Institute of Electrical Power Systems

Harmonics in Transmission Lines

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Statutory Declaration

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Graz, 20.02.2021

Ali Pouriman

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Abstract

This master thesis presents the general information about harmonics and which consequences they have. After that a simplified high voltage network is used as a study case. For the thesis it was necessary to reconfigure the grid model and equip it with non-linear loads. The non-linear loads are modelled as harmonic current sources at 110 kV level such as six pulse and twelve pulse converter that inject harmonics and distort the sine voltage. The influence of increased resistance due to skin effect of grid elements on the damping of resonances will be taken into account.

All simulations will be performed with DigSilent PowerFactory 2020, analysing several compensator configurations. The resulting voltage distortion at 220 kV and 380 kV and the frequency characteristic of the impedance in different substations are discussed. The latter helps to explain increased harmonic levels and to optimise the compensator configuration. To improve the situation, the location of compensator units has been adapted and realised as C-type filter.

Furthermore, a simplified approach for estimating the basic parallel resonance frequency of the system is applied.

List of Symbols

C	Capacitance
f_1	Fundamental frequency
f_r	Resonance frequency
h	Harmonic order
I_1	Nominal current at f_1
I_h	Current at h-th order
L	Inductance
n	Integer n = 2, 3, …
P	Active power
Q	Reactive power
q	Quality factor
R	Resistance
V_1	Voltage at f_1
V_h	Voltage at h-th order
X_0	Inductive reactance of zero sequence
X_1	Inductive reactance of positive sequence
X_2	Inductive reactance of negative sequence
Z_1	Impedance at f_1
Z_h	Impedance at h-th order
ω_1	Angular frequency at f_1
ω_h	Tuned angular frequency at h-th order

List of Abbreviations

12-1 P B	First Twelve Pulse Bridge rectifier
12-2 P B	Second Twelve Pulse Bridge rectifier
6 P B	Six Pulse Bridge rectifier
ACVS	AC Voltage Source
EHV	Extra High Voltage
FS	Frequency Sweep
HCS	Harmonic Current Spectra
HD	Harmonic Distortion
HV	High Voltage
HVAC	High Voltage AC
HVDC	High Voltage DC
HVS	Harmonic Voltage Spectra
MMC	Modular Multi-level Converter
OHL	Overhead line
PCC	Point of Common Coupling
PF	Power Factor
PWM	Pulse Width Modulator
RMS	Root Mean Square
SG	Synchronous Generator
TDD	Total Demand Distortion
THD	Total harmonic Distortion
VSC	Voltage Source converter

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1 Introduction

1.1 General

Since recent decades harmonics have been a serious topic in electrical engineering. They are overall, where power electronics are utilised in a network. They cannot harm the facilities and threaten their life as long as they are kept under limited values. Harmonic distortion, which caused by non-linear loads, can severely change power quality and lead equipment to malfunction.

The presence of harmonics in power lines is unavoidable. They are caused by non-linear loads, particularly in distribution networks, where residential customers have got a big impact on it. Dominant non-linear loads are classified under category of power electronics. Harmonics could change power quality, endanger and shorten the lifespan of equipment, interfere with communication tools if they will not be kept under limit standards. In this master work the main focus is on defining harmonic current sources and modelling them as non-linear loads that inject harmonics into the network, spreading throughout lines causing voltage distortion.

1.2 Motivation

In order to analyse the characteristic and topology of modelled network, the software DigSilent PowerFactory 2020 was used with the main module Power Quality / Harmonic analysis to figure out the voltage distortion at 220 KV and 380 KV bus bars. Every power system could contain compensators. On one hand they have got the task to correct the power factor and reduce transport of reactive power in the network, thus avoiding losses and costs. On the other hand, the supplied reactive power supports the voltage in the system in case of heavy loading. However, they have got a significant impact on harmonic voltage distortion due to resonance phenomena. So after switching on all compensators that are located in different places, distorted voltage can be observed, depicted and be compared with indicative standards.

Harmonic voltage spectra at high voltage level as well harmonic current spectra of non-linear loads will be shown. The frequency sweep is a feature provided in DigSilent to figure out and illustrate the resonance frequencies of the model.

From the figures the resonance frequency can be extracted but to confirm it, we also need to calculate the inductance of AC voltage source and synchronous generators and the capacitance of overhead lines and compensators as well. By having the L and C of the model the angular resonance frequency ω can be obtained. Harmonic mitigation can be done through different approaches such as changing the place of compensators or rebuild a filter from existing compensator and design an appropriate filters and put them in right places to mitigate THD in 220 kV and 380 kV in this work. The results will be compared with the presence of all compensators and a table with THD before and after filter-design.

Skin effect can impact the amplitude of the impedance, therefore synchronous generators, ACVS, two and three-winding transformers plus overhead lines are considered with their frequency dependent resistance. The last and significant part of the work appears in the last chapter, which is all about designing filters and methods of mitigation of harmonics. The frequency dependant resistance (due to skin effect and proximity effect) is taken into account and plays a significant role for damping resonances.

However, there are many different methods to mitigate harmonics but the cost and effectiveness of methods are a big concern. As a result, two alternatives will be offered. Pros and cons of both will be discussed as well.

1.3 Chapter summary

Chapter 2 investigates some basic theory of harmonics. Chapter 3 presents the study case and components of the model. In chapter 4 the presence of compensators due to various reasons is discussed. Chapter 5 depicts harmonic voltage distortion without and with compensators. The impedance and resonance frequency of the network as well as skin effect is illustrated in chapter 6. Chapter 7 offers the method of harmonic mitigation conventionally. In chapter 8 the results are demonstrated. Finally, chapter 9 presents the discussion and conclusion based on results.

2 Theory about harmonics

2.1 Background

Nowadays with the rapid improvement of power electronics in both residential and industrial zones, the presence of harmonics due to non-linear characteristic of solid devices such as thyristors, diodes, and transistors cannot be avoided. On one hand the variety of appliances in household is a big concern to study about harmonics and its impact on power quality. On the other hand, the power quality of a power system should be fulfilled in order to avoid and prevent possible consequence of harmonics.

By using different voltage sources like AC and DC it is important to keep the connection between them together. This task will be done by inverters and rectifiers which bring advantages and disadvantages with. They can be indicated as a harmonic current source that change and distort power quality in particular the shape and form of a sine voltage wave.

In distribution networks where transformers and their magnetising current curves work above the knee point in the B-H curve, the 3^{rd} and 5^{th} harmonics are common. However, they usually do not operate in saturation, thus their influence is negligible. Harmonics can flow from a lower voltage level to a higher voltage level and cause a number of problems. The main point of this work is about multi-phase converters as harmonic current sources which inject not only fundamental current but other components of current that increase the root mean square value and in following higher losses in electrical systems.

2.2 Definition of harmonics

An ideal sinusoidal voltage generated by a synchronous generator in power plants will be transferred throughout transmission lines to substations and then to the distribution networks with variety of voltage levels, based on demand of customers. Any Change in the shape and nature of this voltage can be expressed as power quality pollution. This pollution indicates how much our sine voltage is deformed and particularly distorted from the original form. The distortion is caused by non-linear loads. A Three-phase sine and a distorted waveform are shown in figure 2.1 and 2.2.

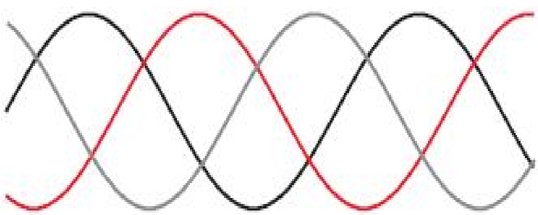


Figure 2.1 a sinusoidal three-phase waveform [1]

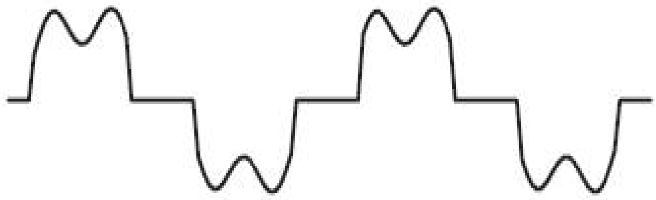


Figure 2.2 a distorted sine waveform [1]

A non-sinusoidal waveform can be expressed with an angular frequency ω and frequency $f = \frac{\omega}{2\pi}$ *and a time period T in form of a Fourier series: [2]*

$$f(t) = F_0 + \sum_{n=1}^{\infty} f_n(t) = \frac{1}{2}\, a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t) \qquad (1\text{-}1)$$

$$a_n = \frac{1}{\pi} \int_0^{2\pi} f(t) \cos(n\omega t) d(\omega t) \qquad (1\text{-}2)$$

$$b_n = \frac{1}{\pi} \int_0^{2\pi} f(t) \sin(n\omega t) d(\omega t) \qquad (1\text{-}3)$$

Where: $F_0 = \frac{1}{2} a_0$ *is the average value of the function,* a_n *and* b_n *are coefficients at nth harmonic. [2]*

Generally, it can be said that a harmonic is a distortion of sine waveform and the sum of all harmonics represents the whole distorted curve in following figure 2.3

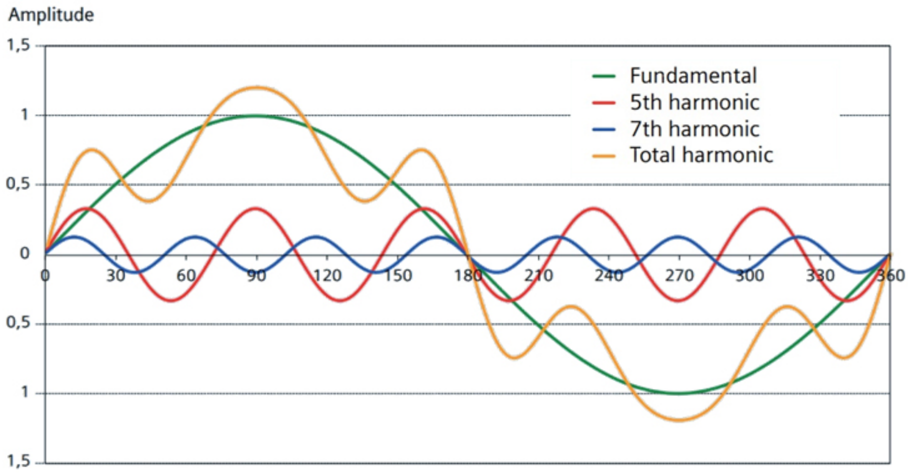


Figure 2.3 sum of all present harmonics [3]

In this chapter a quick look is taken at the basic and general definition of what harmonics are. Then some useful formulas which are connected to the topic and need to be defined to analyse the results. After that the source of harmonic current will be discussed and following the consequence and effect of them on other facilities. At the end of this chapter the indicative harmonic standards at very high voltage levels is introduced in order to maintain the negative impact of harmonics by designing appropriate filters.

- Fundamental frequency

It is the frequency which the system works with. For example, 50 Hz

- Harmonic

A periodic part of a sinusoidal wave form having an integral multiple of fundamental frequency.

For example, if the f_1 = 50 Hz, so the 2^{nd} harmonic is 100 Hz and the 5^{th} one is 250 Hz.

- Point of Common Coupling

Point on a public supply system, electrically nearest to a particular load, at which other loads are, or could be connected. The PCC is a point located upstream of the considered installation. [4]

- Total Harmonic Distortion

It is defined according to IEEE 519-2014 as the ratio of the root-mean-square of the harmonic components to the root-mean-square value of the fundamental harmonic component and expressed in % for both voltage and current. [4]

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} {V_{PCC}}^2}}{V_1} \tag{1-4}$$

- Total Demand Distortion

It is defined as a ration of the root-mean-square of the harmonic content to the root-mean-square of the maximum load current at PCC in %. [4]

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} {I_h}^2}}{I_L} \tag{1-5}$$

2.3 Source of harmonics

By increase in demand of energy as a result of population growth and development of industry in a wide range, the need of using semiconductor and converters in all branchs of electricity networks is significant. The converters are used for various porpuse in industry such as adjustable speed drive, uninterruptable power supplies, switch power modes etc. In the following an overview of the most important harmonic sources in general is mentioned.

2.3.1 Non-linear loads

There are two type of loads generally:

A linear load that draws the current from the supply and is proportional to the applied voltage. The relationship between current and voltage is a linear function and the current of source by flowing through the load remains sinusoidal. This is shown in figure 2.4.

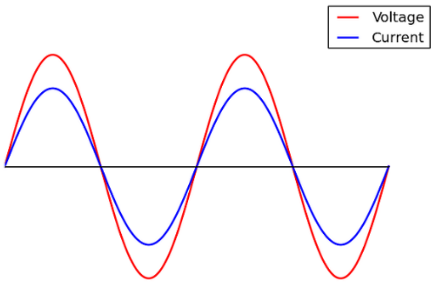


Figure 2.4 voltage & current characteristic of an ideal linear load [5]

A non-linear load is defined if the drawn current does not remain sinusoidal. It means the voltage and current are not proportional to each other as shown in figure 2.5.

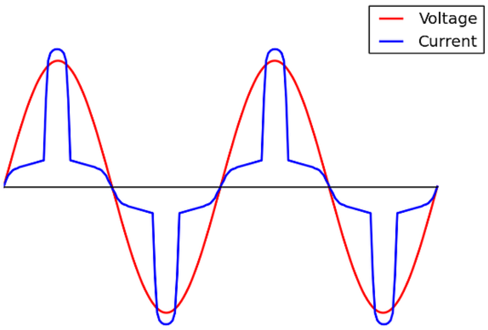


Figure 2.5 voltage & current characteristic of a non-linear load [5]

The non-linear loads contain harmonics that interact with the impedance of network and cause voltage distortion and drops.

2.3.2 Power electronics

Power electronics are devices which the input is controllable and the output has got a desired value. They consist of diode, thyristor, transistor and everything that is made of semiconductors. They also can be classified into residential and industrial facilities. They can be used in single-phase or three-phase.

Residential power electronics are for example:

- Computer-based equipment
- Television
- Fluorescent lighting
- LED lamps
- Ventilators
- AC PWM drives

VSCs are designed to connect HVAC to HVDC systems and capable of generating AC voltage without being independent on AC side which can control the active and reactive power flow. VSC is a modern technology with benefit of feeding power into a network where no active source exists. The used core element in a VSC is transistors in which commutation is executed by bidirectional current. Cascaded connection of VSCs builds up an MMC which enables to reach different voltage levels resulting in lower switching frequency and therefor better sinusoidal waveform by using PMW.

Power electronics are involved in both residential and industrial zones. Nowadays their most significant role is to convert ac to dc or dc to dc with desired outputs. They can be made in 6, 12 and 24 pulse rectifiers in which higher pulse numbers, two or more six bridges are connected parallel. They can be mentioned as harmonic current sources with spectra:

$$h = n.p \pm 1 \tag{1-6}$$

Where,

h = harmonic order

n = number of integer 1, 2, 3…

p = number of pulses

The amplitude of higher harmonic currents caused by rectifiers can be approximated by:

$$I_h = \frac{I_1}{h} \tag{1-7}$$

Where I_h is the amplitude of harmonic current at order h and I_1 is the current at fundamental frequency.

2.3.2.1 6 pulse rectifier

A multiple-phase rectifier can be made of diodes or thyristors. In case of diodes the output voltage cannot be regulated but in case of thyristors it is capable of being controlled. A very common load in medium voltage is this type of rectifier. The below figure shows a typical schematic of six-pulse rectifier with its output voltage. The harmonic spectra formula is calculated:

$$h = n \,.\, 6 \pm 1 \qquad n = 1, 2, 3\ldots \qquad (1\text{-}8)$$

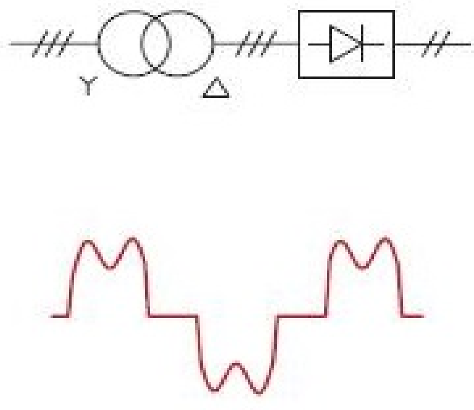


Figure 2.6 6 pulse bridge configuration [1]

2.3.2.2 12 pulse rectifier

A circuit of a 12-pulse convert bridge results from the parallel connection of two 6-pulse converts on the AC side, whereas one converter transformer is arranged as a Yy-circuit, and the other in a Yd-circuit. Due to the phase rotation of the vector groups, the harmonics of the order 5, 7, 17, 19 and so on of the bridges cancel out the equivalent harmonics of the second bridge [7]. A typical 12-pulse rectifier configuration and its output voltage is shown in figure 2.7.

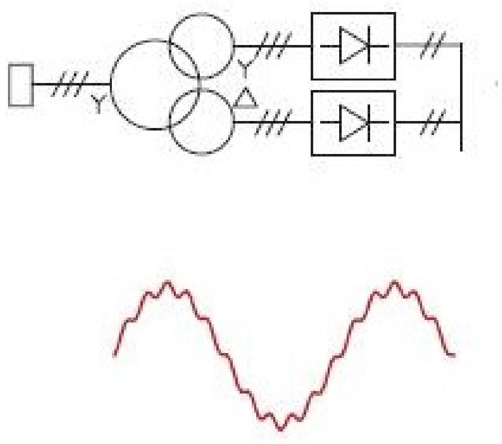


Figure 2.7 12 pulse bridge configuration [1]

Due to the phase rotation of two different transformer's vector groups, remaining harmonics are calculated from:

$$h = n \,.\, 12 \pm 1 \qquad n = 1, 2, 3\ldots \qquad (1\text{-}9)$$

The characteristic harmonics of some rectifiers are shown in table 2.1.

	6 pulse bridge	12 pulse bridge	24 pulse bridge
Harmonic order	5	11	23
	6	13	25
	11	23	47
	13	25	49
	17	35	71
	19	37	73
	23	47	95
	25	49	97

Table 2.1 harmonics spectra of multi-pulse rectifiers

It is absolutely clear the higher number of pulses, less harmonic in spectra and output current waveform. According to the figure 2.7 one of the most common ways to mitigate harmonics is to use higher pulse numbers.

2.3.3 Electric arc furnaces

In industrial zones, where arc furnaces are considered as big loads connected to the PCC may be the most notorious as harmonic producers because they have massive capacity lumped together in one place. The output voltage and current waveforms of an electric furnace is trapezoidal and their magnitude is a function of the arc length. An arc furnace equivalent circuit can be modelled as a resistance and inductance in series with very low power factor operation, so the reactive power needs to be compensated. It is also worth installing filter in case of harmonic mitigation. In this master thesis the assumption is based on the non-linear loads in transmission lines excluding arc furnaces.

