HARMONIC AMPLIFCATION AND MITIGATION IN A MODERN MESHED TRANSMISSION SYSTEM

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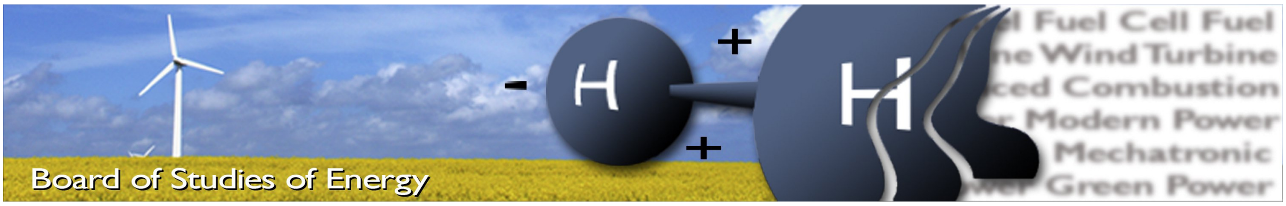
Energy Technology, EPSH4-1033, 2019-05

Master's Thesis

STUDENT REPORT

AALBORG UNIVERSITY



Title:	Harmonic amplifications and mitigation in a modern meshed transmission system
Semester:	10th Semester
Semester theme:	Master Thesis
Project period:	1.2.10 to 31.5.19
ECTS:	30
Supervisor:	Filipe Miguel Faria da Silva and Chengxi Lui
Project group:	EPSH4-1033

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SYNOPSIS:

This master thesis focuses on harmonic propagation in a modern meshed transmission system, and anti-resonance phenomena. The harmonic levels in both the busses in a system, and within the overhead lines and the in underground cables has been investigated, as well a method to quantify the levels. Furthermore, the causes of anti-resonance phenomena, and a filter tuning approach, where the aim is to reduce the effect, has been presented.

Pages, total:	127
Appendix:	4
Supplements:	-

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Preface

This project has been written by group EPSH4-1033 during the 4th semester of the Master of Science in Electrical Power Systems and High Voltage Engineering at the Department of Energy Technology at Aalborg University.

Reading Guide:

Throughout this report, source notes will be appearing in brackets. The reference notes have been made using the IEEE notation. The notes in the text will be stating the number of appearances. The notes will refer to the complete source list at the end of the report, where books are listed with author, title, year, publisher and ISBN, and web pages are put with author, title, URL and date. the given chapters. Figures, equations, appendices and tables are numbered in order of the chapter of their appearance. For example, the third figure in Chapter 4, will be numbered 4.3, the same applies for equations and tables. Every figure and table is provided with a caption, explaining its content. All the figures in this project report have been made by the project group itself. In the few exceptions in which these have been directly taken from a source, this is openly referred in the figure caption. All the mentioned content of this report is implemented through hyperlinks.

Software:

- LaTeX is used to write the report.
- MATLAB® is used for calculations and to process data.
- DigSilent PowerFactory® 2019 is used for modelling and simulations.
- Phyton® used to program the simulations run for data collecting.

Acknowledgements

The authors of this this thesis would like to thank Energinet, for the cooperation. A special thank is directed to Chris Skovgaard Hansen, at Energinet, for his help, suggestions and feedback.

Executive Summary

Denmark is undergoing a change in the power system, where a larger share of offshore wind power plants are implemented, more high voltage direct current connections to neighbouring countries are introduced, and a larger share of cables are installed in the transmission system. The increased amount of power electronics and cables that are associated with this development, is leading to a higher level of harmonics in the power system, which can reduce power quality, damage components and reduce their lifetime. Therefore, more attention is put within the field of harmonics, and harmonic mitigation. This master thesis, written in cooperation with the danish transmission system operator, Energinet, is thus focusing on harmonic propagation and harmonic mitigation. The following problem statement has thereby been formulated.

How can system-wide harmonic propagation and the causes of anti-resonance phenomena be explained, and how can the anti-resonance phenomena be avoided?

The aim of this project is to model a realistic modern meshed transmission system, in order to analyse how harmonics propagate. Furthermore, it is desirable to review the system-wide harmonic levels, not only in the busses in a system, but also within the overhead lines and the cables, and understand how the harmonic levels are determined. Moreover, it is desirable to enlighten the phenomena of anti-resonance, meaning the causes, and how it can be avoided. The focus lies on the amplifications that can occurs in the other harmonic orders than the target frequency, after the implementation of a single-tuned filter. Single tuned filters are used as the harmonic mitigating element in this report, as the risk of anti-resonance is higher after an implementation of this type of filter, compared to other common filters.

Parts of an example grid has been used in the analysis in this report. Namely the example grid developed by Oscar Lennerhag, which is, amongst others, developed for harmonic propagation studies. The system is characterised by a large share of cables at a 400 kV and 220 kV level. Only the 400 kV level is included in

the analysis, as focus of the report lies on the harmonic propagation that occurs on the 400 kV transmission level, and not how it propagates up/down from/to lower voltage levels.

The impact different system parameters have on the system impedance has been analysed, where it was seen that the increased susceptance in cables compared to overhead lines lowers the frequency of the resonance points. That can increase the risk to amplify harmonic orders of lower frequency, where lower limits are set for the harmonic levels.

The harmonic propagation has firstly been analysed in a radial system, and thereafter in the mentioned meshed system. The radial system used, is a radial part of the mentioned meshed system, and was used in order to facilitate the analysis and explain the concept of harmonic propagation. The harmonic levels in a system has been seen to be both affected by the location of the harmonic emission source, the system impedance seen from that bus, and by propagation gains from the bus at which the harmonic emission source is located to the other busses in the system. The mentioned propagation gains are determined by the system itself. Furthermore, the RMS harmonic levels within an overhead line and an cable are seen to follow a sinusoidal waveform which could, in addition to a harmonic load flow, be used to explain the harmonic propagation gains in a system.

It has been concluded that the harmonic levels within the overhead lines and the cables in a system, can be be higher than the harmonic levels that are measured at the bus in a system. It has been seen that cables are more susceptible to overcurrents, while overhead lines are more susceptible for over-voltage. Furthermore, higher amplifications occur in longer lines, and at harmonic orders of higher frequencies.

The amplification within the lines means that the lines in a system can be exposed to higher stresses than initially assumed from a harmonic load flow, which can cause damage to the lines like partial discharge, insulation degradation, flash over and excessive sagging. It can be more critical in cables as the high voltage levels can cause partial discharge which can lead to electrical treeing, which again permanently destroys the insulation of the cable.

A method to calculate the maximum stresses and the location of them has been proposed. It should be used together with a harmonic load flow, as it needs values for both the harmonic current and and the harmonic voltage at both ends of a line. The method has been seen to have a sufficient accuracy, when the voltage and current waveform followed the mentioned sinusoidal curve. However, the accuracy is seen to be reduced if a phase-shift occurs within a close vicinity of the bus defined as the starting point of the waveform. This can however be solved by switching the starting point to the opposite bus. The accuracy will therefore only decrease if phase-shift occurs at both busses, which is a special occurrence and then a different method should be used.

The anti-resonance phenomena, caused by a single-tuned filter, has been seen to be caused by the change in the system impedance the filter implementation causes. The change in impedance seen from the bus at which the harmonic emission source is located at has seen to be of great importance. The mentioned change in impedance causes a change in the harmonic levels at which the harmonic emission source is located at. Furthermore, it causes a change in the harmonic propagation gains in the system, and thus changes the harmonic levels in the entire system. The propagation gains are affected as the path of the harmonic current in the system changes due to the change in impedance. The harmonic voltage levels in the entire system are thus also affected. The most significant change in impedance is at the harmonic orders within a close vicinity to the target frequency, due to the impedance single-tuned filters introduce.

The impedance seen from each bus in a system, is different. Therefore the harmonic levels, both before and after a filter implementation, is dependent on the location of the harmonic emission sources in a system. Furthermore, the level of anti-resonance phenomena is dependent on the location of the filter, and the impedance of the filter, as that affect the change in system impedance. The change in the mentioned harmonic propagation gains, are sensitive. A slight change in the system impedance, can shift the systems parallel resonant points to a harmonic order present in a system. That can cause very high harmonic amplifications, and should be avoided.

The levels of anti-resonance phenomena is thus dependent on the location of the harmonic emission source, the location of the filter, and the impedance of the filter. An approach for filter tuning where the system-wide harmonic levels are considered, has been presented. The approach has been seen to have the potential to reduce the anti-resonance phenomena while still effectively reduce the target frequency. The increase in the other harmonic orders than the target frequency, and the reduction of the target frequency has been seen not to be linear when tuning a filter. The filter tuning has been done by adjusting the rated power of the filter, and the quality factor of the filter, which consequently affect the capacitance, inductance and resistance of the filter. A slight change in the rated reactive power can in some cases cause large amplifications of some harmonics, while the reduction of the target frequency is not significantly affected, or vice versa.

