(X_Sheet).Sort.SortFields.Clear
    ActiveWorkbook.Worksheets(X_Sheet).Sort.SortFields.Add Key:=Range(X_Sort_Column), SortOn:=xlSortOnValues, Order:=xlDescending,
DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets(X_Sheet).Sort
        .SetRange Range(X_Range)
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
End Sub
Sub This_Workbook_Path(X_Sheet, X_Range)
    Sheets(X_Sheet).Range(X_Range) = ThisWorkbook.Path
End Sub
Sub Activate_Sheet(X_Sheet)
    Worksheets(X_Sheet).Activate
End Sub
Sub Accelerate_ON()
    Application.ScreenUpdating = False
    Application.EnableEvents = False
End Sub
Sub Accelerate_OFF()
    Application.ScreenUpdating = True
    Application.EnableEvents = True
End Sub
Sub GoToThisFolder()
    ActiveWorkbook.FollowHyperlink ThisWorkbook.Path
End Sub
Sub Plus_one(X_Sheet, X_Range)
That_Cell = X_Range
X_Result = Evaluate("CONCATENATE(LEFT(" & That_Cell & ", MIN(SEARCH({0,1,2,3,4,5,6,7,8,9}," & That_Cell & "&""0123456789""))-
1),IF(RIGHT(" & That_Cell & ", LEN(" & That_Cell & ")-MIN(SEARCH({0,1,2,3,4,5,6,7,8,9}," & That_Cell &
```

```
"&""0123456789""))+1)="""",1,RIGHT(" & That_Cell & ", LEN(" & That_Cell & ")-MIN(SEARCH({0,1,2,3,4,5,6,7,8,9}," & That_Cell &
"&""0123456789""))+1)+1))")
Worksheets(X_Sheet).Range(X_Range).Value = X_Result
End Sub
Sub Minus_one(X_Sheet, X_Range)
That_Cell = X_Range
X_Result = Evaluate("CONCATENATE(LEFT(" & That_Cell & ", MIN(SEARCH({0,1,2,3,4,5,6,7,8,9}," & That_Cell & "&""0123456789""))-
1),IF(RIGHT(" & That_Cell & ", LEN(" & That_Cell & ")-MIN(SEARCH({0,1,2,3,4,5,6,7,8,9}," & That_Cell &
"&""0123456789""))+1)="""",1,RIGHT(" & That_Cell & ", LEN(" & That_Cell & ")-MIN(SEARCH({0,1,2,3,4,5,6,7,8,9}," & That_Cell &
"&""0123456789""))+1)-1))")
Worksheets(X_Sheet).Range(X_Range).Value = X_Result
End Sub
```

Example of Report output file

Case: B-SP-20-N2-100p-NS.txt

```
.......................................................................................................................................................
.                                     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS(R)E     FRI, AUG 10 2018  16:05                              PAGE 1 .
.                                                                                                                                                     .
.                                                            SUMMER PEAK 2020                                                                         .
.                                                                                                                                                     .
.                                                                                                                                                     .
.            *** ACCC OVERLOAD REPORT: MONITORED ELEMENTS LOADED ABOVE 100.0 % OF RATING SET  1 (BASE CASE) OR  2 (CONTINGENCY CASES) ***             .
.                           *** % LOADING VALUES ARE % MVA FOR TRANSFORMERS AND % CURRENT FOR NON-TRANSFORMER BRANCHES ***                            .
.                               *** ELEMENTS WITH BASE CASE LOADING VIOLATIONS ARE NOT CHECKED IN CONTINGENCY CASES ***                               .
.......................................................................................................................................................

AC CONTINGENCY RESULTS FILE:  D:\Documents\PhD Thesis\Evaluation Matrix\Calculus\B-SP-20.acc
DISTRIBUTION FACTOR FILE:     D:\Documents\PhD Thesis\Evaluation Matrix\Calculus\B-SP-20.dfx
SUBSYSTEM DESCRIPTION FILE:   D:\Documents\PhD Thesis\Evaluation Matrix\Calculus\CONTIGENCY_N2.sub
MONITORED ELEMENT FILE:       D:\Documents\PhD Thesis\Evaluation Matrix\Calculus\CONTIGENCY_N2.mon
CONTINGENCY DESCRIPTION FILE: D:\Documents\PhD Thesis\Evaluation Matrix\Calculus\CONTIGENCY_N2.con

**PERCENT LOADING UNITS**
%MVA FOR TRANSFORMERS
% I  FOR NON-TRANSFORMER BRANCHES
**OPTIONS USED IN CONTINGENCY ANALYSIS**
Solution engine:              Full Newton-Raphson (FNSL)
Solution options
  Tap adjustment:             Direct
  Area interchange control:   Tie lines only
  Phase shift adjustment:     Enable
  Dc tap adjustment:          Enable
  Switch shunt adjustment:    Lock all
  Induction motor treatment:  Stall
  Induction machine failure:  Treat contingency as non-converged
Non diverge:                  Disable
Mismatch tolerance (MW ):     1.0
Dispatch mode:                Disable

<--------------- C O N T I N G E N C Y   E V E N T S ---------------><------------- O V E R L O A D E D   L I N E S -------------->  <- MVA(MW)FLOW ->
<--------------- MULTI-SECTION LINE GROUPINGS --------------->  <--------- F R O M ---------> <----------- T O ----------->CKT  PRE-CNT  POST-CNT  RATING  PERCENT
                                                                     -------------------------------------------------CONTINGENCY DOUBLE (16578-16432(1):16432-168
OPEN LINE FROM BUS 16578 [WBLUK61     400.00] TO BUS 16432 [WTSTAN1     400.00] CKT 1
OPEN LINE FROM BUS 16432 [WTSTAN1     400.00] TO BUS 16896 [WTUZL41     400.00] CKT 1
                                                                     16986    *STANAR     110.00 16978    TESTANA     110.00 1      51.8    105.4    100.0    100.8
```

APPENDIX F
Questionnaire

Questionnaire

Operational Experience Factor

With regard to the figure above, based on your operational experience, please rank your choices for the optimal positioning of PST on the following lines:

Scenario	Points
Mostar – Zakucac	
Prijedor – Sisak	
Prijedor – Međuric	
Gradačac – Đakovo	
Tuzla - Đakovo	

Please rank from 5 (best option) to 1 (worst option).

Thanks!