2.4 Effect of harmonics

Harmonic distortion rises a variety problems including reduced power factor, overheating, deteriorating performance of facilities. Due to the presence of harmonics in power system, the RMS value of current does include other components of higher orders. The severest effect of harmonic is an increase in current and as a result of higher losses in another equipment that leads to malfunction of protective relays and stress in dielectrics.

2.4.1 Generator

In comparison with utility power supplies, the effects of harmonic voltages and harmonic currents are significantly more pronounced on generators. Their impedances are typically three to four times bigger than of utility transformers [2]. The produced iron losses consist of eddy and hysteresis losses which eddy loss is proportional to square of frequency but hysteresis loss is only proportional to frequency. As a result, higher voltage harmonics generate additional losses which lead to thermal core overheating and increase in ambient temperature of windings.

2.4.2 Transformer

The effect of harmonic currents at harmonic frequencies causes increase in core losses due to increased iron losses (i.e., eddy currents and hysteresis) in transformers. In addition, increased copper losses and stray flux losses result in additional heating, and winding insulation stresses, especially if high levels of dv/dt (i.e., rate of rise of voltage) are present [2]. A power transformer can be modelled as a pure inductive reactance. This particularly is a big concern if there is also capacitive reactance in a network. The resonance can easily occur and provokes interference with communication devices.

2.4.3 Cables

The resistance of a conductor is dependent on the frequency of the current being carried. Skin effect is a phenomenon whereby current tends to flow near the surface of a conductor where the impedance is least. An analogous phenomenon, proximity effect, is due to the mutual inductance of conductors arranged closely parallel to one another. Both of these effects are dependent upon conductor size, frequency, resistivity and the permeability of the conductor material [2]. At higher frequencies the RMS value of current includes higher harmonic components which contains higher amount of current and respectively the losses. Both phenomena play a vital role in cabling design.

2.4.4 Circuit breakers and fuses

The vast majority of low voltage thermal-magnetic type circuit breakers utilize bi-metallic trip mechanisms which respond to the heating effect of the RMS current [2]. Injected higher current components caused by no-linear loads, increases the RMS value of current. This can severely impact the adjusted trip current of circuit breaker and fuses that causes malfunction.

2.4.5 Capacitor banks

Capacitor banks are installed mainly to enhance poor power factory due to inductive loads. The interaction of harmonics with capacitor banks results in having less capacitive reactance which lets more current flow through, thus leading to overcurrent, overheating and higher voltage stress.

2.5 Harmonic standards

Harmonic standards are used for variety purposes in electrical systems. They specify satisfying levels of harmonics due to interaction of non-linear loads with other networks equipment mostly compensators. Both the maximum voltage and current distortion are defined, in order to have less consequence of harmonics in power system namely high loss, malfunction of facilities and interference with communication tools. Our focus in this work is on voltage distortion at two voltage levels.

2.5.1 IEC 61000-3-6 2nd edition

This standard defines an assessment of harmonic emission limits for the connection of distorting installations to the medium, high and extra high voltage power systems. Harmonic source can be classified into two categories in following:

- *The harmonic currents are injected into the supply system by converters and other harmonic sources. Both harmonic currents and resulting voltages can be considered as conducted phenomena.*
- *The harmonic currents may induce interference into communication systems. This phenomenon is more pronounced at higher order harmonic frequencies because of increased coupling between the circuits and because of the higher sensitivity of the communication circuits in the audible range.* [8]

Different voltage levels are defined in this standard in following:

- *Low voltage refers to $U_n \leq 1$ kV*
- *Medium voltage refers to 1 kV < $U_n \leq 35$ kV*
- *High voltage refers to 35 kV < $U_n \leq 230$ kV*
- *Extra high voltage refers to $U_n > 230$ kV*. [8]

Indicative values of planning levels for harmonic voltages in percent of fundamental voltage in medium, high and extra high voltage are illustrated in figure 2.8. In Europe and most countries this standard is common and used for keeping THD and individual harmonics under limit.

Odd harmonics non-multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Harmonic Order h	Harmonic Voltage %		Harmonic Order h	Harmonic Voltage %		Harmonic Order h	Harmonic Voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1,8	1,4
7	4	2	9	1,2	1	4	1	0,8
11	3	1,5	15	0,3	0,3	6	0,5	0,4
13	2,5	1,5	21	0,2	0,2	8	0,5	0,4
$17 \leq h \leq 49$	$1{,}9 \cdot \frac{17}{h} - 0{,}2$	$1{,}2 \cdot \frac{17}{h}$	$21 < h \leq 45$	0,2	0,2	$10 \leq h \leq 50$	$0{,}25 \cdot \frac{10}{h} + 0{,}22$	$0{,}19 \cdot \frac{10}{h} + 0{,}16$

Figure 2.8 individual harmonic voltage distortion limit for medium, high and extra high voltage [8]

The total harmonic distortion in high and extra high voltage level must not exceed 3%. This standard is our reference for filter design.

2.5.2 IEEE standard 519-2014

This standard represents the design of electrical systems include both linear and non-linear loads only in steady state condition and the worst case [4]. Recommended harmonic voltage limit is shown in figure 2.9. This standard is mostly popular in the USA and Canada.

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

Figure 2.9 individual and THD at different voltage levels [4]

Note: [a] high voltage system can have up to 2.0 % THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected [4].

3 PowerFactory and network model

3.1 Introduction

This programme DigSilent PowerFactory, is a modern and sophisticated computer software to fulfil the wish and desire of analysis of high power systems, distribution network, industrial and residential networks for engineers. The design of this advanced integrated and interactive software has contributed a lot to electrical power systems to find out statistics, a better analysis and reach desired goals through planning and optimisation.

DigSilent is an abbreviation for Digital Simulation of Electrical Networks [9]. This outstanding software provides for power systems an integrated graphical single-diagram and detailed analysis. There are many great features like cable analysis, reliability analysis, protection and arc flash analysis as well static and dynamic calculations.

PowerFactory has hired so many qualified electrical and computer programmer engineers with many years of experience to offer the highest and best power system analyser. The result of analysis of this software was compared with many existing projects and accuracy and validity of the results were confirmed by organisations involved in planning power systems worldwide.

The licence of this master thesis is limited with maximum 200 allowed nodes in a network.

3.2 Related function

As it has been mention this programme is able to do different tasks and calculations of a massive network based on the usage of users like short circuit, cable analysis, reliability analysis, optimal power restoration and power quality and harmonic analysis. For this work the power quality and harmonic analysis is activated specially to focus on harmonic distortion and find an optimisation to mitigate harmonics.

Another tools of this function will be explained for the statistics and interpretation of extracted data of simulation. PowerFactory is primarily intended to be used and operated in a graphical environment. By drawing the element to the environment of the programme, a simple circuit can be created in single-line diagram.

Harmonic content of current and voltage is one of many issues of power quality. *Harmonic analysis can be performed either in the frequency-domain or the time-domain* [9] with the help of Fourier analysis. This programme uses the frequency-domain to analyse harmonics. The following functions are included in PowerFactory:

3.2.1 Harmonic load flow

This feature is based on IEC 61000-3-6 standard and has got duty to calculate harmonic indices of current and voltage distortion, losses caused by harmonic current sources. PowerFactory carries out a steady-state analysis of the network at each frequency at which harmonics are defined and the results can be illustrated in either bar or curve diagrams.

3.2.2 Frequency Sweep

This option does a continuous frequency-domain analysis. With the help of this function we can estimate the impedance of the network in series or parallel resonance. The resonance can be identified and retrieved from figures at which harmonic currents cause higher voltage distortion. In order to design a filter, knowing the impedance of a network is of a particular significance.

In this master thesis the simulation will be performed in DigSilent PowerFactory 2020 and the basic model of the analysed transmission system already exists. A rather big high voltage system is simplified to a small one with maximum 200 nodes.

The purpose is to mix linear and non-linear loads and see how the harmonics interact with the network and what occurs if compensators are on in order to correct PowerFactory and keep the voltage constant at some points. For this the function of Power Quality and Harmonic Analysis is active. By illustration of harmonic spectra of voltage, it can be seen which part of the network has got the highest distortion and what action is needed to be done. In the following figure 3.1 a small part of a power system consists of different voltage levels which is coloured and highlighted.

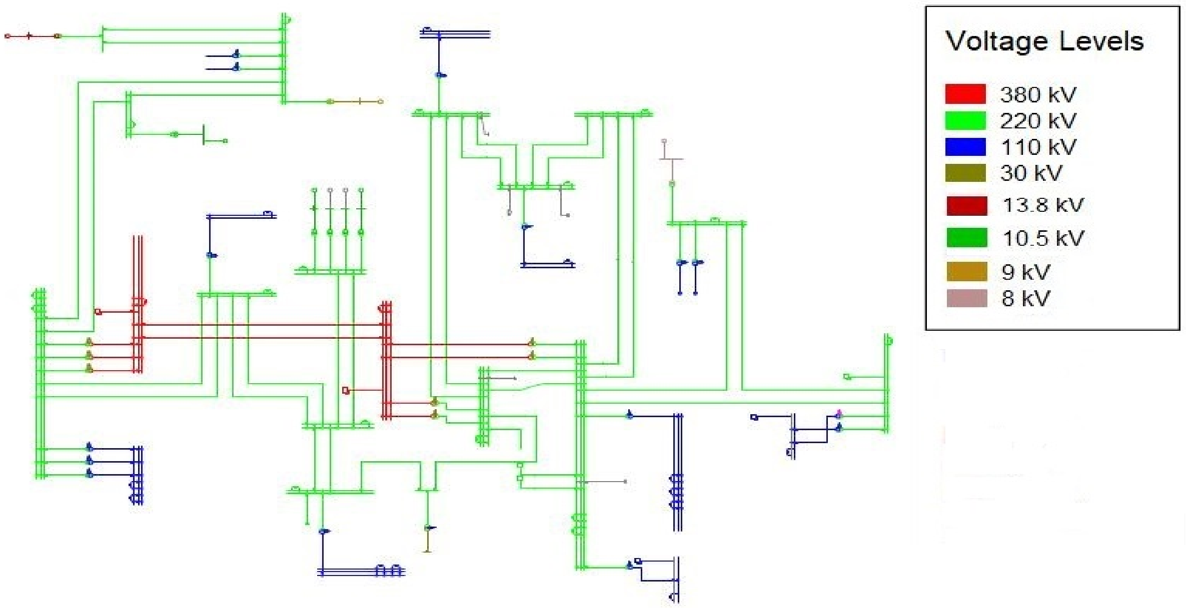


Figure 3.1 model of the network without any loads

3.3 Components of model

Like other power systems this model consists of a variety of components which will be explained in the following.

3.3.1 Synchronous generators

The electrical energy is generated by synchronous generators in power plants converting another type of energy such as solar, wind, coal into electricity. In this model five generators are distributed in different places with Y connection which is listed and highlighted in figure 3.2.

SG	U_n in kV	S_n in MVA	PF	X_d'' in p.u
Substation 1	10.5	98	0.85	0.2
Substation 2	9	35	0.8	0.195
Substation 3	13.9	166	0.9	0.197
Substation 4	10.5	30	0.8	0.185
Substation 5	8	42.5	0.8	0.185

Table 3.1 all synchronous generators of model

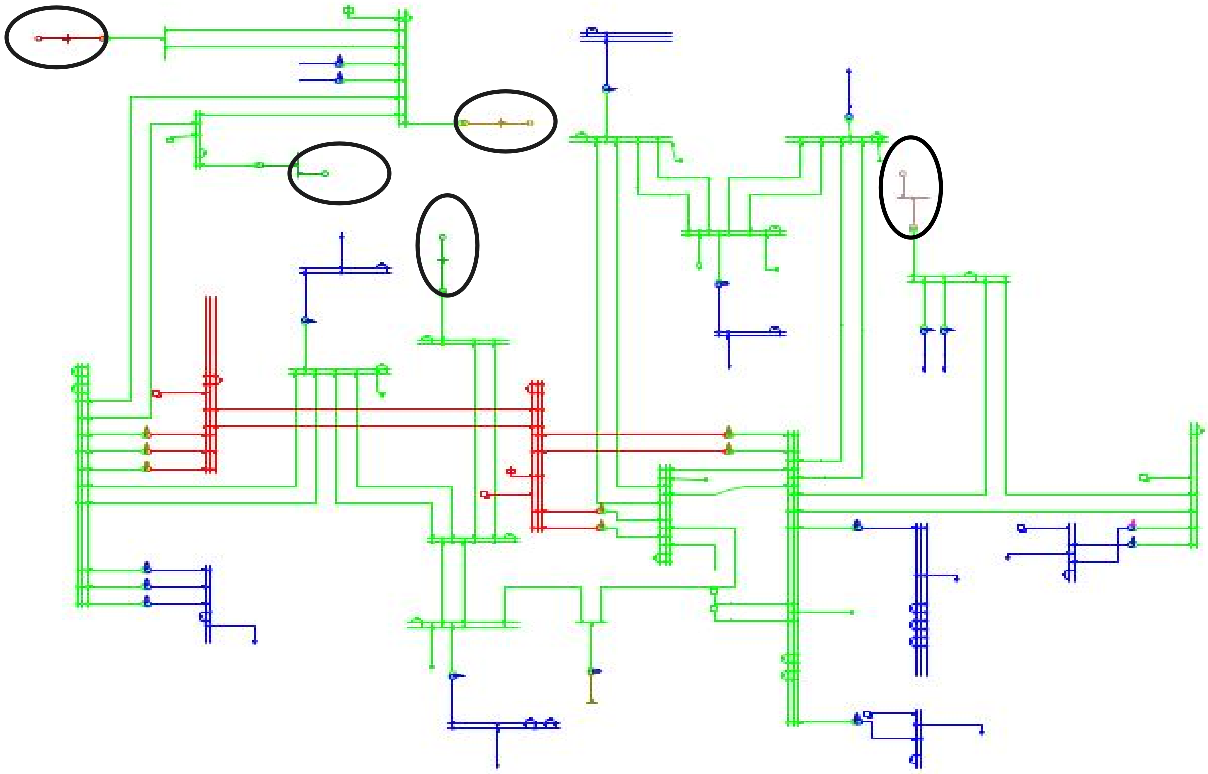


Figure 3.2 located synchronous generators

3.3.2 Two and three winding transformers

Transformers in a power system have got the duty to change the level of voltage based on demand in distribution or high voltage network. They are connected to bus bars where synchronous generators are located nearby. All information of this model's transformers is listed in table 3.2 and 3.3.

2-winding	HV in kV	LV in kV	S_n in MVA	Vector group
Transformer 1	220	110	220	Ynd 0
Transformer 2	230	10.5	85	Ynd 11
Transformer 3	230	9	35	Ynd 5
Transformer 4	230	13.8	170	Ynd 5
Transformer 5	230	10.5	60	Ynd 5
Transformer 6	230	8	85	Ynd 11

Table 3.2 two-winding transformers of the model

All three-winding transformers have got the vector group YN0yn0d5.

Voltage level	Three-winding Transformers	Rated power in MVA			Rated voltage in kV		
		HV	MV	LV	HV	MV	LV
220 kV	Transformer 1	220	220	33	232	116	10
	Transformer 2	300	300	30	232	116	10
	Transformer 3	200	200	30	220	120	10
	Transformer 4	300	300	30	232	116	10
	Transformer 5	300	300	30	232	116	10
	Transformer 6	200	200	30	220	120	10
	Transformer 7	40	40	6.67	220	30	10
	Transformer 8	200	200	30	220	110	10
	Transformer 9	220	220	33	232	116	10
	Transformer 10	60	60	30	232	116	10
	Transformer 11	200	200	30	220	110	21.5
	Transformer 12	200	200	30	220	110	10
380 kV	Transformer 1	600	600	150	400	230	30
	Transformer 2	550	550	150	400	230	30
	Transformer 3	550	550	150	400	230	30

Table 3.3 three-winding transformers of the model

3.3.3 Bus bars

Voltage level	Bus bar	Located colour
220 kV	Bus bar 1	
	Bus bar 2	
	Bus bar 3	
	Bus bar 4	
	Bus bar 5	
	Bus bar 6	
	Bus bar 7	
	Bus bar 8	
	Bus bar 9	
	Bus bar 10	
	Bus bar 11	
	Bus bar 12	
	Bus bar 13	
	Bus bar 14	
	Bus bar 15	
	Bus bar 16	
380 kV	Bus bar 1	
	Bus bar 2	

Table 3.4 all bus bars of model in high and extra high voltage

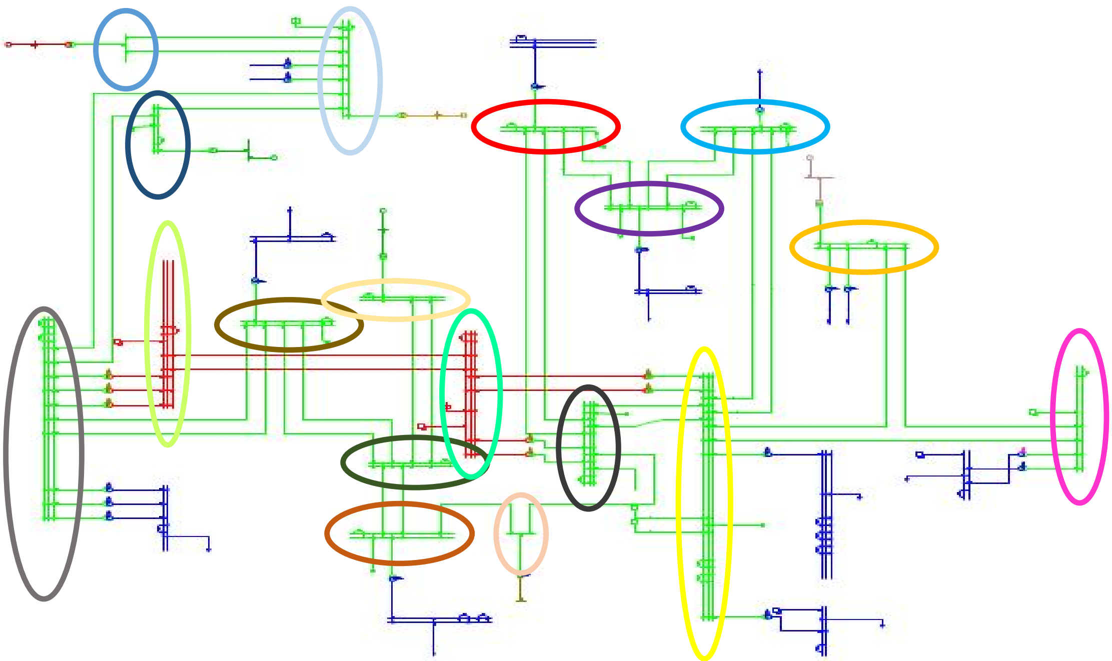


Figure 3.3 located bus bars

3.3.4 AC voltage sources

AC voltage source	Voltage in kV	X_1 in Ω	Located colour
ACVS 1	110	544.5	● (orange)
ACVS 2		63.8	● (green)
ACVS 3	220	29.5	● (dark grey)
ACVS 4		175	● (blue)
ACVS 5		175	● (brown)
ACVS 6	380	32.8	● (turquoise)
ACVS 7		17.8	● (purple)