Contents

List of Abbreviations

RMS root mean square . . . 7

TSO transmission system operator . . . 1

UGC underground cable . . . 2

VSC Voltage Source Converter . . . 4

WPP wind power plant . . . 1

Chapter 1

Introduction

The theme of this project is harmonics in modern meshed transmission systems. More specifically, harmonic propagation and amplification in transmission systems, with a focus on high voltage (HV) and extra high voltage (EHV) levels in Denmark. The aim of this chapter is to introduce why this is an important topic to investigate, to provide an overview of the topic and to give the basis for the problem definition defined in Chapter 2. Firstly an overview of the development of the Danish transmission system is given, including a description of the increasing issue that has been detected regarding harmonics. Thereafter the definition of harmonics is explained, in addition to an explanation of how they are generated, how they propagate, and the effect they may have on a power system. Lastly an explanation of mitigation techniques is presented and how harmonics are coordinated by the transmission system operator (TSO) in Denmark, namely Energinet.

1.1 Development in the Danish Transmission System

Energinet, the Danish TSO, is responsible of maintaining the security of supply of electrical power in Denmark, as well as integrating and increasing the amount of renewable energy sources in the grid, [1]. The Danish transmission system is thus under a continuous development, where a trend of integrating more renewable and fluctuating energy sources have been seen the past years. The trend is expected to continue according to Energinet's most recent analysis assumptions, an annually published prediction of the future Danish power system, [2]. Furthermore, more high voltage direct current (HVDC) connections have been implemented in the grid, contributing in balancing the amount of power generated and the amount of power consumed, in order to maintain the security of supply and utilise the surplus power generated by fluctuating power generating units as wind power plant (WPP)s. This results in an increased amount of power electronic units, and thus also the need to analyse harmonics.

The development of the Danish transmission system and the increased amount of renewable energy sources in the grid is generating a need of reinforcing the transmission system, in order to avoid overloading the lines. When the grid is being reinforced, there is an interest of implementing a large amount of underground cable (UGC)s, rather than overhead line (OHL), with the aim of protecting the nature and the physical view. That has though been seen to introduce new challenges for the TSO. In addition to that, there is an interest of replacing some of the already existing OHLs by UGCs. The government of Denmark have though adjusted the strict framework for implementing and replacing OHLs by UGCs, known as "kabelhandlingsplanen". The adjusted framework states that the existing part of the 132-150 kV network should be maintained as OHLs with UGCs in chosen sections, and that new parts should be implemented as UGCs. Regarding the 400 kV network, it is stated that new parts should be implemented as OHLs with UGCs in chosen parts. Furthermore, it states that the already determined projects of replacing parts of the 400 kV OHLs by UGCs should still stand. It is thus planned to implement UGCs in new parts of the 132-150 kV (HV) network, and in some parts of the 400 kV (EHV) network, [3].

The implementation of HV and EHV cables can cause issues in regards of maintaining the harmonic levels in the grid below the upper limits set for the system. The main difference between UGCs and OHLs is that for the same length UGCs generally have a significantly larger shunt capacitance than OHLs, [4]. HV UGCs have a shunt capacitance 20-50 times larger than and equivalent OHL of the same length, which is causing the system resonances to move to lower frequencies, which can amplify the voltage harmonics at those frequencies, [5]. In July 2017 an 8 km long UGC implementation was taken in use in Vejle Ådal. A significant increase in the harmonic levels was then recorded in the 400 kV substation in Trige, close to Århus and in Fraugde, close to Odense, which is about 80 km away from the location of the implemented UGC. The geographical location of these busses can be seen in Figure 1.1, where the red lines indicate the 400 kV transmission system, and the busses of interest are marked with yellow circles, [6]. There is thus a risk when implementing HV and EHV UGCs in the transmission system, due to the amplifying effect it can have on the harmonic levels in the grid.

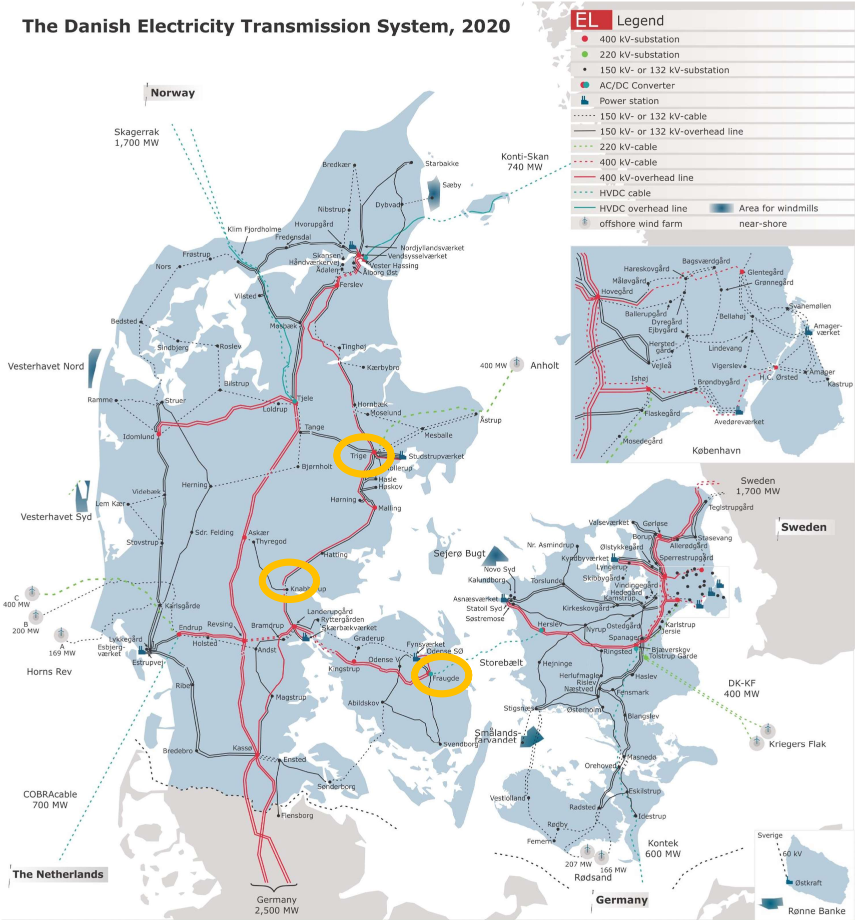


Figure 1.1: Geographical location of the bus in Vejle, Trige and Fraugde, [7].

In a meshed transmission system long EHV UGCs can cause system-wide harmonic amplification, and it has proven to be a difficult task for TSOs to accurately estimate the amplifications, and thus design harmonic mitigating filters. There is a risk that the filters mitigate the harmonics locally, but have an amplifying effect at other locations in the transmission system. This is by the Danish TSO, Energinet, defined as anti-resonance phenomena, where a shift in the harmonic amplification occurs, [8].

Offshore WPPs in Denmark are connected to the grid on the mainland by the use of submarine cables. As mentioned, an increased amount of renewable energy sources, especially offshore WPPs, is expected to be connected to the Danish grid, which is causing an increase in the amount of cables in the grid and an increased amount of power electronics. Power electronics are known to emit harmonics into the power system, as explained in Section 1.2.4. According to the mentioned analysis assumption, [2], the total offshore wind capacity is expected to increase by 1181 MW in 2030, meaning an increase of 165 % compared to the installed capacity in 2017.

The total capacity in HVDC connections is expected to increase from 6.3 GW, which was the capacity in 2017, to 10.7 GW in 2030. The general converter technologies used on the Danish side of the HVDC connections are Line Commutative Converter (LCC)s and Voltage Source Converter (VSC)s, where the newer and future implementations are VSCs. Both LCCs and VSCs generate harmonics, with the LCCs generating considerably higher magnitudes. The harmonics generated by HVDCs are usually mitigated by the use of a local filters, like a single-tuned filter, but an increased amount of harmonics are seen in the transmission grid.

The development of the Danish transmission system and the changes that are implemented is affecting the power quality which is related to the voltage at a given point in the power system. According to Dansk Standard, [9], the main characteristics of the voltage are described in terms of frequency, magnitude, waveform and the symmetry of the line voltages. The increased level of harmonics may thus reduce the power quality in the system if it is not mitigated sufficiently. The increased amount of HVDC converters, WPPs and UGCs may all increase the level of harmonics, and make the mitigation more complex. The effects this may have in a power system is explained in Section 1.2.2, but firstly the definition of harmonics is explained.

1.2 Harmonics

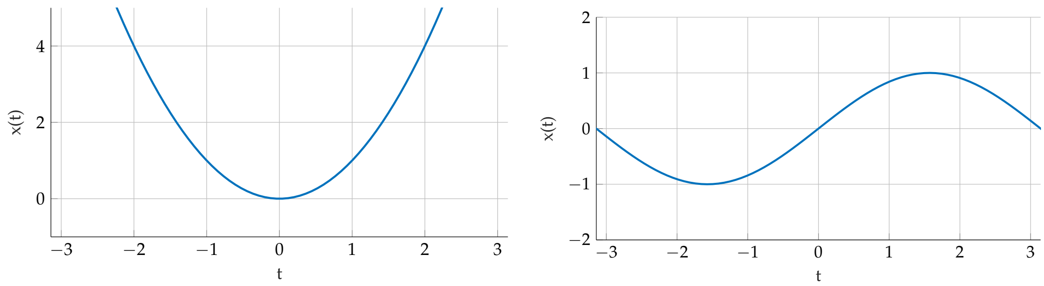
In this section harmonics are explained. Firstly the definition of harmonics is presented, followed by the generation of harmonics and the effect of harmonics in a power system. Lastly, how harmonics in a power system can be mitigated is explained.