Table 3.5 AC voltage sources of the model

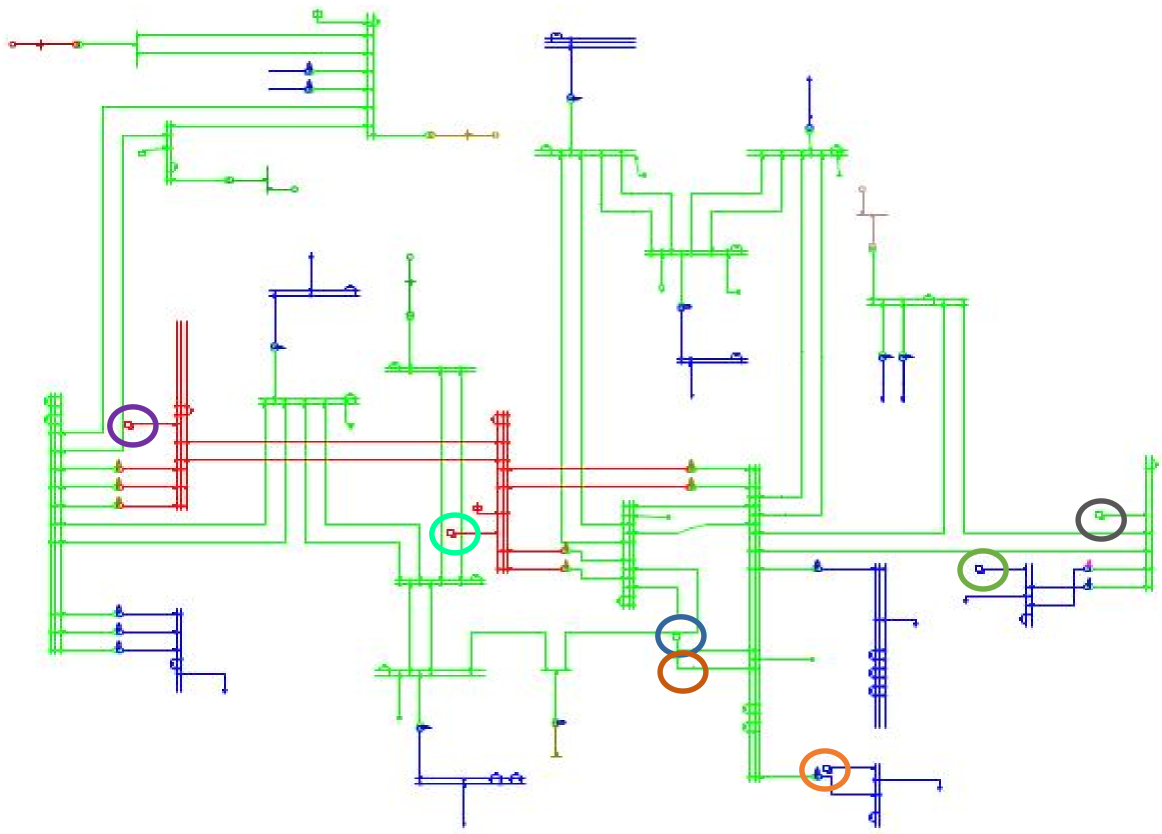


Figure 3.4 location of AC voltage sources

3.3.5 Compensators

This part will be discussed in 4.4.

3.3.6 Loads

All loads are connected to medium voltage 110 kV and they operate in the balanced case.

Type of loads	Load	$P_{MW}+jQ_{Mvar}$	Connected to	Located colour
Non-linear	12-1 P B	20+j10	Bus bar 9	
	12-2 P B	20+j10	Bus bar 15	
	6 P B	7+j3	Bus bar 11	
Linear	General load	25+j5	Bus bar 13 via Transformer	
	Industrial load1	25+j10	Bus bar 4	
	Industrial load(1)	25+j10	Near bus bar 7	
	Industrial load(2)	25+j10	Bus bar 16	
	Industrial load(3)	25+j10	Near bus bar 15	

Table 3.6 characteristic of all loads

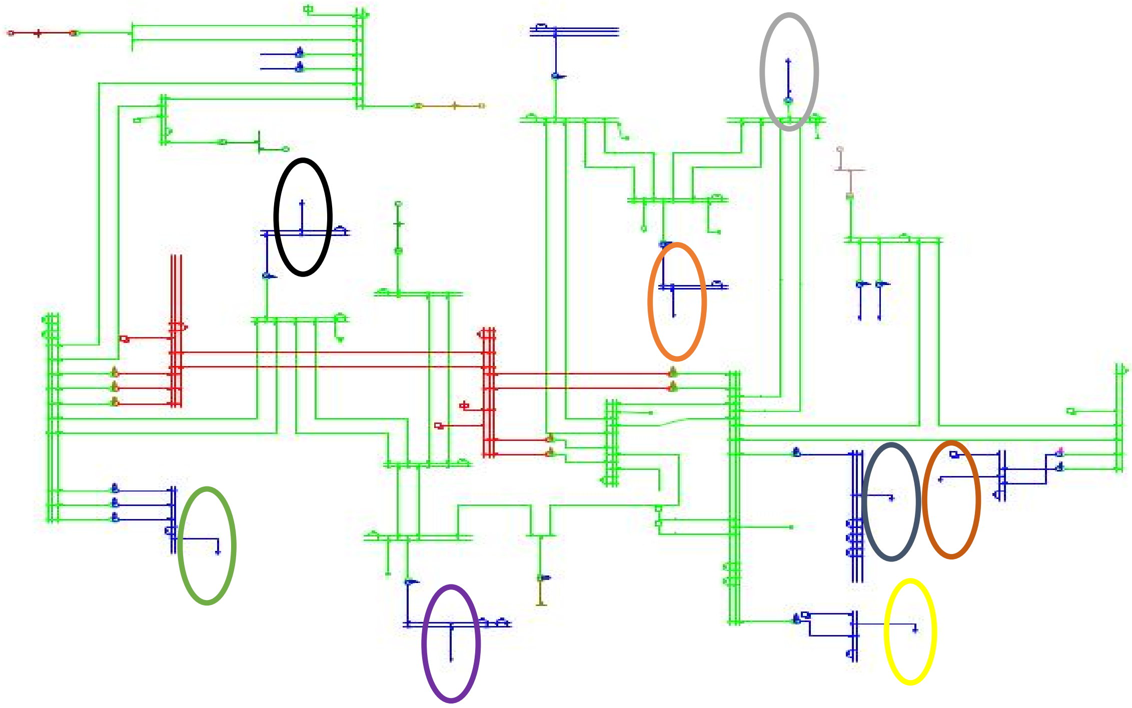


Figure 3.5 the network with linear and non-linear loads

3.4 Harmonic current spectra

The next step is to add some general loads to the 110 kV bus bars and change some of their characteristic in order to make non-linear loads of them. There are totally eight loads distributed in different places of the network. For this, six and twelve pulse rectifier from the main library are added to the study case and a general load that can be modelled either as current source or an impedance.

Harmonic current spectra which is based on IEC 61000 is depicted. It can be seen that higher harmonic orders, less current amplitude.

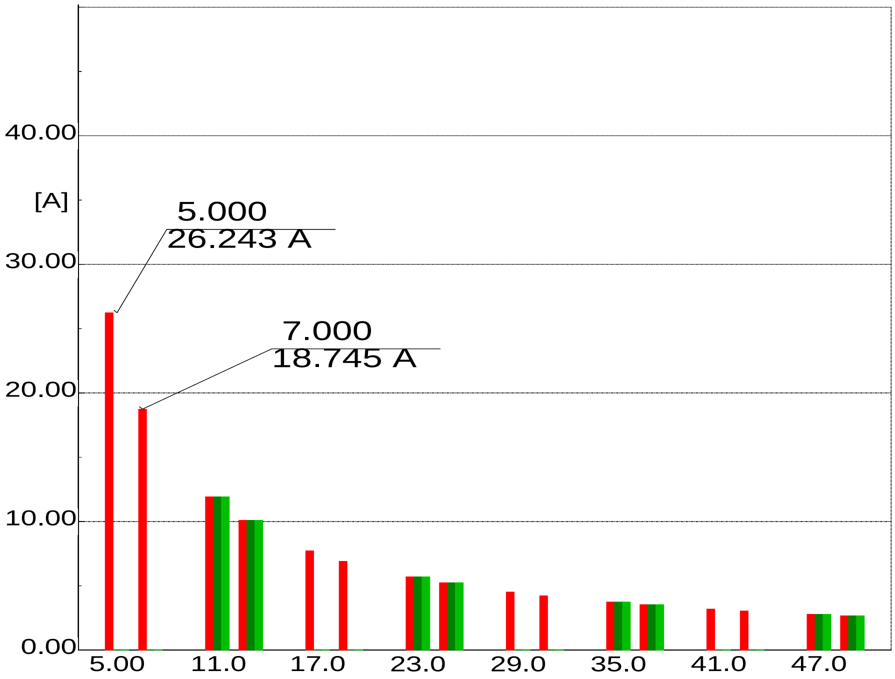


Figure 3.6 harmonic current spectra of non-linear loads

4 Compensator’s analysis

4.1 Introduction

Consumption of reactive power in power systems is indicated mostly by inductive loads, components of the network such as transformers and synchronous and asynchronous motors.

Flowing so much reactive power in a network can provoke a variety of issues such as increase in losses, weaken the reliability and poor power factor. The oscillation of reactive power flow from source to the consumers causes additional losses due to long distance. This can be compensated by shunts which can be connected directly to the point of loads.

In the power system, reactive power should be maintained balanced, or otherwise, it would worsen the system voltage, and even cause the voltage collapse accidents [10]. In case of lower voltage as expected, much current flows through the lines and therefore additional losses. In order to optimise and enhance the operation of the power network, it is significant to control and regulate the reactive power which can be performed by injecting capacitive reactive power.

Reactive power can be leading or lagging [11]. Nowadays most devices and equipment can be modelled either as resistance-inductance such as transformers, motors, generators or resistance-capacitance such as overhead lines and cables. The reactive power can be generated by capacitances or consumed by inductances. Both components contribute to reactive power.

The majority of connected and distributed loads in a network consists of the inductive part and reactive power needs to be provided. From economical point of view, if reactive power supply is located in the near of loads, this correspondence can be attenuated and therefore the capacity of power system gets better. Reactive power can be generated by capacitors and consumed by inductors both either in shunt or series with the circuit based on the demand of the network.

The main task of compensators is to cancel out the lagging power with leading power which results in having pure resistive power indicated as active power. Compensators can be implemented in any voltage level according to demand. A very typical way of supplying capacitive reactive power is to add shunt compensators to bas bars or lines.

4.2 Roles of compensators

4.2.1 Reactive power control

The fundamental definition of reactive power can be explained by first looking at the relationship between a sinusoidal voltage and current waveforms of the same frequency [13].

A simple way to define the reactive power is when the voltage and current have got an angle. This describes that the network is not pure resistive but it includes inductance and capacitance. In case of resistive - inductive equivalent circuit the reactive power will be consumed. In contrast to resistive – inductive which it is called resistive-capacitive, the reactive power will be generated.

One of many reasons of voltage failure is circulation of too much inductive reactive power in a network. Reasons to cause voltage failure can be mentioned mostly in the following:

- Switching on a huge amount of loads gathered in one place at the same time
- Malfunction of components
- Switching off large components like power transformers, generators and very long lines

The task of compensators in a power system is to provide reactive power due to inductive impedance of network which is caused by magnetic fields. Flowing reactive power from the source to the consumers occupies the capability of the power system and leads to extra losses and eventually maintenance cost.

It can be that a system instead of having resistance and inductance includes only capacitance, so it can increase the voltage at the end of the line and cause severe problems. The study and observation of reactive power is of a significance topic in electrical networks.

4.2.2 Power factor correction

Power factor is defined as cosine of angle between voltage and current in a power system. There is an angle difference between voltage and current in an AC circuit. In case of an inductive circuit, the current lags and voltage leads, so power factor is referred to as lagging. However, in a capacitive circuit the current leads and voltage lags, so power factor is referred to as leading. Another definition of power factor can be expressed as the ratio of active power on apparent power.

A small amount of reactive power can enhance and improve power factor of a system. The lagging reactive power is responsible for lower power factor. The active power represents the work which is done useful but reactive power does not do any useful work and it flows back and forth in both directions between source and consumers.

Due to dependency of current and active power of a system on cosφ, if the Power factor is less that unity it can have disadvantages in following:

- Greater conductor size
- Increase in copper losses
- unstable voltage
- Reduction in power system capacity

Transformers and generators are design for a specific apparent power in power systems. Apparent power contains active and reactive power. The smaller reactive power by keeping active power *constant, the smaller apparent power. Therefore, power factor correction can contribute a lot to the lower apparent power but the same active power* [14].

Power factor correction can be executed in many ways:

• **Distributed power factor correction**: in this method the individual capacitor bank is employed and connected directly to a load locally. *The installation is simple and inexpensive; capacitor and load can use the same protective devices against over currents and are connected and disconnected simultaneously* [14].

• **Group power factor correction**: if a large number of loads with the same characteristic is needed to be compensated, a shunt capacitor can be installed to enhance power factor.

• **Centralized power factor correction**: *For installations with many loads, where not all the loads function simultaneously and/or some loads are connected for just a few hours a day, it is evident that the solution of distributed power factor correction becomes too onerous since many of the installed capacitors stay idle for a long time. In centralized power factor correction automatic assemblies are normally used* [14].

• **Combined power factor correction**: a mixture solution of both distributed and centralised power factor correction. *In such way, the distributed compensation is used for high power electrical equipment and the centralized modality for the remaining part* [14].

• **Automatic power factor correction**: in most cases, the reactive power demand of installation cannot be specified. It means they operate in a day several times at different time schedule. It is important to supply reactive power intelligently which is done by automatic regulators in step by step way.

4.2.3 Voltage control

One of the serious issues in a power system is keeping voltage around a satisfying point and area. Maintaining voltage constant in normal operation or stable after any disturbance, can be defined as voltage stability. *A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage* [13].

A traditional and simple way to keep the voltage at a bus bar is to install the capacitor bank near the load where the power factor is less than 0.9. The capacitor injects reactive power to the load and the magnitude of current decreases and consequently losses. Reduced current causes less voltage drops, so a slight increase at the bus bar results in improvement of terminal voltage.

A common and popular method and approach to enhance and improve the voltage of a system is to use Static Var Compensator (SVC).

The main advantage of SVC over simple mechanically switched compensation schemes is their near instantaneous response to change in the system voltage. For this reason, they are often operating at close to their zero point in order to maximize the reactive power correction. They are in general, cheaper, higher capacity, faster, and more reliable than dynamic compensation schemes [15].

4.3 Concern of compensators

A typical method and way of keeping voltage constant and enhancement of power factor is to utilise capacitive compensators. By adding the capacitance to the network, the impedance of the network might be reduced at the fundamental frequency but the installation of shunt capacitors can result in harmonic resonance and cause an increase in the system impedance at the corresponding frequency.

In the case that a source of excitation such as harmonic currents of nonlinear loads exists with a frequency near or equal to the system natural frequency, large harmonic voltage distortions can result due to the occurrence of resonant conditions [16]. The possibility of a parallel resonance is more likely to occur with the presence of huge non-linear loads in a circuit. The most relevant issue of parallel resonance can be referred to overheating of fuses and circuit breakers which leads to premature failure.

A resonance is a phenomenon in a power system where the frequency of the network corresponds to the harmonic sources. Most loads are inductive, therefore the reactive power will be absorbed and power factor at bus bar is less that unity so their disadvantages are: increase in losses and reduction in capacity of transmission lines and voltage drops. On the other hand, shunt capacitors are used to enhance the Power factor and reduce reactive power correspondence from the main supply to the loads.

The whole impedance of a power system is a function of inductance and capacitance. In high voltage level the ratio of $\frac{R}{L}$ is negligible and only L plays a significant role. By installing a capacitor bank the resulted impedance is a mixture of inductive and capacitive impedance, which at a specific frequency occurs the resonance. The resonance frequency can be expressed:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{4-1}$$

There are two kinds of resonance:

4.3.1 Series resonance

This type of resonance happens when L and C forms a series connection in the whole system. In series resonance inductance and capacitance cancel each other at a specific frequency whereby the impedance reaches its least value, therefore a high amount of current flows in the circuit and can damage facilities severely. This occurs rarely in power systems.

4.3.2 Parallel resonance

The inductive and capacitive reactance are connected parallel to each other. At a specific frequency they have the same value but with opposite sign therefore the impedance becomes enormous significantly.

Installation of capacitors affects directly the resonance frequency of the system and sometimes may contribute to harmonic resonance problem [16].

The possibility of parallel resonance is higher than series in power system. In parallel resonance the total impedance becomes a maximum. A resonance frequency, resulting in a high voltage that can damage the equipment. The figure 4.1 shows us this equivalent circuit.

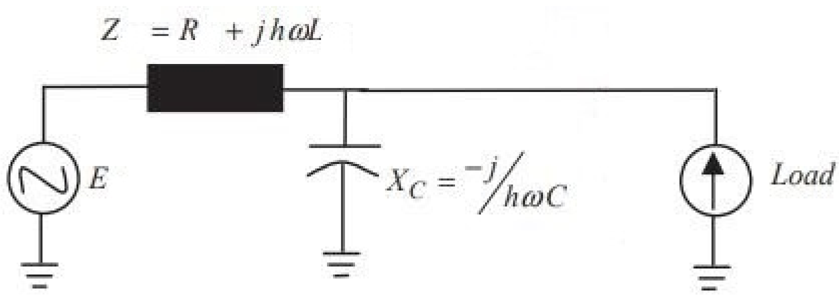


Figure 4.1 equivalent circuit of a parallel resonance [16]

It is realized that during parallel resonance, a small harmonic current can cause a large voltage distortion at the resonance harmonic [16]:

$$V_{resonance}^{bus} = Z_{resonance}\, I_{load}^{h} \qquad (4\text{-}2)$$

The current flowing in the capacitor bank would be:

$$I_{resonance}^{capacitive} = V_{resonance}^{bus}\,(h_{res}\,\omega C) = h_{res}\,\omega\,\frac{L}{R}\,I_{load}^{h} \qquad (4\text{-}3)$$

It is clear that currents flowing in the capacitor bank will be magnified by the factor $\frac{L}{R}$ [16].

5 Simulated voltage distortion

5.1 Voltage distortion without compensators

After creating and adding the loads in the network, calculation method can be performed by selecting Load Flow, AC load flow, balanced, positive sequence and then harmonic load flow by tab Basic Option choosing balanced with only positive sequence to see the harmonic voltage distortion caused by non-linear loads at every high and extra high voltage bus bars. The results of variables of harmonic flow will be saved in Harmonic without Compensators

5.1.1 Harmonic voltage distortion of 220 kV

All statistics are based on IEC 61000-3-6 standard which individual harmonic limit is activated and demonstrated as red hatched columns at every harmonic order.