1.2.1 Definition of Harmonics

Harmonics in a power system are defined as a sinusoidal voltage or current waveform, which frequency is integers of the fundamental frequency, [10]. By the use of Fourier series, as seen in Equation 1.1, any periodic waveform can be explained as the sum of a direct current (DC) component, a fundamental sinusoidal component and a series of harmonics, [10].

$$x(t) = a_0 + \sum_{n=1}^{\infty} \left(a_n cos\left(\frac{2\pi nt}{T}\right) + b_n sin\left(\frac{2\pi nt}{T}\right)\right) \tag{1.1}$$

In the equation a_0 is the average of $x(t)$, and a_n and b_n are the coefficients of the sine and cosine expressions. If the signal is symmetric either a_n or b_n is zero, which reduces the complexity of the signal. Harmonics are said to be either even (2nd, 4th, 6th, etc) or odd (3rd, 5th, 7th, etc). The waveform of even harmonics have an even symmetry, that complies with the equation and waveform seen in Figure 1.2a. The waveform of odd harmonics on the other hand have an odd symmetry complying with the equation and waveform seen in Figure 1.2b. The term a_n and b_n in Equation 1.1 is zero for odd and even harmonics respectively. Note that the DC component, if any is present, is not included when reviewing whether the waveform complies with either even or odd symmetry.



(a) $x(t) = x(-t)$ **(b)** $x(t) = -x(-t)$

Figure 1.2: (a) x^2 represents an even harmonic (b) $sin(x)$ represents an odd harmonic.

Half-wave symmetry exists for a signal which repeats itself with reversed sign every half period, as expressed in Equation 1.2, and only holds true for odd harmonics. In the equation T is the period of the cycle. The difference between half-wave symmetry and odd symmetry is that odd symmetry can include a DC signal, while a half-wave symmetric signals does not. The power system is mainly alternating current (AC), which is half-wave symmetric. As most harmonic sources in the system follow this wave form, a significant part of harmonics are odd. [11]

$$x(t) = -x(t + T/2) \tag{1.2}$$

The amplitude of odd harmonics generated would mathematically follow the expression seen in Equation 1.3, where h is the order of the harmonic. The amplitude is thus usually lower for higher order odd harmonics. The equation is however only valid under ideal conditions and can thus in practice only be used to give an estimate of the amplitude.

$$A = 1/h \tag{1.3}$$

Fourier transform and its inverse, seen in Equation 1.4, are used to transform the expression for harmonics between time domain and frequency domain. Harmonics represented in the two domains can be seen demonstrated in Figure 1.3.

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi fT}\,dt \quad \Leftrightarrow \quad x(t) = \int_{-\infty}^{\infty} X(f)e^{j2\pi fT}\,df \tag{1.4}$$

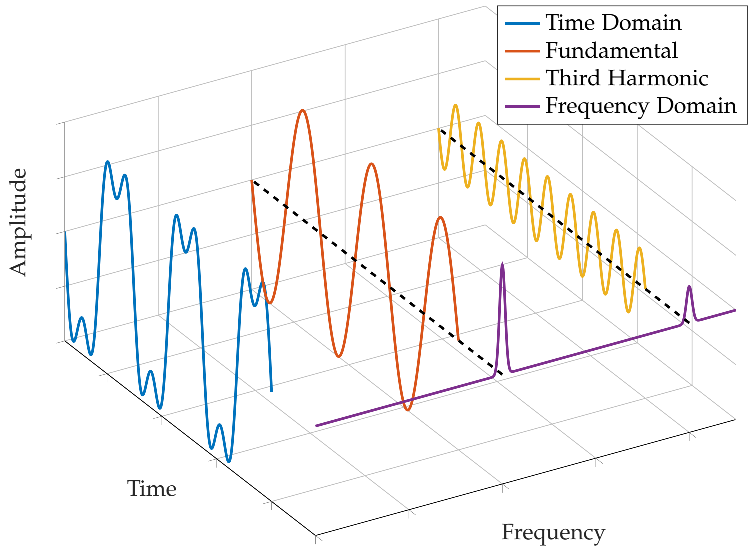
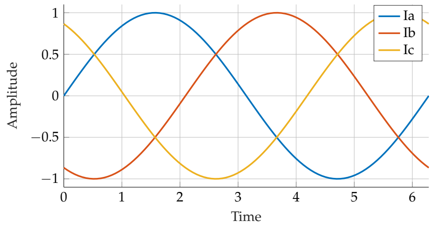


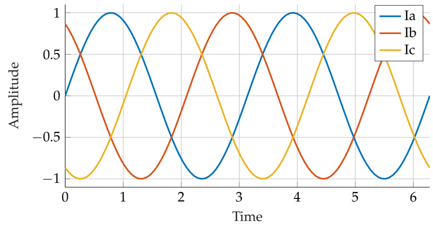
Figure 1.3: Harmonics represented in the time domain and the frequency domain.

An arbitrary periodic signal can thus be split up into simpler frequency terms, where it can be analysed, solved and then transformed back to the time domain.

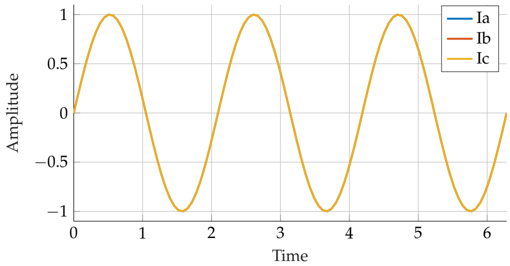
Harmonics are often balanced and can therefore be split into sequence components as seen in Figure 1.4. They follow a pattern where $3x + 1$ is positive, $3x - 1$ is negative and $3x$ is zero sequence. The harmonics can therefore be analysed in sequence models which is decoupled and therefore more efficient. If the transmission network is unbalanced, either from unbalanced sources or an unbalanced formation of lines, it will cause sequence couplings which results in harmonics consisting of not one, but several sequences. A sequence model is then not sufficient and a phase model which includes coupling between phases is necessary to properly model the couplings. [12]



(a) Fundamental Harmonic, positive sequence.



(b) Second Order Harmonic, negative sequence.



(c) Third Order Harmonic, zero sequence.

Figure 1.4: Fundamental, second order and third order harmonic waveform in time domain.

1.2.2 Effects of Harmonics

Harmonics in a power system is in general undesirable due to the effect it has in a power system and on the system components. It may increase the ageing process and thus reduce the lifetime, and it may cause components to malfunction. Furthermore it may increase the losses the in generation, transmission and the utilisation of the power in the system, in addition to causing relays to operate when the should not. There is also a possibility that series and parallel resonances can amplify the harmonics, leading to even more harmful effects, [10].

Harmonics cause an increase in the root mean square (RMS) current, defined as seen in Equation 1.5, which consequently causes an increase in power losses, as seen in Equation 1.6. As seen the losses increase with the size of the current, and the size of the current increase when there are harmonic currents present in the system.

$$I_{\text{RMS}} = \sqrt{I_0^2 + I_1^2 + \sum_{h=2}^{n} I_h^2} \tag{1.5}$$

In Equation 1.6 I_n is the harmonic current, and R_n is the system resistance at the harmonic frequency. Skin and proximity effect, which are known to increase the losses, are both functions of frequency. The resistance of the cable is increased with frequency, and thus the losses are increased. The increased losses in the system can cause increased operational temperatures, which can reduce the lifetime of the components.

$$P_{ohmic} = \sum_{n=2}^{\infty} I_n^2 R_n \tag{1.6}$$

Harmonic currents can also cause an increased voltage drop in the system. In a weak system, meaning a system with a larger impedance and thus low fault levels, higher voltage deviations will occur due to harmonics, [10].

Harmonics can also increase the peak voltage in the system, dependent on the angular relation between the harmonics and the fundamental signal, even though the RMS voltage is maintained within the limits. This can cause undesirable corona effects in the system. Furthermore, an increased voltage can increase the dielectric losses in the system, as expressed in Equation 1.7, [10].

$$P_{dielectric} = C(tan\delta)\omega_n V_n^2 \tag{1.7}$$

In the equation δ is the loss factor and is expressed as seen in Equation 1.8, $\omega_n = 2\pi f_n$ and V_n is the RMS voltage of the n-th harmonic.

$$tan\delta = \frac{R}{1/(\omega C)} \tag{1.8}$$

The biggest concern regarding harmonics in transformers is the additional heat generated by the harmonics in the load current, which again can reduce the lifetime of the transformer. Additionally, there are concerns regarding mechanical insulation stress in both the winding and the insulation due to increased hysteresis and eddy currents which increase with frequency, and the core vibrations that harmonics may cause. Furthermore, if the windings of the transformer is delta connected the winding can be overloaded due to circulating zero sequence harmonic currents, if those currents are not taken into account during the design phase. Transformers are mainly inductive and may cause a resonance between the system capacitance, as explained further Section 1.2.4. [10]

Rotating electrical machines may experience excessive heating issues if harmonics are injected to the machine. Harmonics can increase the losses in both the stator and rotor windings and lamination. Furthermore harmonics may cause torque pulsations, leading to additional mechanical stress which reduces the lifetime of the machine. [10]

The protection system in a power system can be affected by harmonics as the harmonics can disturb the operation of protective relays, [10]. Relays designed to operate according to peak or zero voltage or current measurements may malfunction by the presence of harmonics, and electromechanical relays time delay may be affected, [13]. Malfunctioning in a protection system can have severe consequences, as circuit breakers may not operate when they are supposed which might damage system equipment severely.