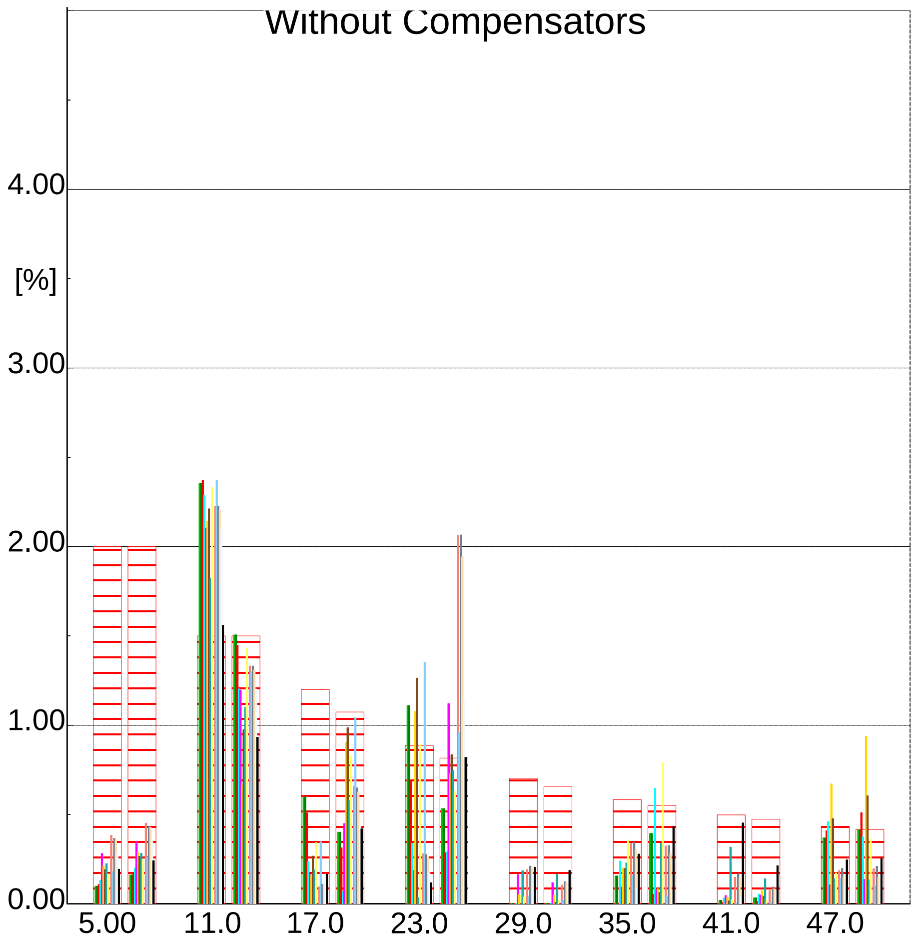


Figure 5.1 harmonic voltage distortion of 220 kV

It is clear that some individual harmonic orders exceeded the IEC 61000-3-6 standards and need to be considered to avoid and keep them under indicative standards.

5.1.2 Harmonic voltage distortion of 380 kV

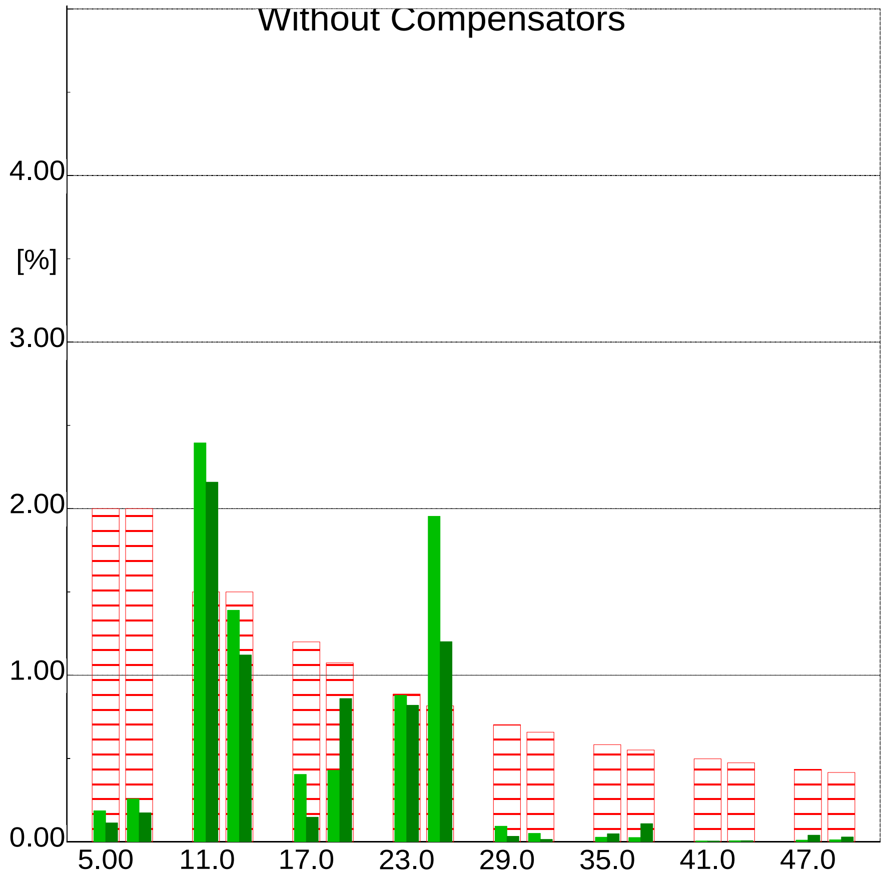
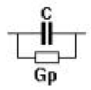
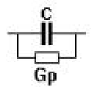


Figure 5.2 harmonic voltage distortion of 380 kV

It is obvious according to the figures 5.1 and 5.2 that at 220 kV the 11th and 25th are dominant and at 380 kV the 11th and 25th. This is specially the case for without compensators.

5.2 Voltage distortion with compensators

The study case is equipped like a typical power system with compensators in different places. The characteristic, properties and structure of them is listed in following.

Compensators	**U_n in kV**	**Shunt type**	**Technology**	**Q_n in Mvar**	**C in μF**	**Located colour**
C_1	235		3PH-D	114.2	2.2	
C_2	210		3PH-D	114.2	2.75	

C_3	245		3PH-D	114.2	2	
C_4	235		3PH-D	114.2	2.2	
C_5	174		3PH-D	114.2	4	
C_6	174		3PH-D	114.2	4	
C_7	120		3PH-D	50	3.68	Located in sub-sheet of 110 kV

Table 5.1 compensators of model

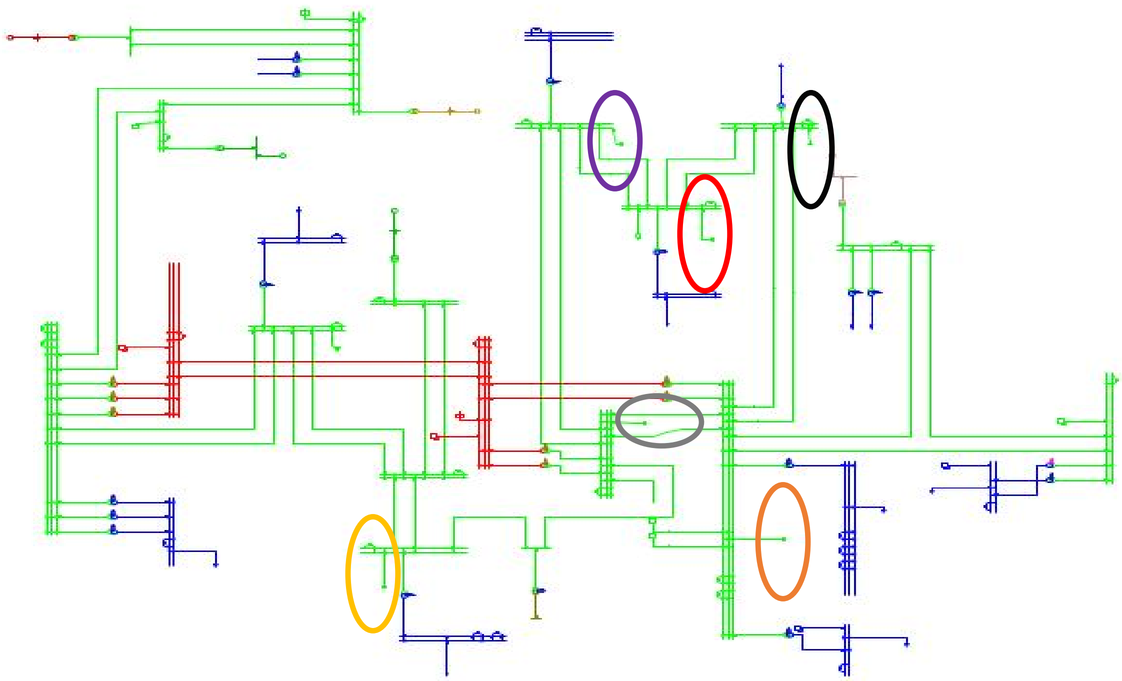


Figure 5.3 location of compensators

5.2.1 Harmonic voltage distortion of 220 kV

If all compensators are on, the resulting harmonics due to the topology and location of compensators will be shifted either towards higher or lower harmonic orders. The below figure 5.4 is depicted to show the result in all sixteen 220 kV bus bars:

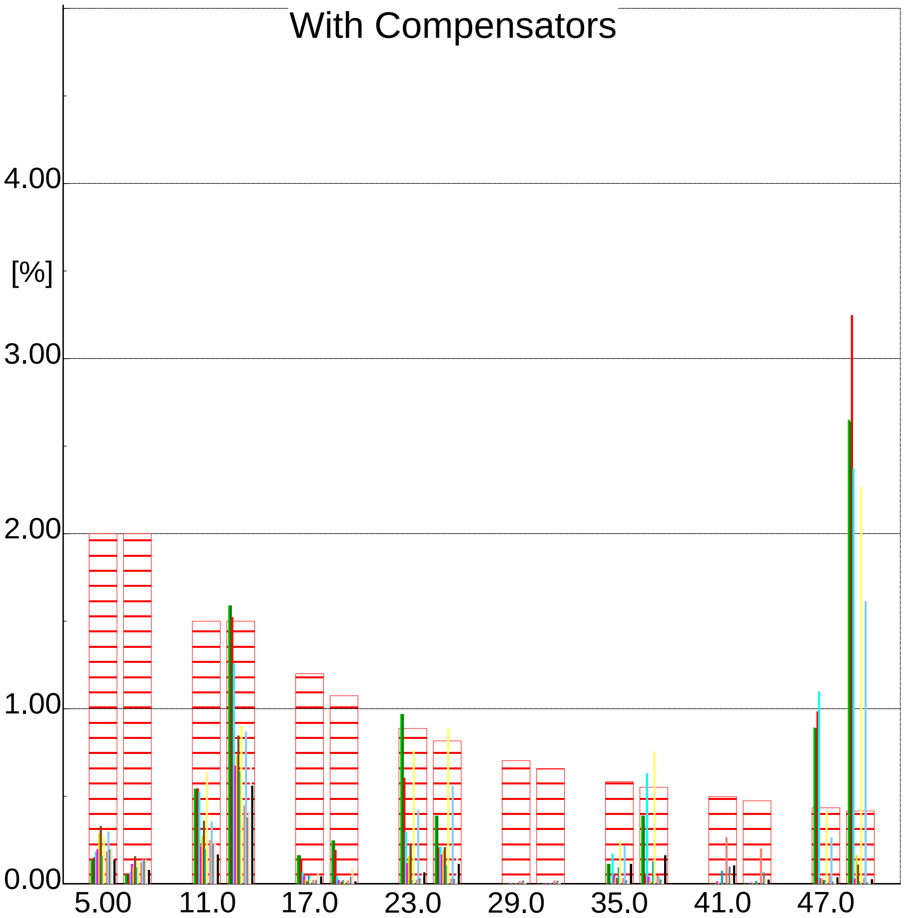


Figure 5.4 220 kV bus bars in presence of all compensators according to IEC 61000-3-6

In comparison with only the mixture of linear and non-linear loads (without compensators) it is clear that the harmonic orders have been shifted to higher order which are now 49th but they were before 11th.

5.2.2 Harmonic voltage distortion of 380 kV

Like 4.2. the new harmonic voltage spectra of two 380 kV bus bars in shown in figure 5.5. Although there are not any compensators in extra high voltage level but it is obvious that the harmonic voltage distortion is changed in 380 kV. It is to see that all individual harmonics are under limit but 13th is close to and in case of network extension, this order must be considered.

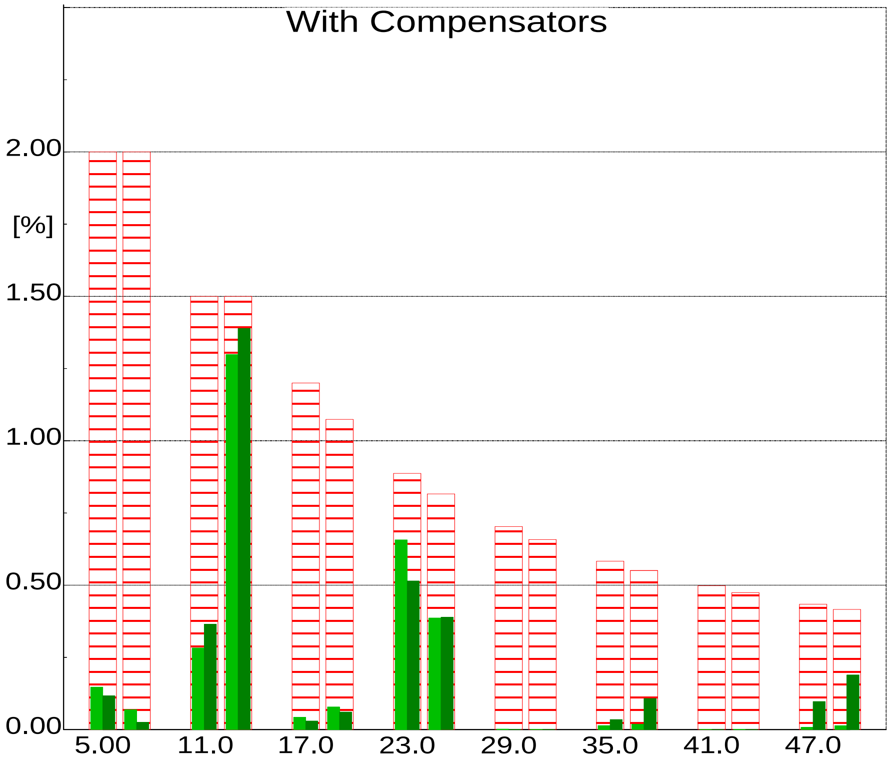


Figure 5.5 380 kV bus bars in presence of all compensators according to IEC 61000-3-6

The maximum voltage distortion before and after switching all compensators are at 11th and 13th harmonic orders.

6 Impedance-frequency-characteristic

6.1 Introduction

The impedance of a network is influenced heavily by harmonic currents. The equivalent impedance of the network can be calculated at every harmonic order. *If a large harmonic current is fed into a bus bar with a large network impedance, a large harmonic voltage will be generated* [17].

A precise study of frequency dependence of components due to skin and proximity effect is needed to analyse the spread of harmonic. *There are three computational methods to analyse harmonics load flow in a power system: [7]*

Computational methods in the frequency domain:

The easiest method, which is thereby of highest importance in practice, is the assumption of the feeding of harmonic currents I_h with predetermined amplitude and angle in the load nodes of the grid. The harmonic currents, which have to be fed into several load nodes, are determined from measurements or from computer-aided simulation in the time domain. Afterwards, the system of equations has to be solved for each harmonic h [7].

$$V_h = Z_h\, I_h \qquad (6\text{-}1)$$

Harmonic network impedance depends on the grid topology, the ongoing short-circuit power and the switching status. Line capacitances play a crucial role especially in high voltage systems as well as in medium high voltage system with huge cable sections. They can lead to critical parallel and series resonance.

Computational methods in the time domain:

With these methods, the differential equations for current and voltage are solved numerically. Non-linear consumers can be installed into computer-aided calculation directly over their current-voltage characteristic. [7]. The pro and con of this method is transient calculation and time-consuming.

Mixture method:

In this method frequency method will be performed partly. Firstly, a conventional 50 Hz power flow calculation is made. The result is a sinusoidal voltage in all grid nodes. In the next step, for each node the harmonic current as a result of the voltage is calculated in the time domain [7].

PowerFactory calculates frequency dependent impedances for a given frequency range using ComFsweep. Frequency Sweep has been used for computation of self- and mutual- network Impedances as the part of the software packages [18]. The purpose of frequency scan execution is to specify different system components and gain right parameters at required frequency.

6.2 Impedance-frequency without compensators

The impedance of a network consists of two parts. One part is real part and is indicated as resistance impedance and another part is imaginary and is indicated as either inductive or capacitive impedance which both parts depend on frequency. With increase in frequency, the skin effect causes increase in resistance. Capacitance of lines and cables are highly dependent on the used material, diameter, shape of conductors. Although the capacitance of cables is more pronounced due to closed arrangement in comparison to overhead lines with big distance from each other. The below figures 6.1 and 6.2 are depicted to show the impedance frequency dependence of the model in 220 and 380 kV without skin effect.

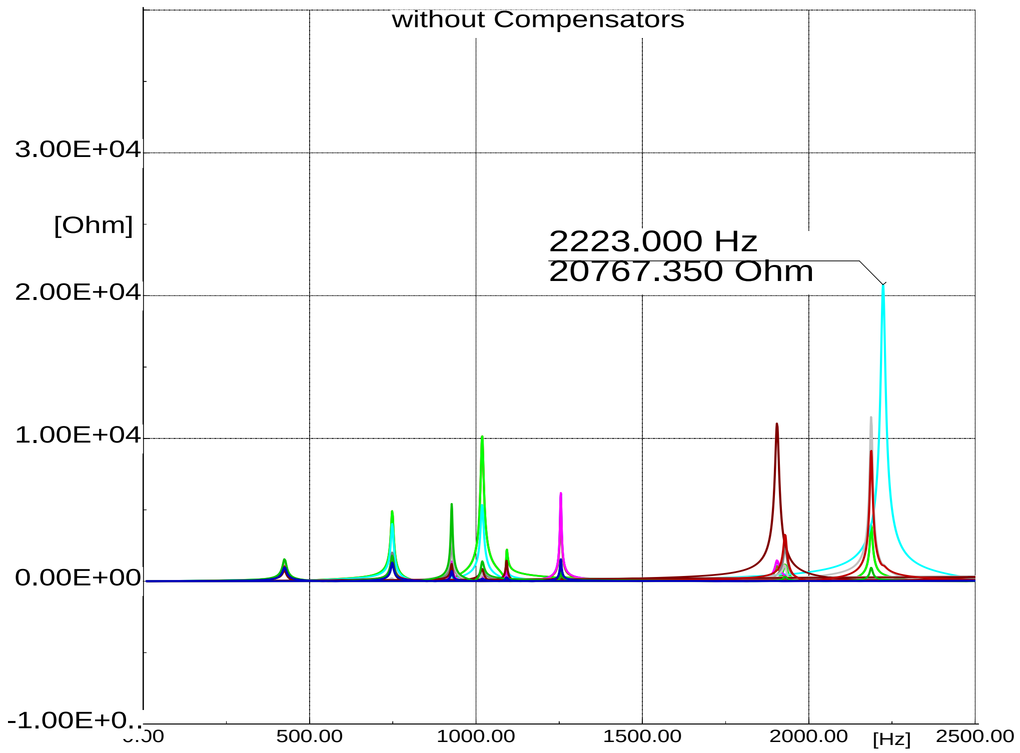


Figure 6.1 Impedance-frequency of all 220 kV bus bars without compensators

The x-axis represents frequency and y-axis the impedance of the network. It is obvious that at 45th the maximum impedance appears in bus bar 5 which has got the value roughly 20.8 kΩ in 220 kV. In 380 kV the maximum impedance is in bus bar 1 at 25th order with value 13.131 kΩ.