Harmonics can in general increase losses, reduce the lifetime of components and increase the need for maintenance in the power system, which leads to economic losses. It is therefore highly undesirable to have a high level of harmonics in a power system, and it is essential to mitigate the levels as explained in Section 1.2.5. Furthermore it is important to identify the harmonic sources and the level of harmonics present, as explained in the following section.

1.2.3 Generation of Harmonics

Harmonics are generated by several different sources in a power system. These sources have a non-linear behaviour in common. Non-linear behaviours causes distorted sinusoidal wave forms, which can be described with a fundamental wave form and its harmonics, as explained in Section 1.2.1. These non-linear behaviours can be generated by transformers, rotating machines, electric arc devices and power electronics.

In transformers the non-linear behaviour is seen in the core as the relation between the magnetic field intensity and the magnetic flux density is non-linear. This relation is assumed linear under normal operations and with the magnetisation current reaching 1-2 % of rated current it does not cause significant harmonics. During re-energisation of a transformer the flux can reach up to 3 times the nominal flux which causes severe saturation and harmonics of all orders. These harmonics are non-periodic and will thus not be considered in the analysis in this report.

Rotating machines generate harmonics because of the non-sinusoidal magnetomotive force (MMF) in the air gap, which induces a non-sinusoidal electromotive force (EMF). This non-sinusoidal MMF can be produced by a non-sinusoidal winding distribution or a salient rotor. If a rotation machine have a single slot per pole its MMF will be a square wave form. This will create all odd harmonics with their amplitude inverse to the order. To have a smoother operation and reduce harmonics, more slots per poles are introduced, which will cause the MMF to gradually build up resembling a sinusoidal wave form as seen in Figure 1.5. If the slots and windings are distributed properly it will reduce the harmonic content, but it would never be able to obtain a perfect sinusoidal wave form.

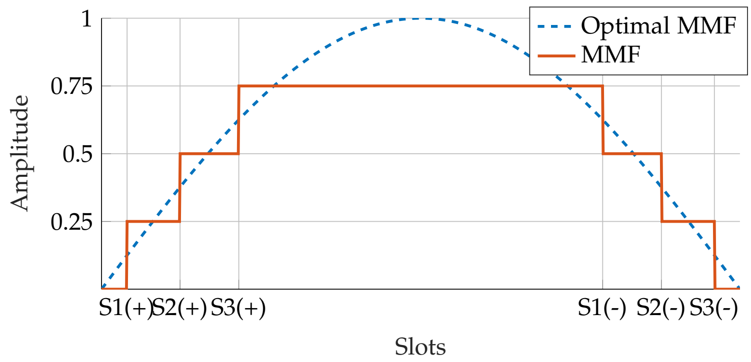


Figure 1.5: Air gap MMF with three slots compared to a perfect MMF.

Electric arc devices have a non-linear voltage-current characteristic, as they are based on igniting an electric arc, which suddenly causes high amounts of current to run through the system. For an electric arc furnace, the arc is maintained and the relationship between voltage and current is depended on the length of the arc and the movement of the materials being melted. As both are constantly changing several harmonics are generated. Discharge-type lightning, like fluorescent lamps can also cause harmonics as they light up a gas via small arcs, causing the current to spike. A single lamp does not cause significant harmonics, but in high numbers it is measurable.

Power electronics are inherently non-linear, both in components and operation. They are generally based upon the principle of switching or blocking the voltage or current to obtain a DC or AC signal of a given amplitude. In Figure 1.6 a PWM signal can be seen, which obtain a near sinusoidal wave form by switching a DC signal on and off. If this signal is connected to a load it is easy to visualise that the current waveform would not be sinusoidal. It would therefore draw a non-sinusoidal current from the grid with a certain impedance, which would cause a distorted waveform.

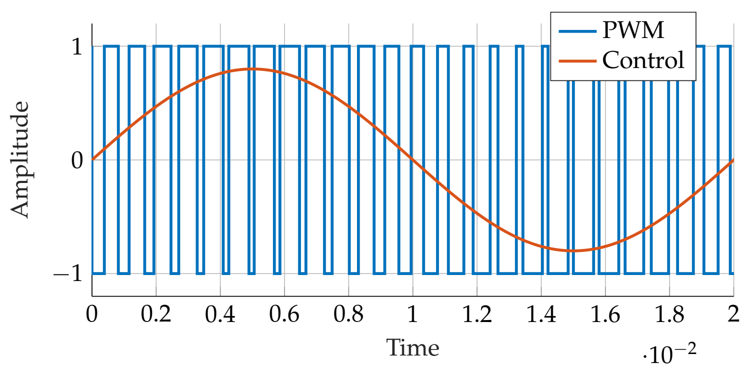


Figure 1.6: PWM signal for a sinusoidal waveform.

Power electronics in the power system may include switch mode DC power supplies, used in households and small commercial buildings, back to back converters, used in wind turbines, and LCCs and VSCs used in HVDC connections. The order of harmonics depends on the application. DC power supplies generates all the odd harmonics, but mainly the third, fifth and seventh. 6-pulse converters, which are common three-phase converters, for medium range power appliances like industry, generates harmonics in the range of $6k \pm 1$, where k is an integer and the amplitude has an inverse relationship with the harmonic order. 12-pulse converters used in LCC and VSCs generates harmonics in the range of $12k \pm 1$.

In the later years the amount of power electronics in the power system have increased as a result of more efficient technology, the increase of renewable energy and the need of a more interconnected transmission system with HVDC connections to neighbouring countries, as explained in Section 1.1. This has increased the generation of harmonics at the transmission level and also at the distribution level, which seems to propagate to higher voltage levels.

1.2.4 Amplification of Harmonics

Increased generation is not the only way to increase the amount of harmonics in the system. It has been seen that different configurations and components in a power system can amplify the harmonics already present to levels beyond the upper limits. This occurs when resonant points in the system impedance coincide with a harmonic of a certain order present. The amplification of voltage and/or current can occur at these points as the system impedance is at its minimum for series resonances and at its maximum for parallel resonances. Both of these points exists an infinite amount of times in UGCs and OHLs. The principle of the resonant points can be explained by reviewing a lumped pi-model of two OHLs, as seen in Figure 1.7.

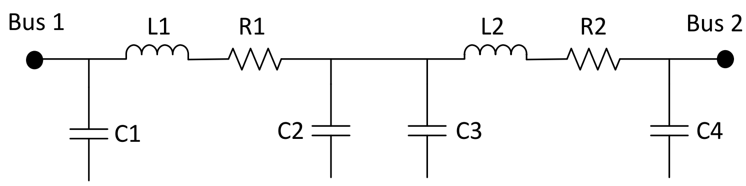


Figure 1.7: Lumped pi-model of two OHLs.

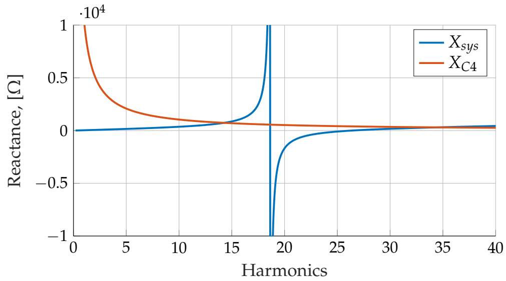
The lumped pi-model, seen in the figure, will only give three resonant points, two parallel and one series. That is though sufficient in this case where the aim is to get an idea of resonant points, and their impact on harmonic propagation. If the impedance of the OHLs is seen from the Bus 2, there will be a parallel resonant point every time the reactance of the capacitor, C4, is equal in magnitude but opposite in sign of the reactance of the rest system. The impedance will increase as seen in Equation 1.9, where the denominator will be equal to resistance which, in a power system, is low compared to the reactance.

$$Z_{par} = \frac{(R_{sys} + X_{sys} \cdot i) \cdot X_{C4} \cdot i}{R_{sys} + X_{sys} \cdot i + X_{C4} \cdot i} \tag{1.9}$$

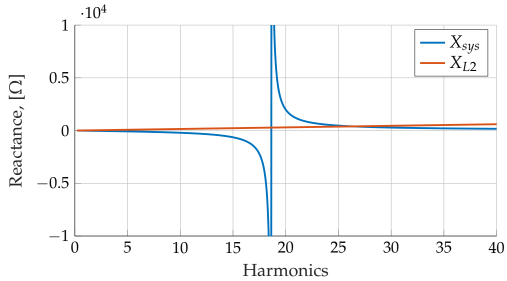
A series resonant point will occur when the reactance of the inductor L2, is of equal magnitude and of opposite sign to the reactance of the rest of the system. As seen from Equation 1.10, the impedance will then only consist of resistances.