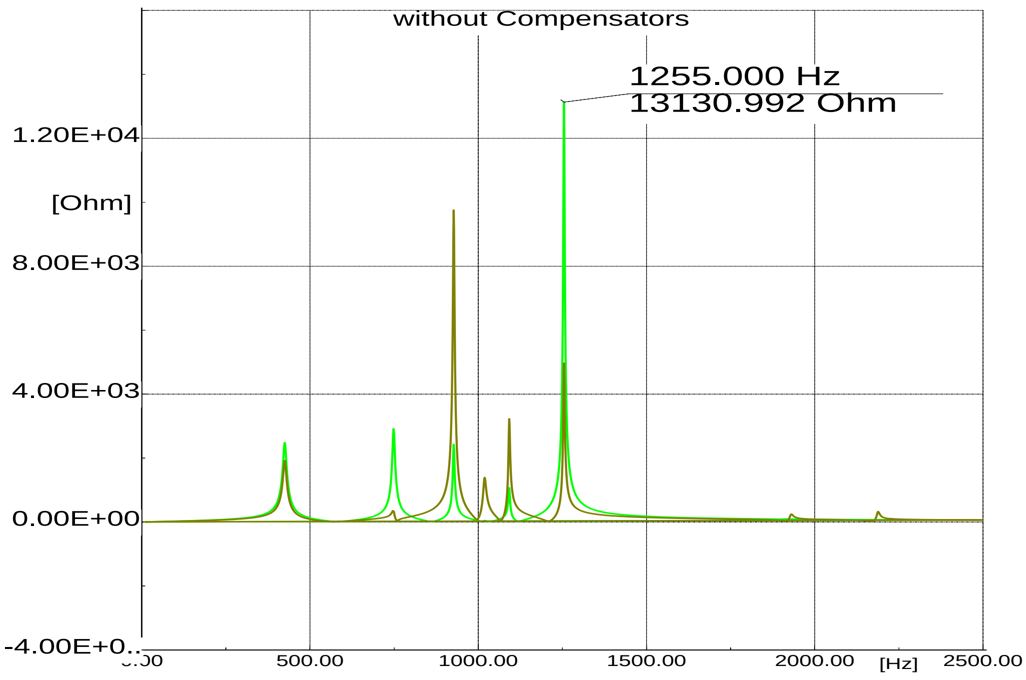


Figure 6.2 frequency sweep of all 380 kV bus bars without compensators

6.3 Impedance-Frequency with compensators

After performing the load flow in balanced mode and switching all compensators on, the frequency sweeps of 220 and 380 kV without skin effect are shown in below figures.

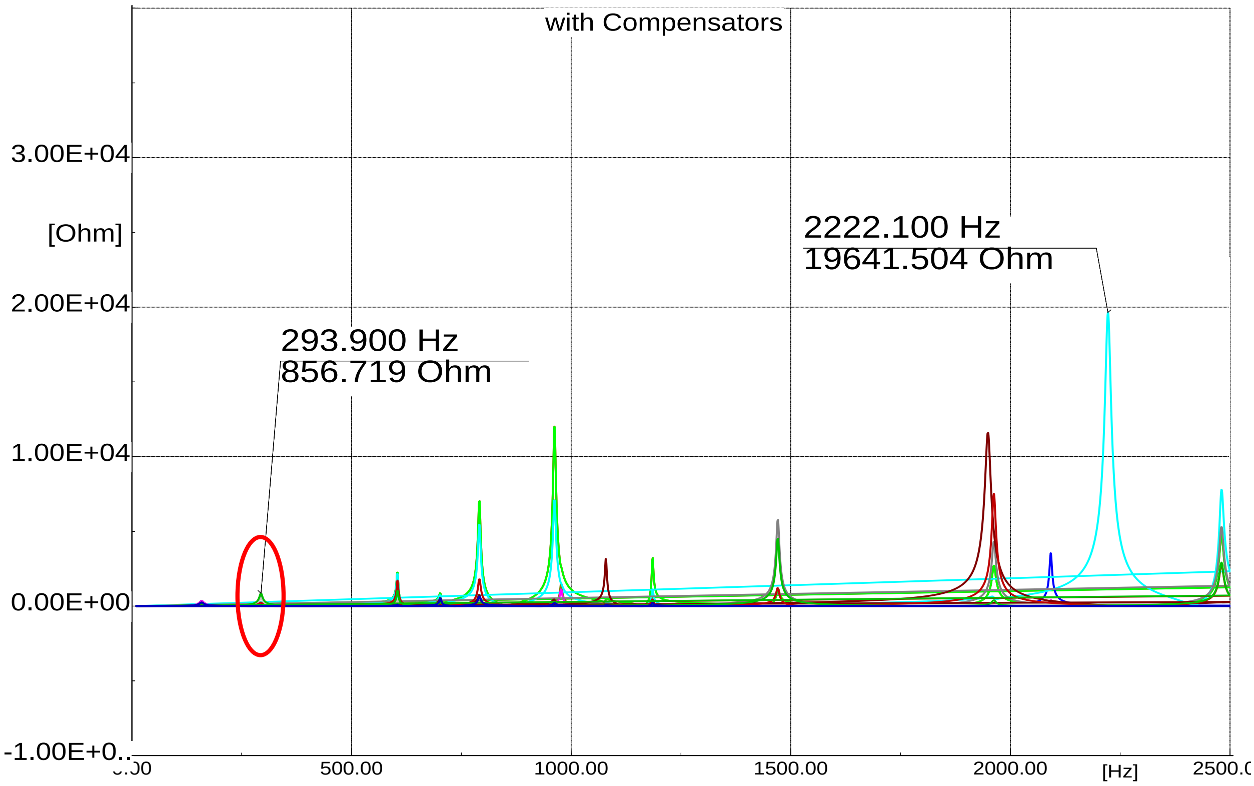


Figure 6.3 frequency sweep of all 220 kV bus bars with all compensators

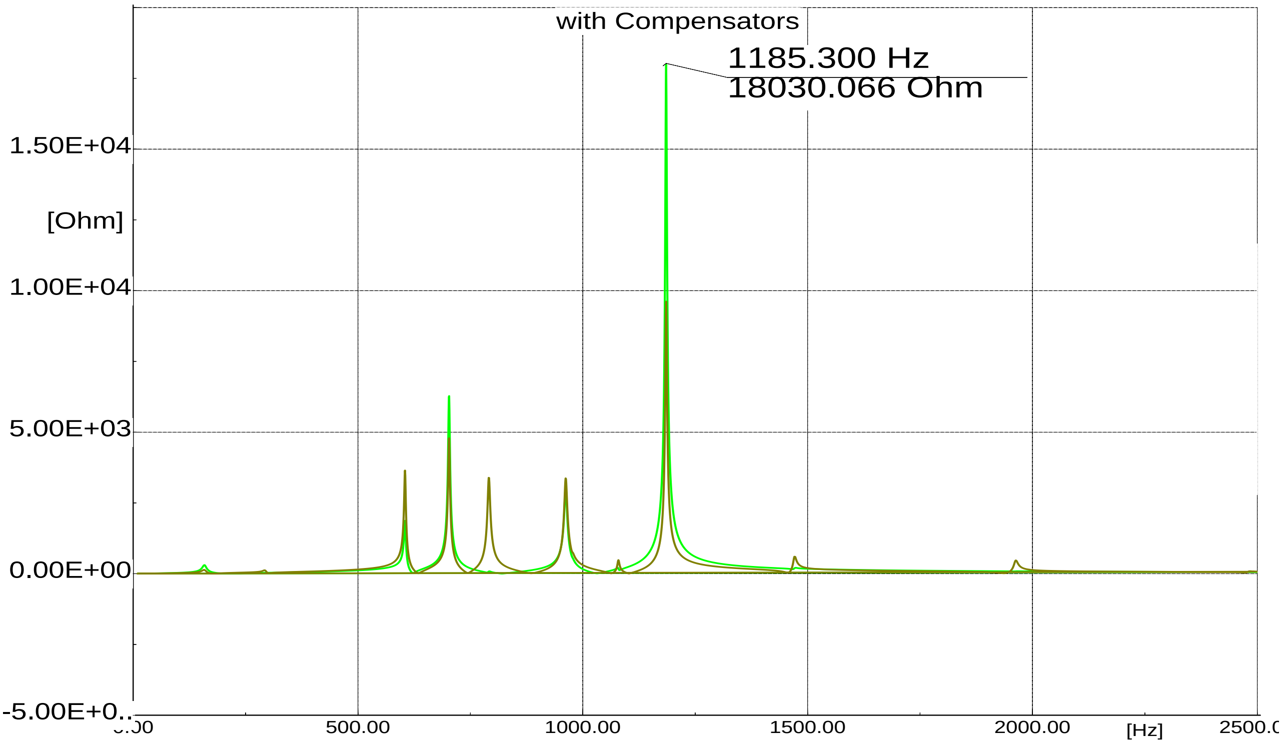


Figure 6.4 frequency sweep of all 380 kV bus bars with all compensators

An interesting point in both voltage levels is that the 3rd and 6th harmonic order appear in the case that all compensators are on. At 6th harmonic order the resonance frequency can be calculated by taking all inductance of synchronous generators and AC voltage sources and capacitance of overhead lines plus capacitance of all compensators into account. The aim of calculation of inductance and capacitance of the study case is to estimate the resonance frequency and match it with figure 6.3.

6.4 Simplified calculation of resonance frequency

In order to estimate the resonance frequency with compensators in both voltage 220 and 380 kV, it is needed to calculate the inductance of AC voltage source and synchronous generators and the capacitance of overhead lines and compensators. After calculation of each parameter, they are referred to 220 kV. The equivalent circuit of a power system for resonance frequency is shown in figure 6.5.

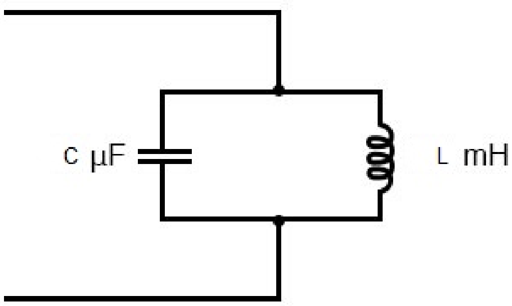


Figure 6.5 equivalent circuit for calculation of resonance frequency

6.4.1 Calculation of L

The AC voltage sources and synchronous generators are connected to the grid in parallel. The sum of every single inductance in parallel results in the total inductance.

$$L_{total} = \frac{1}{\frac{1}{L_{ACVS}} + \frac{1}{L_{SG}}} \qquad (6\text{-}2)$$

AC Voltage Sources:

There are seven AC voltage sources distributed in the grid. The equivalent reactance (only positive sequence) is derived from the short circuit parameters of the sources.

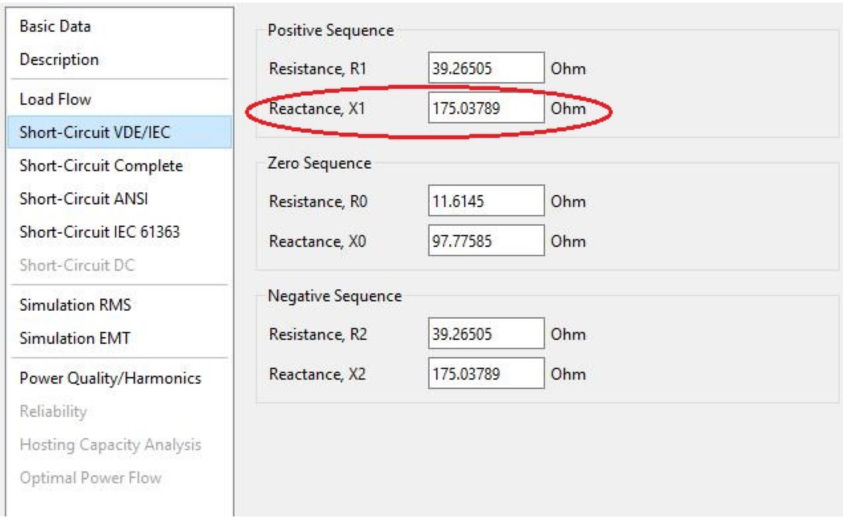


Figure 6.6 positive sequence reactance of ACVS

The formulas to extract inductance and refer to 220 kV are in in the following:

$$X_1 = 2\pi f L \qquad (6\text{-}3)$$

$$\frac{X_1}{X_{220}} = \frac{V_1^2}{V_{220}^2} \qquad (6\text{-}4)$$

ACVS	Voltage level in kV	X_1 in Ω	L on 220 kV in H	Equivalent inductance of L_{ACVS}
$ACVS_1$	110	544.5	7	0.01 H
$ACVS_2$		63.87	0.8	
$ACVS_3$	220	29.5	0.094	
$ACVS_4$		175	0.56	
$ACVS_5$		175	0.56	
$ACVS_6$	380	32.83	0.035	
$ACVS_7$		17.87	0.019	

Table 6.1 inductance of ACVSs

Synchronous generators:

The sub-transient reactance of a synchronous machine plays a crucial role to calculate the inductance.

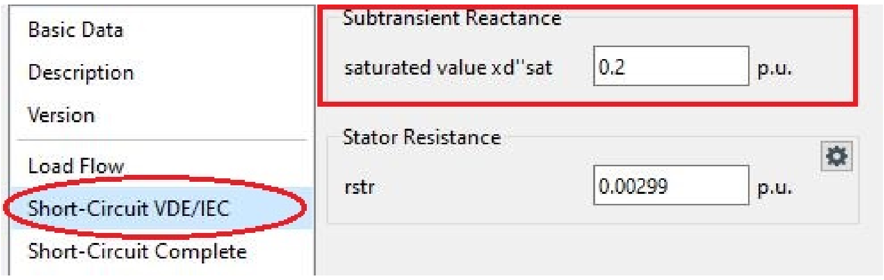


Figure 6.7 sub-transient reactance of SG

The reactance impedance of a SG is expressed by:

$$X_{SG} = \frac{Un^2}{S_G} X_d'' \qquad (6\text{-}5)$$

Where U_n nominal voltage, S_G nominal apparent power and X_d'' is the sub-transient reactance in p.u. All reactance must be referred to 220 kV according to (6-4).

SG	Voltage level in kV	S in MVA	X_d'' in p.u	L on 220 kV in H	Equivalent inductance of L_{SG} in H
SG_1	10.5	98	0.2	0.314	0.08
SG_2	9	35	0.195	0.86	
SG_3	13.9	166	0.197	0.183	
SG_4	10.5	30	0.185	0.95	
SG_5	8	42.5	0.185	0.67	

Table 6.2 inductance of SG

Now the total equivalent inductance of the grid can be calculated with formula (6-2).

$$L = 0.01 \text{ II } 0.08 = 8.8 \text{ mH}$$

6.4.2 Calculation of C

To take the capacitance of the grid into account, compensators and overhead lines are considered. The whole capacitance can be expressed:

$$C = \sum C_{compensators} + \sum C_{OHL} \qquad (6\text{-}6)$$

Compensators:

The capacitance of each compensator can be read by double clicking on it and select the tap Power Quality/Harmonic in the following:

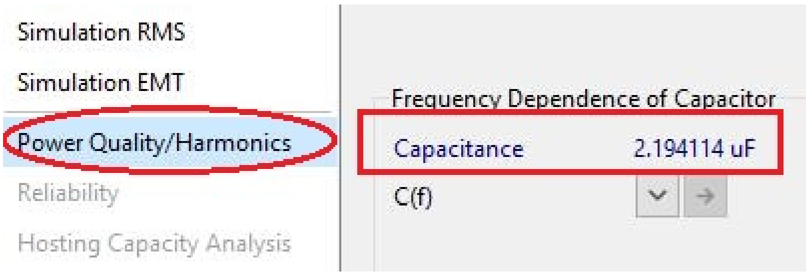


Figure 6.8 capacitance of a compensator

As all compensators are connected on 220 kV, they do not need to be referred to another level expect the one in Lambach.

Compensator	Individual C in µF	Sum of C in µF
C_1	2.2	18.07
C_2	2.75	
C_3	2	
C_4	2.2	
C_5	4	
C_6	4	
C_7 (110 kV)	3.68	0.92 (referred to 220 kV)

Table 6.3 sum of the capacitance of compensators (220 kV level)

Overhead lines and cables:

To determine the capacitance of OHL, just select a line and double click on it and choose type to go further. From the tap Power Quality/Harmonics select the sub-tap advanced to extract the capacitance pro Km which must be multiplied with the length of the line in the following. The lines are modelled as lumped parameters (PI). The capacitance per length C' can be retrieved from every OHL and the referring capacitance to 220 kV is defined as C in the table 6.4.