$$Z_{ser} = R_{sys} + X_{sys} \cdot i + X_{L2} \cdot i \tag{1.10}$$

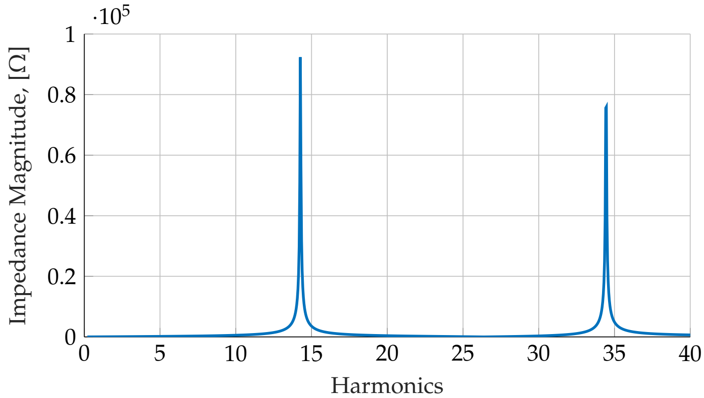
The frequency of the parallel resonance points can be seen graphically by plotting the reactance of the capacitor C4, and the system impedance, seen from Bus 2, as seen in Figure 1.8a. Every time the lines cross there is a possibility of a parallel resonance point. The graphical representation of the series impedance is seen in Figure 1.8b. The impedance seen from Bus 2 can be seen in Figure 1.8c where it is seen that the parallel and series resonant points coincide with the point of crossing in Figure 1.8a and 1.8b. The large increase/decrease of the system reactance around 18.5 harmonic order, is caused by the parallel resonant point of C2/C3. The point of crossing at this frequency will not cause a resonant point as the resistance is far larger than the capacitance, C4, and it is therefore not seen.



(a) Frequency of parallel resonant points seen from Bus 2.



(b) Frequency of series resonant points seen from Bus 2.



(c) Impedance magnitude of the two OHLs seen from Bus 2.

Figure 1.8: Example of system parallel and series resonances.

The resonance points and their infinite repetitions can also be found by the use of wavelength of the electric signals in the OHL. Bus 2 will see the impedance of the source at a frequency corresponding to a half wavelength and the opposite of the impedance of the source at a frequency corresponding to a quarter wavelength. This can be seen in Figure 1.9, where the voltage throughout an OHL, between Bus 2 and a source is seen.

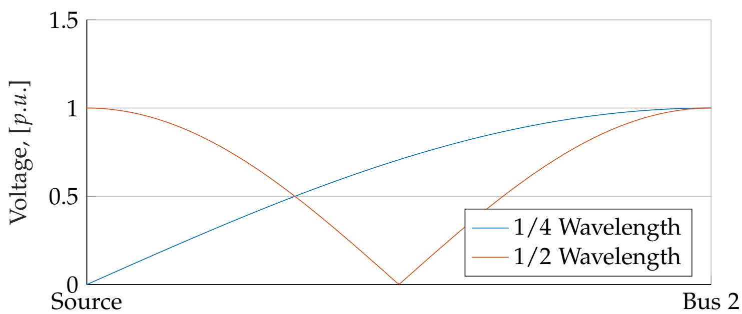


Figure 1.9: Visualisation of half and quarter wavelengths.

At a frequency, where half the wavelength of the electric signal is equal to the length of the OHL, the voltage is seen to be the same at both ends of the OHL. This resembles a short circuit between Bus 2 and the source, only with the resistance of the OHL, which can be seen as a series resonance point. At a frequency, where a quarter of the wavelength corresponds to the length of the OHL, the voltage is seen to be zero at the source. This resembles an open circuit, which can be seen as a parallel resonance point. [10]

Each consecutive parallel and series resonance will occur with half a wavelength between them, respectively, when skin effects are not considered. With a non-ideal source or several lines, both in series and in parallel, will cause the system to become more complex, which will result in more complex impedance scans.

The resonance points are not only associated with cables and OHLs, but also occurs if an inductor and a capacitor affect each other, and especially when these have large values. That is the case when a transformers or a capacitor banks is present in a system. Amplification of lower order harmonics should be avoided as these are often of larger magnitudes and less amplification is therefore needed to increase the harmonics beyond the limits. With the increased amount of UGCs in the Danish power system, this is becoming an issue as they have a lower resonance frequency than OHLs and will shift the resonant points of the entire system to the frequencies of lower-order harmonics. This can cause issues not only at the location of the UGC, but in the entire system.

In this report there is laid extra attention on a phenomena called the anti-resonance phenomena as defined by Energinet, [8]. This phenomena occurs when a passive filter is introduced to the system, reducing the target harmonic, but impacts the system resonances, amplifying harmonics at other order and substations. It is defined as any increase in harmonics in the system, when implementing a passive filter.

The significant harmonic content in the Danish transmission system is the 3rd, 5th, 7th, 11th and 13th order harmonics[14]. The sources of the harmonics are not known with certainty, but the 11th and 13th are presumed to come mainly from the LCCs, while the 5th and 7th are presumed to come from 6-pulse converters from lower voltage levels. Mitigation is needed to keep these harmonics under limits which is explained in the following section.

1.2.5 Mitigation and Coordination of Harmonics

Harmonic mitigation is done in order to reduce the negative effects harmonics can cause in a power system, as explained in Section 1.2.2. When it is known that a harmonic source is to be implemented into a power system it has to be decided, during the planning stages, whether the device is to be set to emit low enough levels of harmonics, or if a compensating device has to be implemented. It is possible to reduce the level of harmonics a device emits, and if the emitted level is within the set limits, no compensating device is required. However, the best solution is often to mitigate the harmonics after implementation, by the use of a local filter, and that is also the approach that is of focus in this report. More specifically, by the use of single-tuned filters. An overview of harmonic coordination and mitigation methods by the use of filters, is given in this section. More details on filters and filter designs and modelling can be found in Chapter 3.

In a power systems, different limits of harmonic distortions is accepted by countries for global co-ordination. These limits and other standards in Europe are defined by the International Electrotechnical Commission (IEC), [9]. The IEC 61000 series includes harmonics and inter-harmonics limits and compatibility levels for all voltage levels from 400 V to 400 kV. They also includes description of sources of harmonics and how to test and measure harmonics. The upper limits for voltage harmonics at HV levels, as defined by IEC 61000 3-6, can be seen in Table 1.1. IEC 61000 3-6 does not provide limits for harmonic currents, those limits are rigorously based on the harmonic voltage limits.

Table 1.1: Indicative planning levels for harmonic voltages in HV-EHV power systems. Values given in percentage of fundamental voltage, [9].

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 %
5	2	3	2	2	1.4
7	2	9	1	4	0.8
11	1.5	15	0.3	6	0.4
13	1.5	21	0.2	8	0.4
17<h<49	1.2 17/h	21<h<45	0.2	10<h<50	0.19 10/h + 0.16

If the harmonic generation from a device is too high, mitigation is often achieved by the implementation of local filters at the terminal of the harmonic generating device. Filters are divided into to main categories, namely active filters and passive filters.

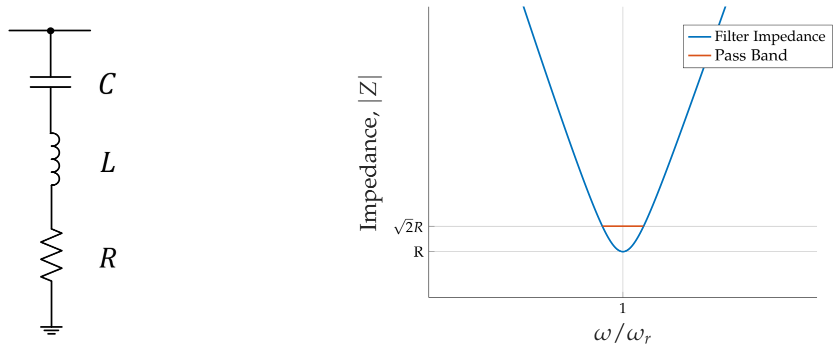
Passive filters aims to reduce the emission of harmonic at specific frequencies or specific frequency ranges. They are called passive filters as they do not require any control and are thus simpler than active filters. They consist of inductor, capacitor and resistor elements, and have a defined quality factor, q, which is used to determine the sharpness of the tuning of the passive filter. Filters are said to either be of high or low q, meaning a high or low level of tuning.

A single-tuned filter schematic and its impedance can be seen in Figure 1.10a and 1.10b respectively. That is a high q passive filters and it is sharply tuned to harmonics at lower frequencies, and typically has a q value between 30 and 60. It is typically used for the frequency of a lower harmonic like 3rd or 5th harmonic. The impedance of the filter is given as seen in Equation 1.11, and is equal to the filter resistance, R, at resonance frequency, which is defined as seen in Equation 1.12, [10].

$$Z_f = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{1.11}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1.12}$$

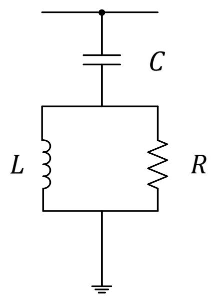
The singe tuned passive filter has the advantages that it has maximum attenuation at a single harmonic and it has low losses. However, it can become detuned by temperature and frequency variations, and may require tap adjustments.