Lines	Voltage level in kV	Length in km	C' in µF/km	C in µF (At 220 kV)	Sum of all OHL and cables in µF
Substation 1 – Substation 2 (a)	110 kV	8.5	0.0235	0.05	14.6
Substation 1 – Substation 2 (b)		8.5	0.0235	0.05	
Substation 8 – Substation 16 (a)	220 kV	4	0.0089	0.035	
Substation 8 – Substation 15 (b)		18.4	0.0089	0.164	
Substation 8 – Substation 15 (a)		4	0.0089	0.035	
Substation 8 – Substation 16 (b)		25.7	0.0089	0.23	
Substation 15 – Substation 16 (a)		25.7	0.0089	0.23	
Substation 15 – Substation 16 (b)		18.4	0.0089	0.164	

Substation 3 – Substation 4 (a)		36.6	0.0093	0.34	
Substation 3 – Substation 4 (b)		36.6	0.0093	0.34	
Substation 2 – Substation 3 (a)		24.5	0.0093	0.228	
Substation 2 – Substation 3 (b)		24.5	0.0093	0.228	
Substation 11 – Substation 13 (b_1)		1.3	0.032	0.042	
Substation 13 – Substation 14 (b_2)		1.3	0.032	0.042	
Substation 5 – Substation 14 (a_1)		9.6	0.012	0.12	
Substation 5 – Substation 14 (a_2)		9.6	0.012	0.12	
Substation 10 – Substation 12 (a)		35.8	0.0089	0.32	
Substation 10 – Substation 12 (b)		35.8	0.0089	0.32	
Substation 15 – ACVS 4		1.76	0.012	0.021	
Substation 15 – ACVS 5		1.76	0.012	0.021	
Substation 5 – ACVS 4		0.54	0.012	0.006	
Substation 6 – Substation 5 (b)		0.54	0.012	0.006	
Substation 13 – Substation 15 (a_1)		4.5	0.012	0.06	
Substation 13 – Substation 15 (a_2)		4.5	0.012	0.06	
APG 493 Kronstorf - Ernsthofen 493		0.7	0.011	0.008	
APG 494 Kronstorf - Ernsthofen 494		0.7	0.011	0.008	
APG 203A St. Peter - Innkreis 203A		35	0.012	0.42	
APG 204A St. Peter - Innkreis 204A		35	0.012	0.42	
Substation 9 – Substation 12 (a)		13.4	0.012	0.17	
Substation 9 – Substation 12 (b)		13.4	0.012	0.17	
Substation 7 – Substation 12 (a)		17.2	0.012	0.2	
Substation 7 – Substation 12 (b)		17.2	0.012	0.2	
Substation 6 – Substation 7		11.7	0.012	0.14	
Substation 6 – Substation 5 (a)		32.1	0.012	0.4	
Substation 13 – Substation 15 (b_1)		11.9	0.012	0.14	
Substation 13 – Substation 15 (b_2)		11.9	0.012	0.14	
Substation 5 – Substation 14 (b_2)		1.5	0.012	0.018	
Substation 5 – Substation 14 (c_1)		14.2	0.012	0.17	
Substation 5 – Substation 14 (b_2)		1.5	0.012	0.018	
Substation 5 – Substation 14 (c_2)		14.2	0.012	0.17	
Substation 11 – Substation 14 (a)		2.5	0.012	0.03	
Substation 11 – Substation 14 (b)		2.5	0.012	0.03	
Substation 1 – Substation 2 (a)	380 kV	111.3	0.011	3.65	
Substation 1 – Substation 2 (b)		111.3	0.011	3.65	
Substation 1 – Transformer 1 (a)		0.7	0.012	0.025	
Substation 1 – Transformer 1 (b)		0.7	0.012	0.025	
Cables					

Substation 11 – Substation 13 (a_1)	220 kV	2.1	0.183	0.38	
Substation 13 – Substation 14 (a_2)		2.1	0.183	0.38	
Substation 1 – Substation 2 (a)		1.3	0.15	0.195	
Substation 1 – Substation 2 (b)		1.3	0.15	0.195	

Table 6.4 capacitance of all OHLs and cables

Now the whole capacitance results in according to (6-6):

$$C = \sum C_{compensators} + \sum C_{OHL} = 18.07 + 14.6 = 32.67\ \mu F$$

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{8.8 \cdot 32.67 \cdot 10^{-9}}} = 296.8\ Hz$$

$$h = \frac{297.7}{50} = 5.9$$

The harmonic order matches to a frequency of impedance-plot of figure 6.3 of the model with compensators. However, it was expected that this resonance frequency should correspond to the peak with the lowest frequency, which is around 150 Hz (3rd harmonic) in the plot. It can be concluded, that the simplified estimation does not give correct results in a meshed transmission system.

6.5 Skin effect

By flowing AC current through a conductor, the distributed current is not completely concentrated in the core of the conductor but rather near the surface which it is called skin effect. The skin effect is highly dependent upon the increase of frequency. At higher frequencies, the current has more tendency to be restricted in a thin layer near the surface. The major influence of skin effect is reduction in cross section of the conductor. Therefore, the increased effective resistance is more likely pronounced.

The skin effect depends upon the following factors:

- *Conductor material: Better conductors and ferromagnetic materials experience higher skin effect*
- *Cross-sectional area of the conductor: skin effect increases with increase in the cross-sectional area*
- *Frequency: increases with increase in the frequency*
- *Shape of the conductor: skin effect is lesser for stranded conductors than solid conductors* [19].

In this study case the main goal is to consider the increase of resistance of network components at higher frequencies. By taking the frequency dependence of the resistance into account, the impedance of the network becomes more likely and the frequency sweep which illustrates the impedance, becomes less amplitude and hence a smoother and dampened curve. The components, which impact the impedance frequency are discussed in the following:

6.5.1 Transformers

By modelling the skin effect of transformers, they do not impact on dampening significantly. The PowerFactory offers the polynomial function in DigSilent library, which can be used for both two and three-winding transformers at 220 and 380 kV. By three-winding transformers it is enough to consider only the high-voltage side with this function.

$$K(f) = 1 + a.((f/f_{nom})-1)^{b} \qquad (6\text{-}7)$$

Where f is the electrical frequency, a and b are coefficient with values 0.2 and 1.6 which are taken from the DigSilent library.

6.5.2 Cable

The possibility of causing resonance frequency of cables is more likely than overhead lines in power systems. A cable can be modelled as a capacitor which interacts with the inductance and leads to resonance.

There is also an option for extra high voltage cable in DigSilent library with polynomial function:

$$K(f) = (1-a) + a.(f/f_{nom})^{b} \qquad (6\text{-}8)$$

Where f is the electrical frequency, a and b are coefficient with values 0.8 and 0.5.

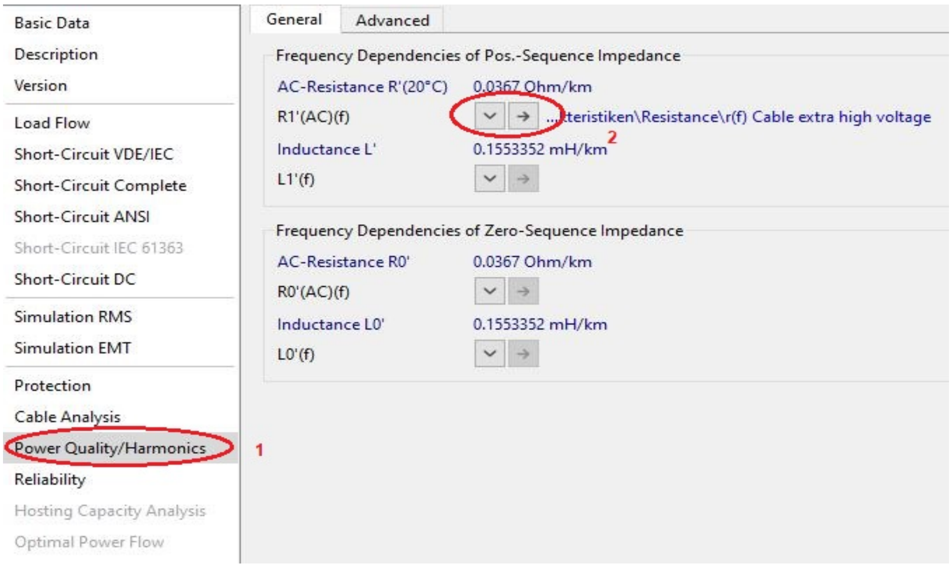


Figure 6.9 consideration of skin effect of cable

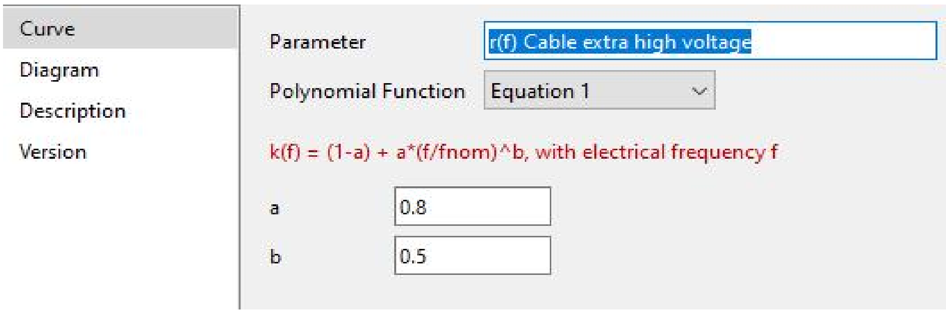


Figure 6.10 polynomial function of cable for skin effect

Our two cable sections are only between bus bar 1 and 2 and partially bus bar 13 at 220 kV. So they only influence this voltage level and was able to dampen our impedance slightly and there is no contribution to 380 kV. Of course large cable sections could impact on impedance much.

6.5.3 OHL

Network harmonic impedance is highly dependent on cables and overhead lines. Any change in the skin effect of OHL can significantly impact the frequency impedance. The function is defined in library as same as for cable:

$$K(f) = (1-a) + a*(f/f_{nom})^{b}$$

The values of a and b are 0.2401 and 0.6434 [18].

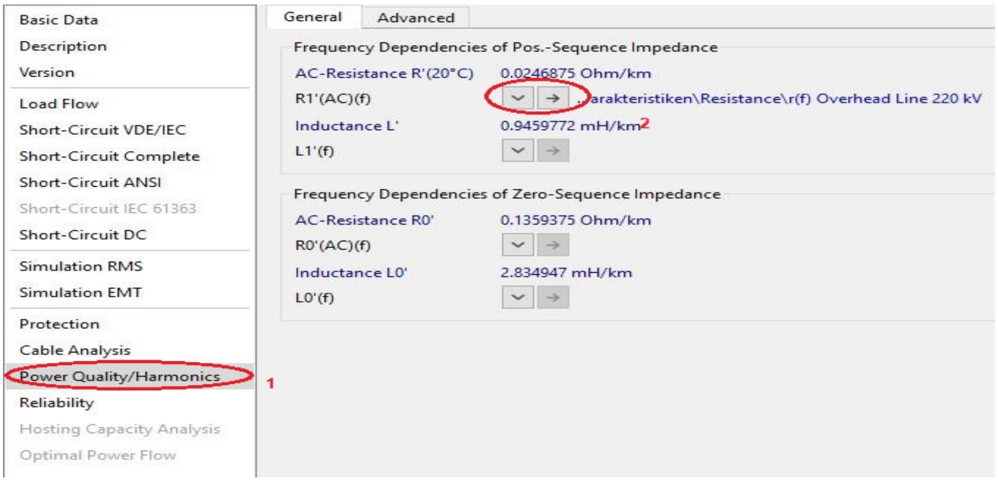


Figure 6.11 skin effect of OHLs

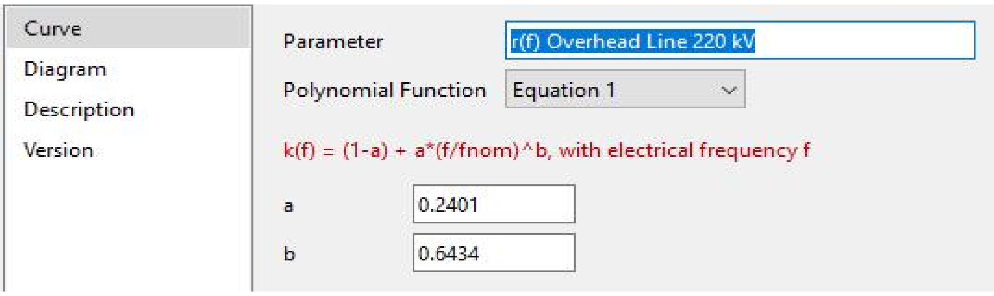


Figure 6.12 polynomial function of OHLs

With consideration of skin effect of three components, the result is shown in below and it is clear that the amplitude of the impedance of the network has been fallen at both voltage levels.

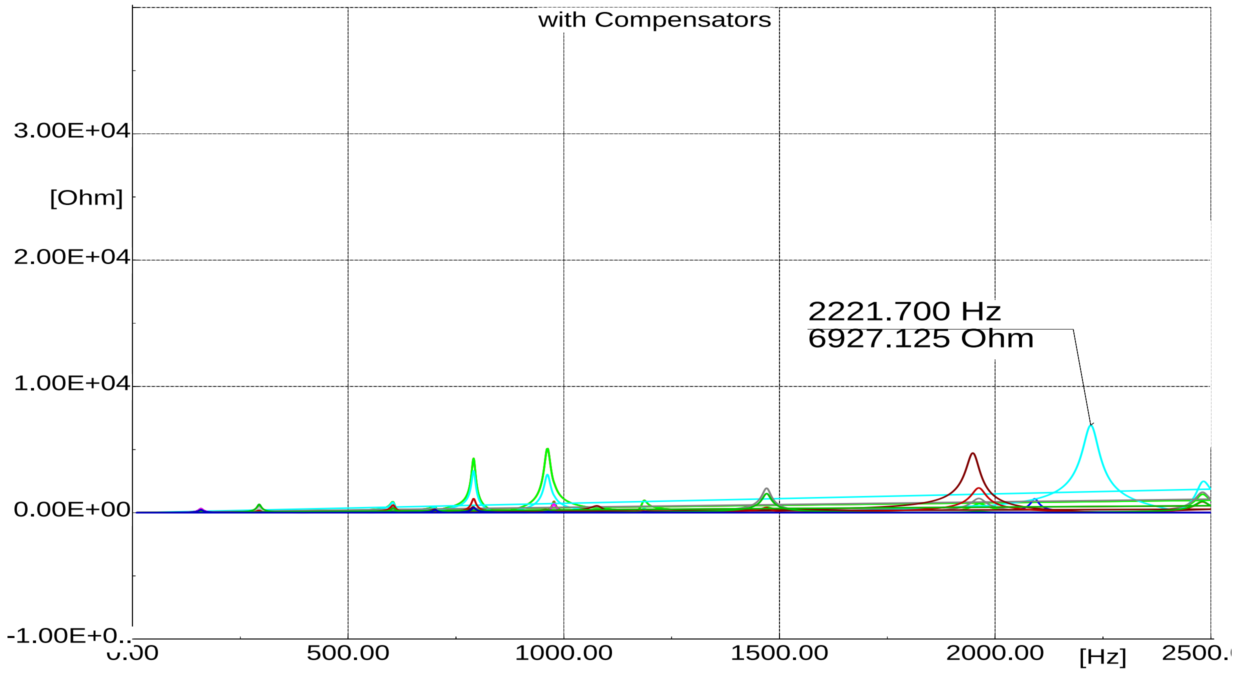


Figure 6.13 consideration of all skin effect for 220 kV

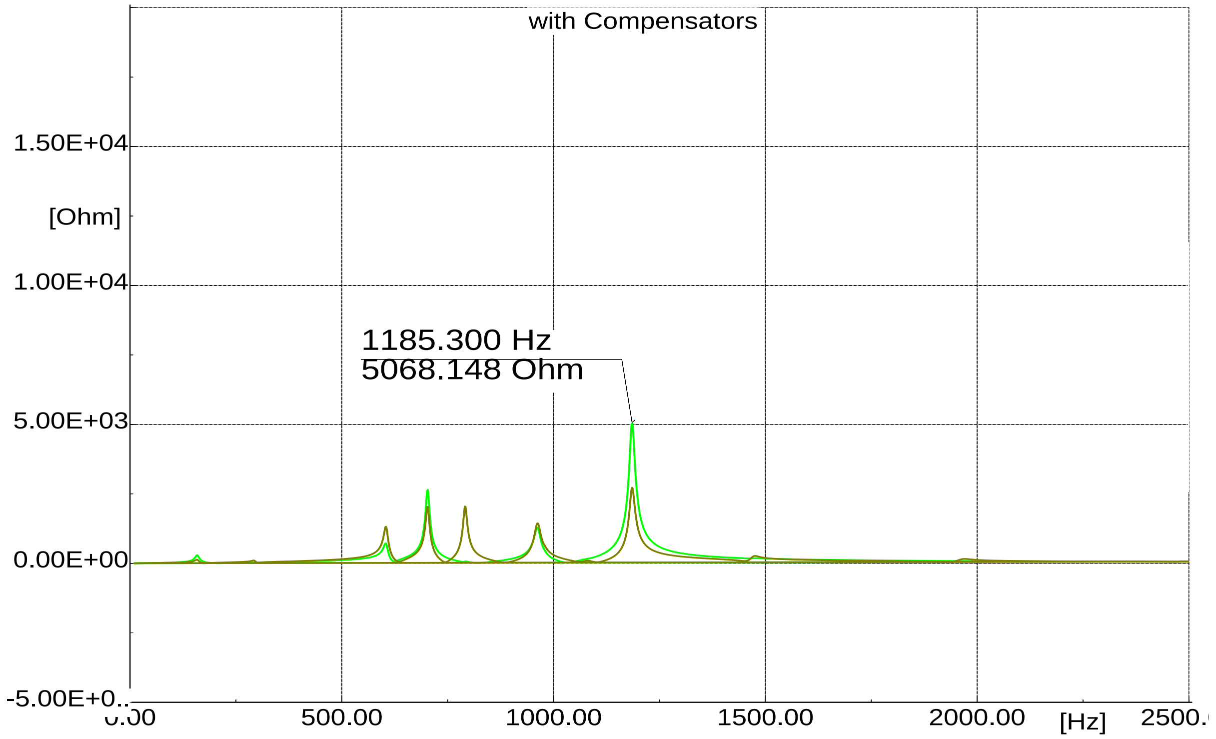


Figure 6.14 consideration of all skin effect for 380 kV

It is clear that skin effect of overhead lines plays a crucial role in reducing the amplitude of the impedance. It is because that the model is made of mostly overhead lines in 220 kV.

7 Filter design

In order to eradicate and mitigate the drawback of harmonics in a power system, some possibilities are thought to be executed such as employment of passive filters which consist of capacitors, reactors and resistors (conventional method) or active filters under operation of power electronics. *Although the basic operating principles of active filters were firmly established in the 1970s, they are attracting increased attention in the last few years because of IGBTs (insulated gate bipolar transistors) and DSPs (digital signal processors)* [21].

7.1 Type of filters

7.1.1 Active filters

The principle work of active filters is based on employing the power electronics. They are made of PWM, an intelligent digital controller. The injected harmonics caused by non-linear loads can be suppressed by injecting the same harmonics but exactly in opposite direction. Active filters are highly capable of mitigating harmonics in a wide range. The structure of this filter is sophisticated and be categorised into series or parallel connection.

In case of series connection, they have to cope with high load current which consequently leads to higher copper losses but very suitable for harmonic voltage mitigation. In parallel connection, the injected current to PCC can contribute to compensation. However, the harmonic voltage could not be impacted directly.

7.1.2 Passive filters

Commonly used filters are: low pass passive filter, high pass filter, band pass passive filter and band stop passive filter [20]. In contrast to active filters, they do not have capability to eliminate harmonics in a wide range. They can be only designed for specific harmonic orders. An exact study of the network is required to avoid becoming a burden to the system due to a poor or false design.