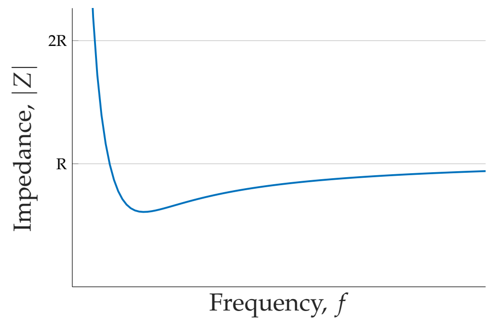
(a) Filter circuit. **(b)** Filter impedance over frequency.

Figure 1.10: Single-tuned, high q, passive shunt filter.

Low q filters, with the filter circuit and impedance as seen in Figure 1.11, has a lower impedance over a wide range of frequencies, and usually has a q value between 0.5 and 5, [10]. These types of filters usually have a high resistor value, and thus also high losses. They also must be designed with high VA rating. However, they are less sensitive to parameter variations and filter a wider spectrum of harmonics, [10].



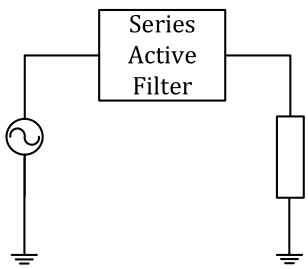
(a) Filter circuit.



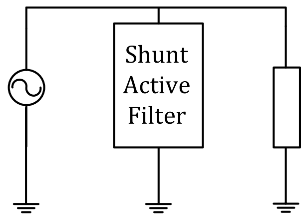
(b) Filter impedance over frequency.

Figure 1.11: Second-order, low Q, damped shunt filter.

Active filters consist of power electronics and does thus require a control strategy. The development of the active filters have mainly been encouraged by the increased complexity and high losses of the passive filters, in addition to their restricted capability of eliminating inter-harmonics and non-characteristic harmonics. The filters can be implemented in series or in shunt, as seen in Figure 1.12a and 1.12b, to respectively prevent the transfer of harmonics and to reduce the harmonics in a network in general. Active filters are in general more complex and more expensive than passive filters, and the focus in this report lays on mitigation by the use of passive filters.



(a)



(b)

Figure 1.12: Series and shunt implementation of active filters.

Completely eliminating all harmonics is not economically feasible. Therefore, filters are usually aiming on reducing the level of harmonics, so that the harmonics in the system is sufficiently low and below the set limits.

Chapter 2

Problem Formulation

Denmark is undergoing a change in the power system, where a larger share of offshore wind power plants are implemented, as well as more high voltage direct current connections to neighbouring countries. Furthermore a larger share of underground cables are installed in the transmission system. The increased amount of power electronics and cables that are associated with this development, is leading to a higher level of harmonics in the power system.

The Danish transmission system operator, Energinet, is working to ensure the security of supply as well as socially economically operating the transmission system. They therefore set upper limits for harmonics, based on the European standard IEC 61000, and continuously measures the harmonic levels, in order to ensure that the negative impact of harmonics is reduced. In addition to that, they relay on models of the power system and simulations in order to analyse the harmonic impact new components and upgrades in the system will introduce. Furthermore, they use the models when the objective is to reduce the harmonic levels. The aim is to ensure that the system-wide harmonic levels is below the set limits, and to ensure that the harmful effects harmonics can cause is mitigated.

Harmonic mitigation has though been seen to be a challenging task, and there is room for further research in order to determine how to make the assessment efficient. The anti-resonance phenomena that can occur after a filter implementation, meaning the amplification of the other harmonic orders than the targeted frequencies that are present in the system, can potentially have a large impact on the system-wide harmonic level.

System modelling for harmonic studies is a complex manner, and will be investigated in this report. Furthermore, it is valuable to further understand harmonic propagation and amplifications in a power system. Moreover, the causes of anti-resonance phenomena will be analysed, with the aim of enlightening the topic, and proposing possible approaches to avoid it. That basis has led to the following problem definition, where the assessments will be conducted through modelling and simulations in DIgSILENT PowerFactory 2019.

2.1 Problem Definition

How can system-wide harmonic propagation and the causes of anti-resonance phenomena be explained, and how can the anti-resonance phenomena be avoided?

2.1.1 Objectives

On the basis of the problem definition, the following objectives have been formulated for the report;

- State of the art review of power system modelling for harmonic studies, and passive filter design.
- Investigation of system-wide harmonic propagation, including the levels in the busses in a system, and the levels within the over head lines and the under ground cables.
- Investigate the causes of anti-resonance phenomena on a system-wide level.
- Analyse how to mitigate or how to prevent anti-resonance phenomena.

2.1.2 Delimitation

The simulations conducted in this report has been conducted in DigSilent PowerFactory 2019, where the modelled used in the analysis is a balanced three phase system. The analysis is conducted in the positive sequence domain.

The system used in the main analysis in this report is a meshed grid at 400 kV. The harmonic propagation down to the lower voltage levels are out of the scope in project, and are therefore not included in the model. The frequency range of interest in this project is 50-2050 Hz, as that gives a good representation of the harmonic behaviour in both the low and high frequency range.

2.1.3 Methodology

The state of the art review, in Chapter 3, includes studies conducted, and gives an overview of modelling and simulations required to conduct harmonic propagation studies. It is based on a newly published report by CIGRE with state of the art analysis of network modelling for harmonic studies, [15]. Furthermore, the chapter includes a description of the impact the choice of study domain has on harmonic analysis.

The simulations conducted in this report is based on an example grid for harmonic propagation studies developed by Oscar Lennerhag, [16]. At Luleå University of Technology he has developed a power system model for resonance studies. The example system is intending on giving a realistic grid, where parts of the model are based on existing and planned transmission grids. The example gird is characterised by a large share of cable at a 400 kV and 220 kV level, with a first resonance frequency between 100 and 150 Hz. However, the analysis conducted is taking part of the grid, and expanding it according to the simulation conducted. Harmonic emission sources are not included in the example grid, and is thus implemented according to the studies. The mentioned example grid and the system modelling is explained in Chapter 4.

An analysis of harmonic propagation, in both a radial and a meshed system, is explained in Chapter 5. The aim of the analysis is to understand the system-wide harmonic levels in a power system, and how harmonics propagate. That includes understanding the factors affecting harmonic propagation and the harmonic levels in the system, but also understanding, not only the harmonic levels in the busses in a system, but also the levels within the overhead lines and underground cables. A method is proposed to quantify the maximum levels of harmonic voltage and currents, in a system, and to find the exact location where the highest levels can be found.

Chapter 6 presents the analysis conducted of harmonic mitigation and the anti-resonance phenomena. The focus is on the system-wide harmonic levels after the implementation of a single-tuned filter aiming to mitigate one specific harmonic order. Furthermore, it is on the impact a filter implementation can have on the harmonic levels in the bus at which the filter is implemented, the bus at which a harmonic emission source is located, and the impact it has on the harmonic propagation in the system. Lastly, an analysis of how the tuning of a single-tuned filter can reduce anti-resonance phenomena on a system-wide level, while still effectively reducing the targeted frequency, is presented.

Four Appendices are included in the report, presenting supplementary analysis conducted for both Chapter 5 and Chapter 6. Appendix A, presents the effect, changes in a system, which consequently affect the impedance in a system, has on harmonic propagation. Appendix B presents how harmonics propagate in more complex radial system, i.e. systems consisting of several paths. A supplementary analysis of harmonic propagation in a meshed system is explained in Appendix C, and supplementary analysis of the anti-resonance phenomena in a meshed system is explained in Appendix D.

Chapter 3

State of the Art

This state of the art review is mainly based on CIGRE's guide for network modelling for harmonic studies, providing comprehensive guidelines for performing harmonic distortion assessments, [15]. Furthermore, it is based on [14], and [17], which both focuses on the western part of the Danish transmission system. In all the studies, the parts relevant for the studies of this report is presented. That is done in order to give a baseline for the modelling and simulations conducted in order to conduct the analysis, that is presented in the following chapters.

3.1 Modelling Approaches and Study Domain

Harmonic studies can be preformed in either the frequency domain or the time domain, which relation can be described by the use of Fourier series, as explained in Section 1.2.1. Furthermore the studies can be conducted in a hybrid between the two mentioned domains, which is striving to combine the advantages from the two domain methods. The choice of method depends on the study requirements.

3.1.1 Frequency Domain

Frequency domain methods are the most common method for harmonic analysis. An overview of the frequency domain methods can be seen in Figure 3.1, where frequency scans and harmonic penetration studies are the most common.

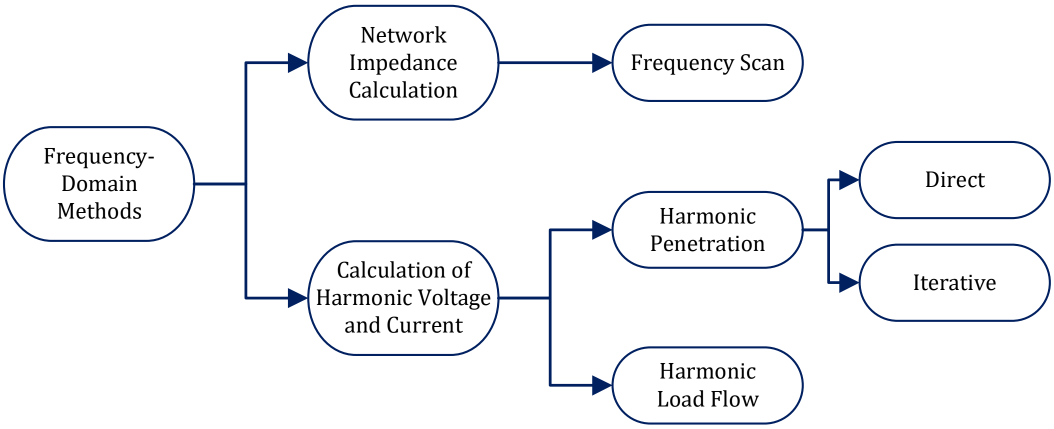


Figure 3.1: Overview of frequency domain methods, [15].

The aim of a frequency scan is to get an overview of the frequency response in a network, seen from a specific node, so the impedance is plotted against frequency. It is mathematically calculated as seen in Equation 3.1, where $[Y_h]$ is the admittance matrix, and $[V_h]$ and $[I_h]$ is the voltage- and current-vectors respectively. A value is calculated at each frequency, in a frequency scan of interest, where a 1 p.u. current is applied to a single entry in $[I_h]$, and all the other entries are zero.

$$[Y_h][V_h] = [I_h] \tag{3.1}$$

Frequency scan is a simple and effective method to detect resonance points, and is commonly used for filter design. However, it does not include non-linearity, meaning that $[Y_h]$s dependency on system voltage and current is not included, which is a limitation of the method.

The harmonic penetration method are divided into direct and iterative method. In the direct method the admittance matrix is reformulated at each harmonic order, and then any harmonic current injection is considered at that order, and Equation 3.1 is then directly solved. The influence of the fundamental and harmonic voltages of the source are then not considered. The iterative method is an extension of the direct method which iteratively recalculates the harmonic current injections and considers their dependency on the harmonic voltage.

Harmonic load flow method takes the voltage and current dependency of power components into account by recalculating the admittance matrix at every iteration and harmonic order. This requires detailed knowledge of the devices in the system. These can be solved with regular methods like Newton-Raphson or Gauss-Seidel.

Frequency domain should be used for harmonic propagation studies, impedance scans and evaluation of filters. It is a numerical robust and time-effective method, that provides sufficient accuracy for devices working in linear region, but has limited modelling of non-linear devices and control systems.

3.1.2 Time Domain

Time-domain methods are based upon using differential equations to represent system behaviour. It accurately considers nonlinear devices and their controllers, but is computationally very heavy. It can also be difficult to include frequency dependent parameters and to obtain impedance characteristics. The methods can be carried out by the use of the conventional Brute Force (BF) solution, or by fast periodic steady-state solutions.

The BF procedure is based on integration of the differential equations once the transient response has died out. However this might require integration over long periods, if the system is not sufficiently damped. The fast periodic steady-state solutions is based on Newton iterations, where only a portion of the transient response is needed to calculate the periodic signal.

Time domain should be used when modelling detailed non-linearities, AC/DC cross modulation or real-time simulations. It is a very time consuming process and impractical for larger systems.

3.1.3 Hybrid Methods

Hybrid methods, meaning a combination of the time- and frequency domain, are the most powerful methods that provide flexibility in terms of modelling. However, they are usually not available in commercial software packages. The linear part of the system will be modelled in the frequency domain, while non-linear and time-varying are modelled in the time domain. The harmonic voltages and currents are found by an iterative process with a current mismatch at non-linear nodes between the time and frequency domain. Hybrid methods have the benefits of both domains, but there is a risk of getting the disadvantages of both domains if it is not used properly as it requires knowledge of both domains and a manual interface between the domains.

3.1.4 Harmonic Domain

The harmonic domain is a general frame of reference for a steady state model which is solved using a full Newton method. The technique can explicitly represent nodes, phases, phase unbalance, linear, non-linear and time varying components, harmonics and harmonic cross-coupling effects. It is solved by linearising non-linear behaviours around a particular operation point which results in Norton harmonic equivalents. If the convergence criteria is not met, the calculated harmonic voltage will be the operation point for a new linearisation. It is a robust methodology which can model most non-linear components such as power transformers, arc furnaces, rotating machines and power electronics. It does though require considerable skill and effort in addition to a complex program to be able to represent the components and utilise the harmonic domain.

3.1.5 Sequence/Phase Domain

In harmonic studies it is a common approach to assume that the system is symmetrical, meaning the components have equal self- and mutual impedance between all three phases at the h-th harmonic, such that the harmonics follow their natural sequence, [5]. The three-phase network can then be decomposed into its equivalent sequence network, which eases the calculation burden. That results in the systems sequence impedance matrix as seen in Equation 3.2, [15].

$$Z_{0+-}(h) = \begin{bmatrix} Z_0(h) & 0 & 0 \\ 0 & Z_+(h) & 0 \\ 0 & 0 & Z_-(h) \end{bmatrix} \tag{3.2}$$

In a power system, however, there are no real components that are perfectly balanced, and the asymmetry inherent in a power system should not be simplified and studied using sequence reference frame, [10]. Field measurements indicate that especially near unsymmetrical formations, i.e. an flat formation single core HV UGC, the harmonics can be unbalanced and thus contain a portion of all three sequences. Using sequence reference frame can in such cases lead to inaccuracies of the harmonic levels, [5]. A full phase representation of the system impedance, as seen in equation 3.3 is then required, [15].

$$Z_{abc}(h) = \begin{bmatrix} Z_{aa}(h) & Z_{ab}(h) & Z_{ac}(h) \\ Z_{ba}(h) & Z_{bb}(h) & Z_{bc}(h) \\ Z_{ca}(h) & Z_{cb}(h) & Z_{cc}(h) \end{bmatrix} \tag{3.3}$$

In the case of symmetry the three self-impedances, and the six mutual-impedances, in Equation 3.3 are equal to each other. All the off-diagonal elements in the sequence impedance matrix, seen in Equation 3.2, are in that case zero, and the decoupled sequence frame can be used in the harmonic studies without any loss in accuracy, [15].

The inter-sequence couplings are related to the off-diagonal terms in Equation

3.2 and are either zero, in the case of a balanced system, or neglected, when using a decoupled sequence reference frame. However, the effects of inter-sequence couplings are especially noticeable around and at the resonance points. Then an injection of a purely positive sequence harmonic can affect the other sequences.

An accurate phase-domain model requires a geometrical description of all transmission lines and all components. It can be very time consuming to construct such a model, which is the reason why decoupled sequence frame is commonly used, despite its evident limitations.

A typical harmonic spectrum up to the 20th harmonic in the Danish transmission level, presented in [5], can be seen in Figure 3.2. The data is from measurements at Trige 400 kV substation, which is near the unsymmetrical formation of an flat formation single core HV cable going to Anholt WPP. It can be seen that there is an unbalance in some of the harmonic levels, for instance that the 11th harmonic voltage of phase B is almost twice the size of phase C. Furthermore, the third harmonic, which is often assumed to be a pure zero sequence harmonic, indicates an unbalance and thus a more diverse content in the sequence domain.

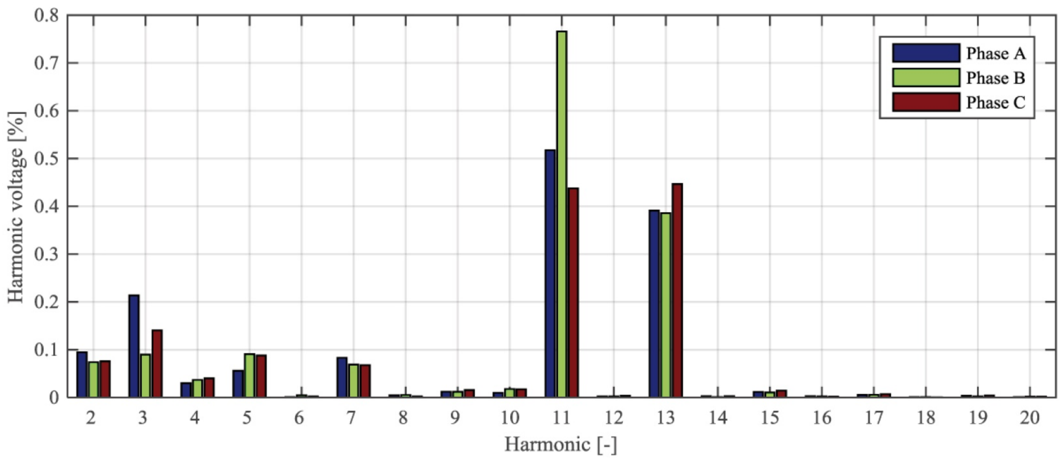


Figure 3.2: Harmonic sequence components at Trige 400 kV, [5].