On one hand the main advantage of passive filters is to provide the reactive power and consequently enhancement of power quality*. On the other hand, they can be used for elimination of a particular harmonic frequency, so the number of passive filters increases with the increase in number of harmonics on the system* [24].

Passive filters can be classified into:

- Shunt filters: providing low impedance for a range of harmonics. Only fraction of the load current is to withstand. They generate reactive power as well.

- Series filters: providing high impedance at a specific harmonic. Due to series connection with the line they have to withstand with the whole current of load which causes voltage drops additionally. They consume reactive power as well.

7.1.2.1 Single tuned filter

The most common type of passive filter is the single-tuned "notch" filter. This is the most economical type and is frequently sufficient for the application. The notch filter is series-tuned to present low impedance to a particular harmonic current and is connected in shunt with the power system. Thus, harmonic currents are diverted from their normal flow path on the line through the filter Notch filters can provide power factor correction in addition to harmonic suppression [24].

Shunt capacitors can be employed and considered to correct power factor indeed. They are appropriate to be tuned at low harmonic frequencies. At the tuned frequency, the shunt cancels out the reactor hence remaining only resistive impedance.

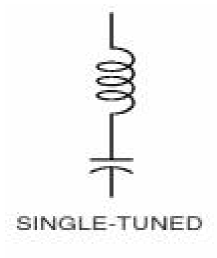


Figure 7.1 topology of a single-tuned filter [24]

The impedance – frequency characteristic of the filter is depicted in figure 7.2

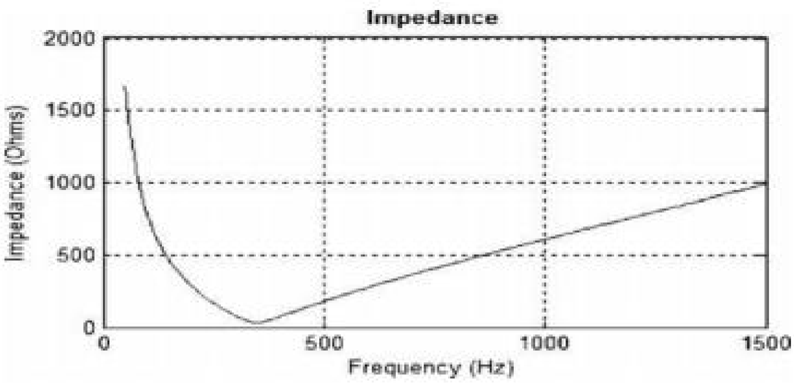


Figure 7.2 Z (f) of a single-tuned filter [24]

The notch frequency is defined as:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (7\text{-}1)$$

And the sharpness of tuning is determined by so-called quality factor q:

$$q = \frac{\sqrt{\frac{L}{C}}}{R} \qquad (7\text{-}2)$$

Additional losses due to the presence of resistance and simple adjustment can be mentioned as the main advantage and disadvantage of this filter. The range of quality factor of single tuned filter can be between 30 to 60.

In this master thesis passive filters are of more significance and the main focus of this chapter is all about passive filters in particular the C-Type filter.

7.1.2.2 C-type filter

Using C-type harmonic filter banks to provide reactive power support in a network system has many advantages over single-tuned harmonic filters. Unlike single-tuned filters, C-type filters are not susceptible to changes in system impedance which is of particular concern in networked HV and EHV systems [20]. They provoke the lowest power losses at fundamental frequency. The single line diagram of this filter is shown in figure 7.3.

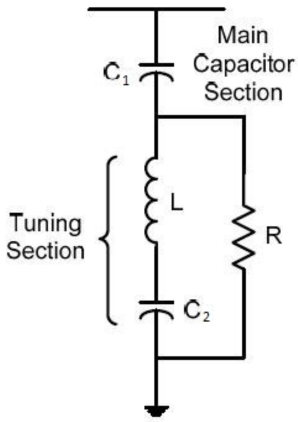


Figure 7.3 one-line diagram of C-type filter [20]

The impedance-frequency curve of a C-type filter is depicted in figure 7.4.

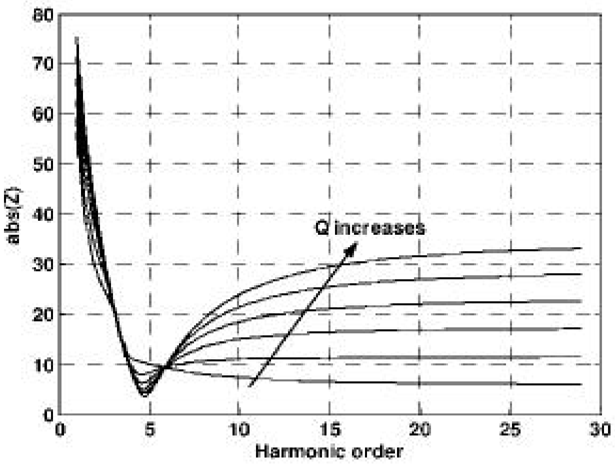


Figure 7.4 Z (f) of a C-Type filter

The structure of this filter is mad of three main parts namely: the main capacitor C_1, tuning section and a damper parallel to tuning section. C_1 supplies the required reactive power and fundamental frequency.

The capacitance, C_2, and inductance, L, are designed to be in series resonance at nominal frequency; thereby, effectively eliminating the effect of the damping resistance, R. This significantly reduces, and theoretically eliminates, any power frequency loss [20].

7.2 Parameters of the C-type filter

Three significant parameters of the filter should be specified firstly:

- Nominal voltage V_1
- Tuning frequency f_0 at which harmonic will be eliminated
- The required nominal reactive power Q_n

The whole impedance of the filter can be written:

$$Z(\omega) = \left(j\omega L - \frac{j}{\omega C_2} \right) || R + \frac{1}{j\omega C_1} \tag{7-3}$$

Which this equation results in:

$$Z(\omega) = \frac{R\,(\omega^2 LC_2 - 1) + j\,R^2 \omega C_2 (\omega^2 LC_2 - 1)}{(R^2 C_2^2 \omega^2) + (\omega^2 LC_2 - 1)^2} - \frac{j}{\omega C_1} \tag{7-4}$$

Minimization of power loss at fundamental frequency:

$$\omega_1^2 LC_2 - 1 = 0 \tag{7-5}$$

Therefore, the impedance of the filter at fundamental frequency is expressed:

$$\mathrm{Z}(\omega_1) = \frac{-\mathrm{j}}{\omega_1 \mathrm{C}_1} = \frac{-\mathrm{j}\,\mathrm{V}_1^2}{\mathrm{Q_n}} \tag{7-6}$$

At tuned frequency the total reactance is equal to zero:

$$\frac{R^2 \omega C_2 (\omega_h^2 LC_2 - 1)}{(R^2 C_2^2 \omega_h^2) + (\omega_h^2 LC_2 - 1)^2} - \frac{j}{\omega_h C_1} = 0 \tag{7-7}$$

The total resistance at tuned frequency is:

$$\mathrm{r} = \frac{\mathrm{R}\,(\omega_\mathrm{h}^2 \mathrm{LC}_2 - 1)}{(\mathrm{R}^2 \mathrm{C}_2^2 \omega_\mathrm{h}^2) + (\omega_\mathrm{h}^2 \mathrm{LC}_2 - 1)^2} \tag{7-8}$$

Where ω_h is the tuned angular frequency.

So the tuning section can be calculated as:

$$C_2 = \frac{(h_0 - 1) Q_n}{\omega_1 V_1^2} \tag{7-9}$$

$$L = \frac{V_1^2}{(h_0 - 1) Q_n \omega_1} \tag{7-10}$$

$$R = \frac{q\, V_1^2}{Q_n h_0} \tag{7-11}$$

Where h_0 is defined as:

$$h_0 = \frac{\omega_1}{\omega_h} \tag{7-12}$$

And q is quality factor [25].

The generalised topology of the C-type filter and its parameters in PowerFactory is illustrated is figure 7.5.

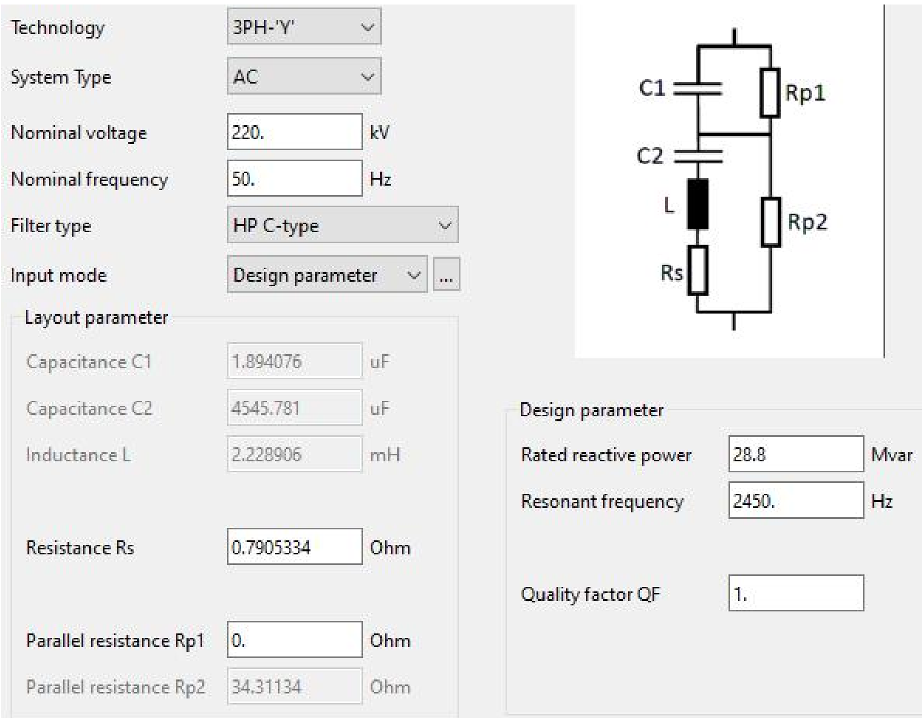


Figure 7.5 a typical C-Type filter in PowerFactory

According to the figure 7.5, C-type filter in PowerFactory has got three resistances.

R_s which is connected in series with tuning section. Presence of R_s is beneficial to reduce the sharpness of Impedance-Frequency curve which means the impedance is dampened. Zero value of R_s contributes to minimise total losses of the filter. R_{p1} is connected in parallel to the main capacitor and also causes dampening for impedance. In the case of $R_{p1} = 0$, the total losses will be decreased dramatically. The resistance R_{p2} is the main resistance as explained before and is determined by quality factor. High amount of R_{p2} means minimisation of losses but small amount of it means high losses but a wider bandwidth and in other words better dampening.

8 Results for voltage distortion with filters

8.1 Alternative 1

This alternative is based on mitigation of harmonic in the best way. This concept does not consider losses, so the value of R_s and R_{p2} is set to zero to obtain the best result for loss minimisation. In reality, R_s is determined by the quality factor of the inductance.

Filter date		
Name	**Bus bar 1**	**Bus bar 3**
Filter type	HP C-type	HP C-type
Nominated voltage	380 kV	220 kV
Technology	3PH-Y	3PH-Y
Rated reactive power	114 Mvar	104 Mvar
Resonance frequency	650 Hz	300
Quality Factor	5000	10000
Parallel resistance R_{P2}	490401.8 ohm	797802.2 ohm
L	24 mH	42.32 mH
C_2	421.9 µF	239.39 µF

Table 8.1 filter data

Shunt Data			
Shunt	**Voltage in kV**	**Q in Mvar**	**Located**
C	175	171.3	At bus bar 9

Table 8.2 auxiliary shunt data

8.1.1 THD

After installation of filters at required places, the harmonic load flow is performed and the result of THD is listed in table 8.3. According to standard IEC 61000-3-6 the maximum THD of high voltage and extra high voltage is not allowed to exceed more than 3%.

Voltage level	Bus bar	THD without compensators in %	THD with compensators in %	THD with alternative 1 in %
220 kV	1	3.2	3.2	0.6
	2	3.2	3.2	0.6
	3	3	3.6	0.7
	4	2.8	2.9	0.5
	5	2.8	0.8	0.8

	6	3	0.9	0.3
	7	3.2	1	0.6
	8	2.4	0.7	0.6
	9	3.2	2.8	0.9
	10	2.2	0.6	0.6
	11	3.4	0.6	0.8
	12	3.4	1.9	0.7
	13	3.4	0.5	0.8
	14	3.3	0.5	0.8
	15	2.8	0.8	0.8
	16	2.2	0.6	0.5
380 kV	1	3.5	1.5	0.4
	2	2.9	1.5	0.2

Table 8.3 THD of all HV and EHV with alternative 1

8.1.2 Individual harmonic distortion

Individual harmonic distortion of all bus bars is also of a big concern. The possibility of extending the network due to future demand lets us to keep them under limit. Figure 8.1 and 8.2 represent the harmonic voltage spectra of all bus bars at high and extra high voltage level.

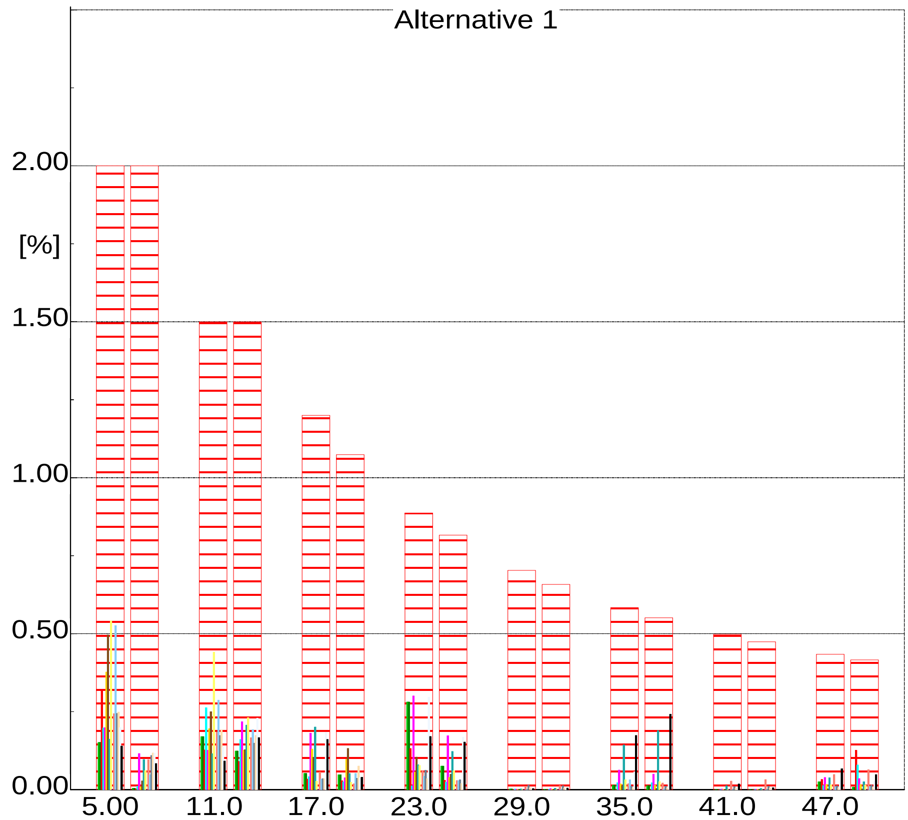


Figure 8.1 individual harmonic distortion of model in HV

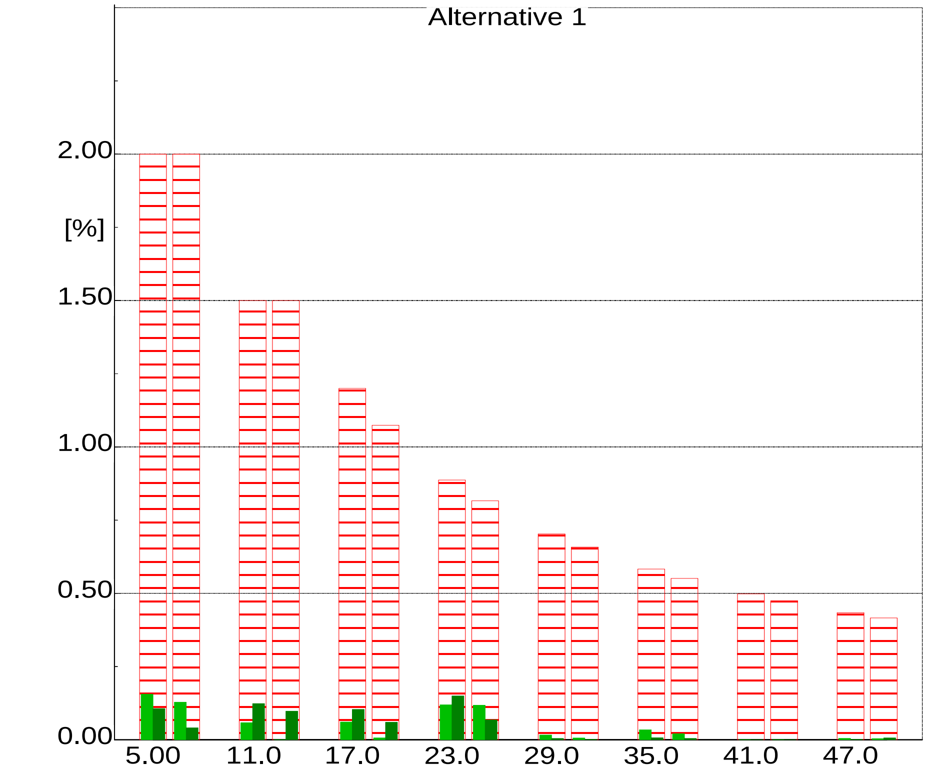


Figure 8.2 individual harmonic distortion of model in EHV

8.1.3 Impedance-Frequency

The frequency response of the model after installing the filters with consideration of all skin effect is depicted in below. Due to a filter in bus bar 3, our interest point is only at 220 kV at this bus bar.

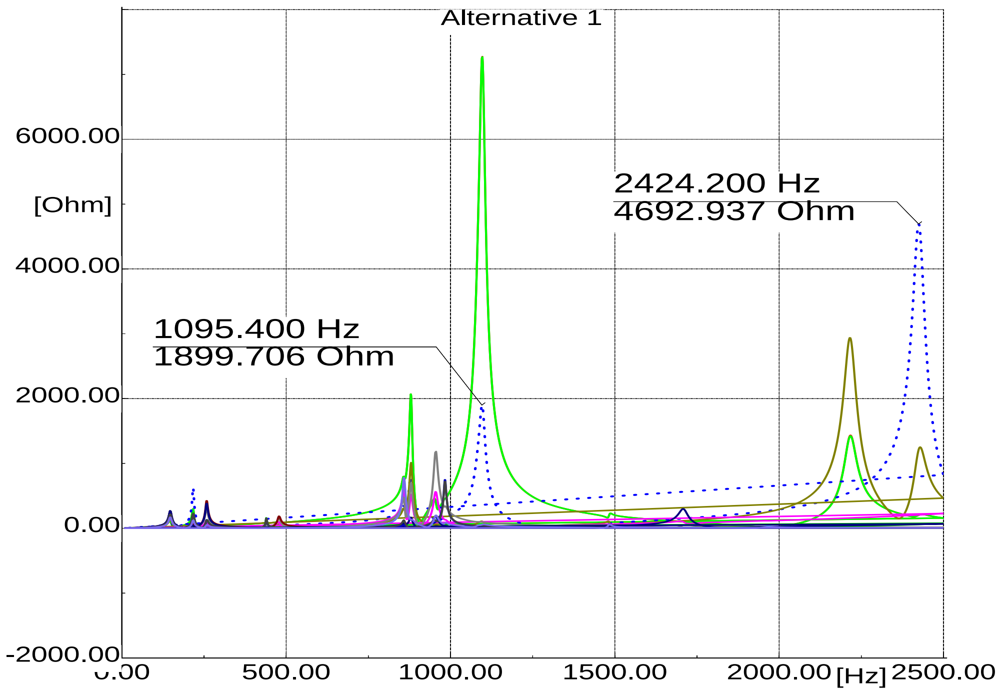


Figure 8.3 Impedance-Frequency characteristic of 220 kV with alternative 1

At 380 kV there is a filter and changing parameters such as R_s and R_{p1} can dampen the impedance of the bus bar 1 significantly but in contrast the losses get higher. In reality, R_s is determined by the quality factor of the inductance.

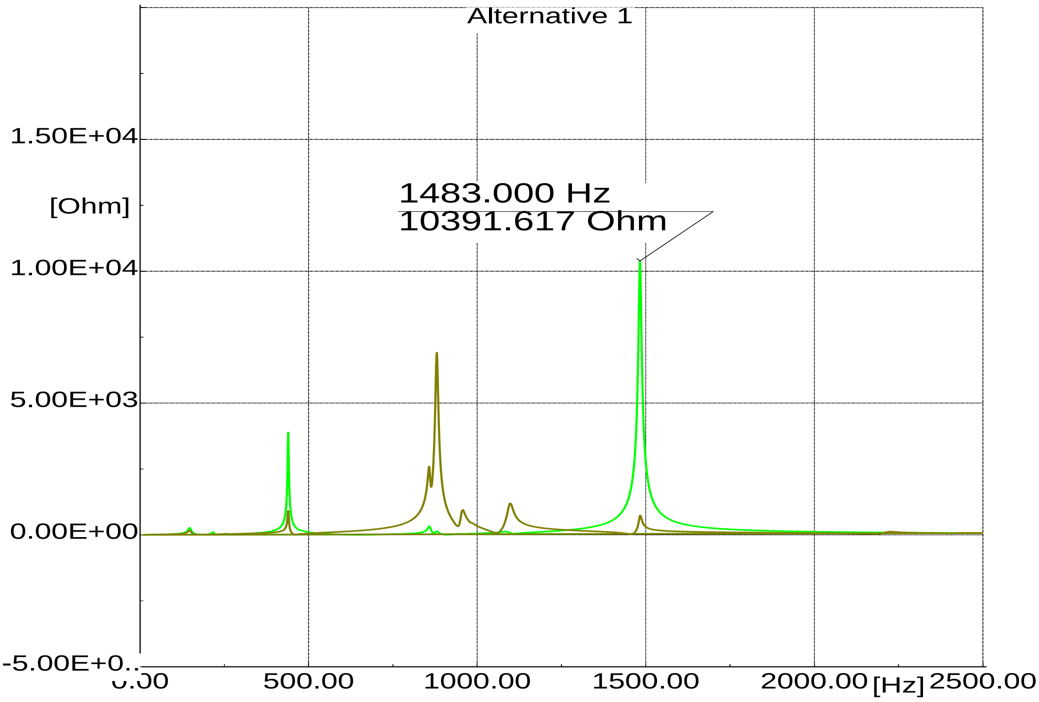


Figure 8.4 Impedance-Frequency characteristic of 380 kV with alternative 1

8.2 Alternative 2

This alternative is based on harmonic mitigation in an economical way. This concept uses an existing shunt capacitor as a filter but an auxiliary shunt is also required to supress harmonics in other places.

Filter date	
Name	**Bus bar 11**
Filter type	HP C-type
Nominated voltage	220 kV
Technology	3PH-Y
Rated reactive power	100 Mvar
Resonance frequency	250
Quality Factor	10000
Parallel resistance R_{P2}	1008333ohm
L	64.20 mH
C_2	157.83 µF

Table 8.4 filter data

Shunt Data			
Shunt	**Voltage in kV**	**Q in Mvar**	**Located**
C	190	50	At bus bar 9

Table 8.5 auxiliary shunt data

8.2.1 THD

Voltage level	Bus bar	THD without compensators in %	THD with compensators in %	THD with alternative 2 in %
220 kV	1	3.2	3.2	1.5
	2	3.2	3.2	1.5
	3	3	3.6	1.4
	4	2.8	2.9	1.2
	5	2.8	0.8	1
	6	3	0.9	0.8
	7	3.2	1	1.1
	8	2.4	0.7	0.9
	9	3.2	2.8	1.5
	10	2.2	0.6	0.8
	11	3.4	0.6	1
	12	3.4	1.9	1.1
	13	3.4	0.5	1
	14	3.3	0.5	1.2
	15	2.8	0.8	1
	16	2.2	0.6	0.7
380 kV	1	3.5	1.5	1.2
	2	2.9	1.5	1.1

Table 8.6 THD of all HV and EHV with alternative 2

According to the above table, THD of every bus bar is in the range of 0.8 – 1.5. The maximum THD is in bus bar 1,2 and 9 and, minimum are in bus bar 6, 10 and 16.

8.2.2 Individual harmonic distortion

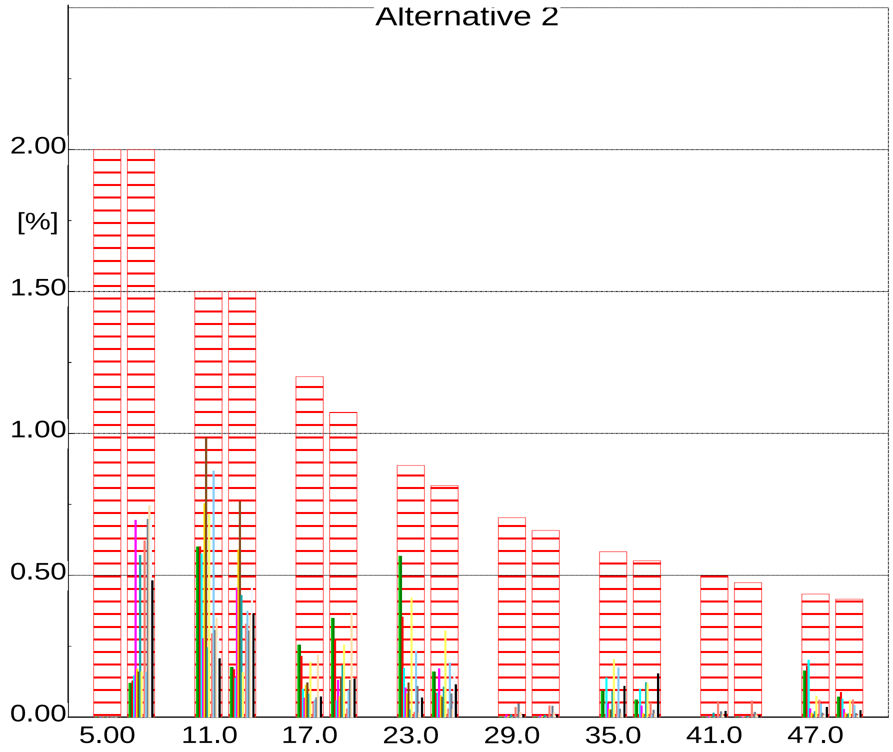


Figure 8.5 individual harmonic distortion of model in HV

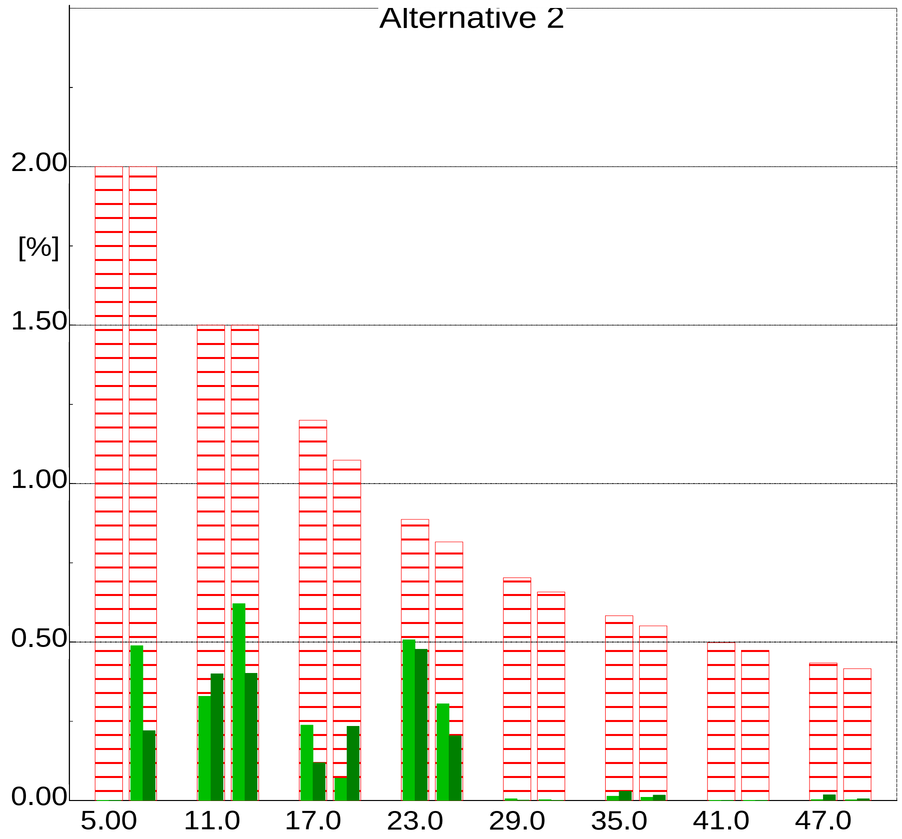


Figure 8.6 individual harmonic distortion of model in EHV

8.2.3 Impedance-Frequency

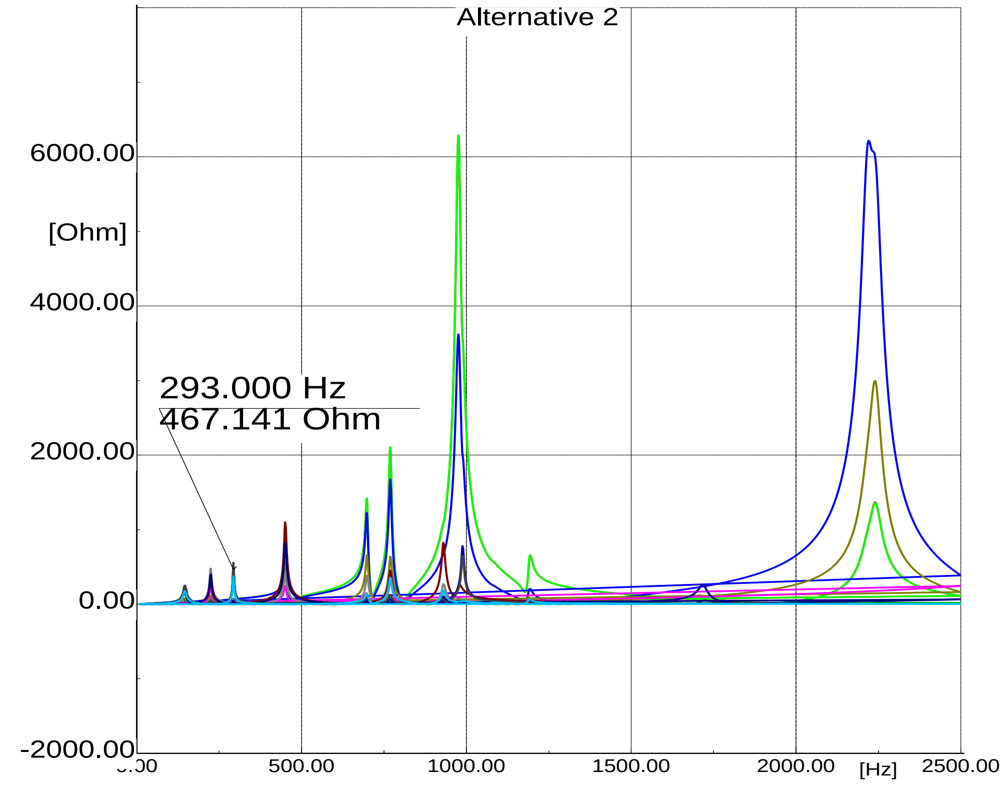


Figure 8.7 Impedance-frequency characteristic of 220 kV with alternative 2

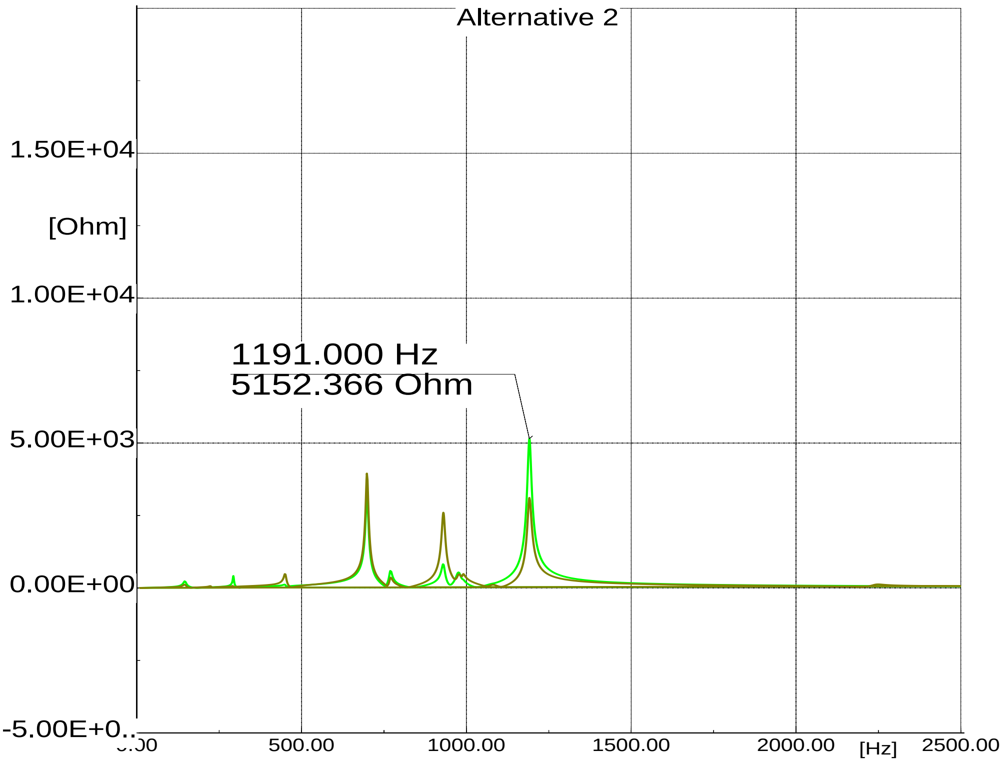


Figure 8.8 Impedance-frequency characteristic of 380 kV with alternative 2

The filter is located only in bus bar 11 at 220 kV and influences the impedance of this bus bar by changing R_s and R_{p1}. By increasing the value of both R_s and R_{p1}, the total loss of filter increases incredibly and by decreasing those value the loss decreases but the bandwidth, particularly dampening is weak. The purpose is to minimise power losses so R_s and R_{p1} are set to zero. Impedance-Frequency of 380 kV remain unchanged.

9 Discussion and conclusions

The aim of this thesis is to gain general knowledge of harmonics in transmission systems, analyse the harmonic load flow, interpret harmonic voltage distortion caused due to interaction of compensators with non-linear loads, study sensitivity analysis of parameters and finally design measures to attenuate the harmonic voltage level.

The presence of shunt capacitors plays a decisive role in power system to enhance the performance of the system such as injection of reactive power or maintain the voltage constant. On the other hand, they can cause resonance frequencies as well. All bus bars are observed while all compensators are on in the system and it is shown that the maximum distortion appears on 220 kV level at 49^{th} and on 380 kV level at 13^{th} harmonic.

Skin effect is a phenomenon in a power system which increases with the frequency. For an exact analysis, it is needed to have the frequency-dependent resistance of all components in the network. In this model the skin effect of OHL (lumped parameters π due to short transmission lines) is more significant and reduces the amplitude of the impedance curve dramatically. Consideration of skin effect has shown clear impact on the amplitude of impedance and it does not change or shift the resonance frequency.

The conventional harmonic impedance calculation is done to extract parallel resonance frequencies due to interaction of shunt capacitors. In order to estimate the main resonance frequency, the whole inductance and capacitance of the network are calculated. However, this simple approach does not match with the basic resonance frequency calculated with the exact model.

Harmonic mitigation particularly by filter design proves how effectively they mitigate and eliminate some harmonics. Moreover, an exact study of reactive power load flow and displacement of shun capacitors can yield harmonic mitigation without any additional costs. C-type filters have got the benefit of power loss minimization. By increasing the value of R_{P1}, the current goes up and results in more losses. Any reduction in the value of quality factor makes the Impedance curve smoother (wider bandwidth) and helps mitigating unwanted harmonics, but high amount of quality factor minimises power losses.

There are two alternatives to offer harmonic mitigation in this work.

In alternative 1**,** the worst harmonic distortion at 220 kV is in bus bar 1 to bus bar 3. So a filter with required reactive power is installed to eliminate the 49^{th} harmonic order in bus bar 3. At 380 a filter is placed in bus bar 1 to mitigate the 13^{th} harmonic order. In addition, a shunt with 173.1 Mvar made from the half reactive power of C_2, C_3 and C_4 at 220 kV is installed in bus bar 9 to optimise the system. The possibility of extending the network in the future will not bring any issues with. Mostly THD of every bus bar according to table 8.3 is under 1% which it totally fulfils the IEC 61000-3-3 standard.

In contrast to alternative 1, in alternative 2 an existing compensator at bus bar 11 is modified into a filter. The cost is of a great significance and efficiency is not much more important. Therefore, an auxiliary shunt is added to bus bar 9 to optimise the performance of the system. Although the filter at bus bar 11 cannot mitigate and keep individual distortion under limit alone. By extending the network a new study of harmonic load flow is required to not exceed distortion of standards. Only the filter in bus bar 11 can influence and dampen the impedance at 220 kV by changing the parameters of that filter. As it is obvious according to table 8.6, THD remain always in the range of 0.7 to 1.5.

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