The sequence domain harmonic voltages can be seen in Figure 3.3. It can be seen here that the third harmonic contains all three sequences, due to the unbalance as indicated in Figure 3.2. Furthermore, it can be seen that the 11th harmonic, which usually is expected to be of negative sequence also contains a positive sequence, which is of a non-negligible magnitude.

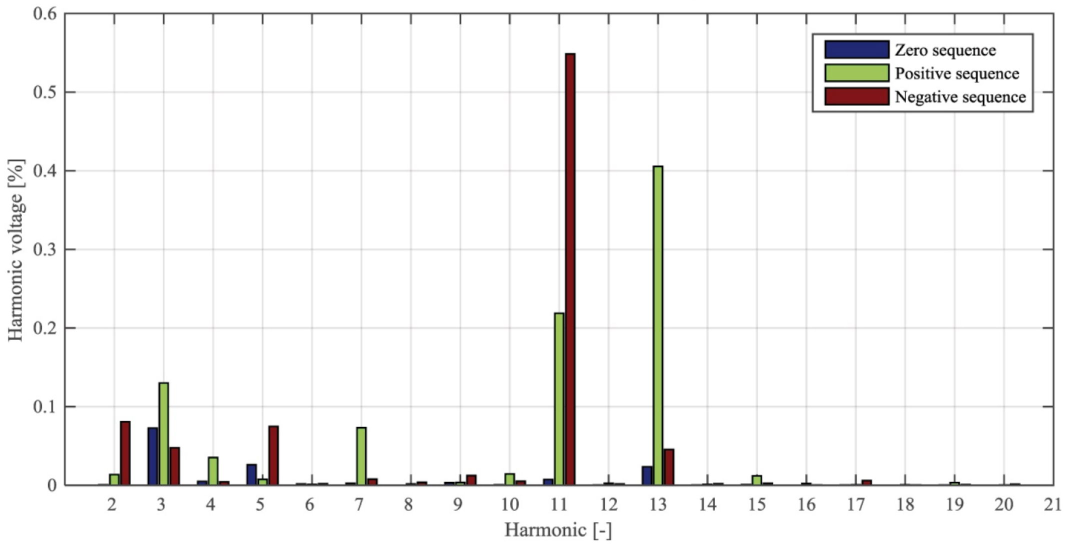


Figure 3.3: Harmonic magnitudes measured at Trige 400 kV, [5].

It was on that bases concluded that the assumptions that each harmonic order contains only one unique sequence component will lead to an underestimation of the harmonic voltage, [5].

3.2 Line Modelling for Harmonic Studies

This section explains how the modelling detail of OHLs and UGCs can affect the accuracy of the simulations of harmonic propagation in a power system. When modelling OHLs and an UGCs for harmonic studies, long-line effects, frequency dependency and line imbalance all need to be considered, as they all have an effect on harmonic propagation. Higher frequencies increase the electrical distance of a circuit, and frequency dependency affect the skin effect and the earth-return path for zero sequence currents. UGCs usually have a lower series impedance and a higher shunt capacitance than OHLs, causing resonances at lower frequencies where damping usually is lower than at higher frequencies. However, the general effect the modelling detail has on the line component is the same in what concerns OHLs and UGCs, and the affect of the modelling detail will thus be explained in parallel throughout this section.

Accurately modelling of OHLs and UGCs can be difficult as harmonic studies can be carried out during planning stages where the final parameters for the lines are not yet determined. Furthermore, the fact that the real values and the values given in the data sheet for the components often deviate, affect the accuracy. This can result in a deviation between simulation results and measurements from a power system.

Single-phase representations is based on positive sequence data and thus does represent a perfectly balanced system, and should be chosen if that complies with reality as it reduces the computation time compared to three-phase models. Three-phase models should however be chosen if a significant unbalance is present in the system. That is more common as most OHLs and UGCs are asymmetrical, including mutual impedances and different resonant frequencies for each phase. Transposition generally reduces the unbalance at fundamental frequency, but it can also increase the unbalance at that frequency and others, which can be critical if those frequencies are around the resonance points, where it can increase the harmonic voltage amplification. It is therefore important to accurately model transposition in detail for three-phase models of OHLs.

Transmission lines include both series parameters, namely resistance and reactance, and shunt parameters, namely conductance and susceptance. These parameters are in reality distributed along the length of the line, and are affected by frequency. PI-models are usually used to model lines, either with a nominal or an equivalent configuration. A nominal PI model, using lumped parameters can be sufficient for shorter lines and lower frequencies, while an equivalent PI model should be used for longer lines and higher frequencies, distributing the parameters. Cascaded models, where the parameters are partially distributed can also be sufficient. Theoretically an infinite amount of cascades is equivalent to a distributed model, so increasing the number of cascades increases the accuracy of the model, but also increases the computational time.

A nominal PI model is only capable of representing the first resonance point, as it does not include the long-line effect, as seen in Figure 3.4. The figure shows a comparison of the impedance profile of an OHL, with both distributed and lumped models, with the line lengths of 50 km and the distributed model at both 50 km and 200 km. The resonance point in the lumped model can be seen to be slightly lower in frequency than in the distributed model, and at a higher magnitude. The accuracy of a nominal PI-model can be sufficient if the frequency of interest is below the first resonance point.

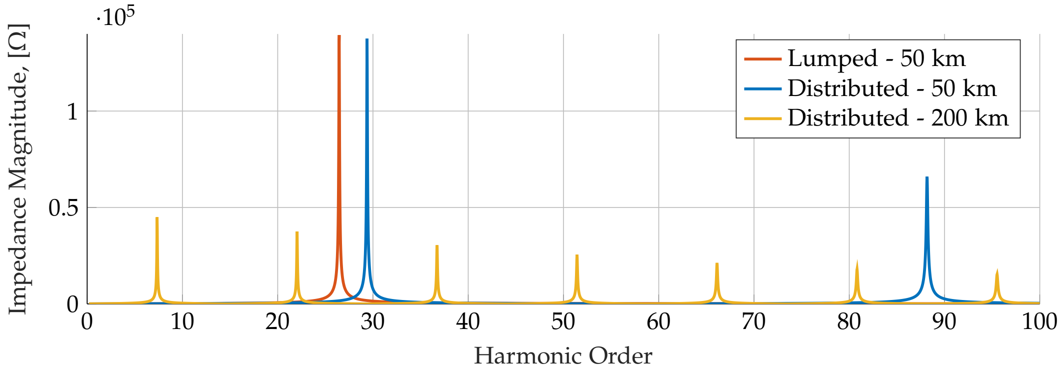


Figure 3.4: Impedance of 50 and 200 km line, with distributed and lumped parameter models, [15].

Increasing the length line in UGCs and OHLs affects the number of resonance points within a certain frequency range, and increasing the length of a line shifts the location of the resonance points to lower frequencies, which can be seen in Figure 3.4 as well. The number of resonances within a frequency range thus increases, however the magnitude of them decreases as the increased resistance of a longer line will cause higher damping of the resonant peaks.

Skin effect is only noticeable in the resonant points, and reduces the value of the resonant points, and thus provides an increased damping, as seen in Figure 3.5. The damping is increased with frequency, and neglecting skin effect will introduce an increased error at higher frequencies. At high frequencies there is also a small increase in the resonant frequency, seen at the third resonant point in Figure 3.5, as the inductance of the phases are reduced by the skin effect.

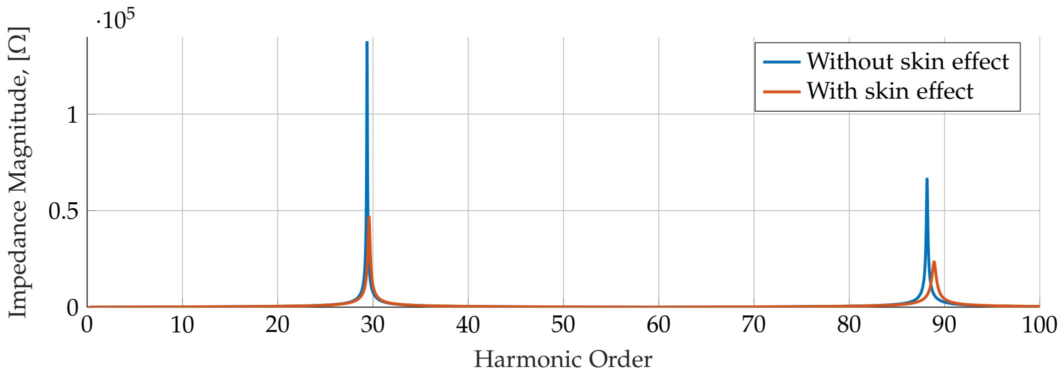


Figure 3.5: Change in positive-sequence impedance in an OHL with and without skin effect, [15].

Higher earth resistivity causes higher positive sequence impedance at the parallel resonance points. The increase in impedance is larger at higher frequencies, but the difference is not significant enough to have an impact. The zero sequence impedance is though highly affected by earth resistivity as seen in Figure 3.6, and is highly dependent on frequency. Higher earth resistivity leads to significantly lower damping throughout the entire frequency spectrum. It is therefore important to accurately represent earth resistivity in the case when zero sequence currents are present in the system from unbalance or from zero sequence harmonics.

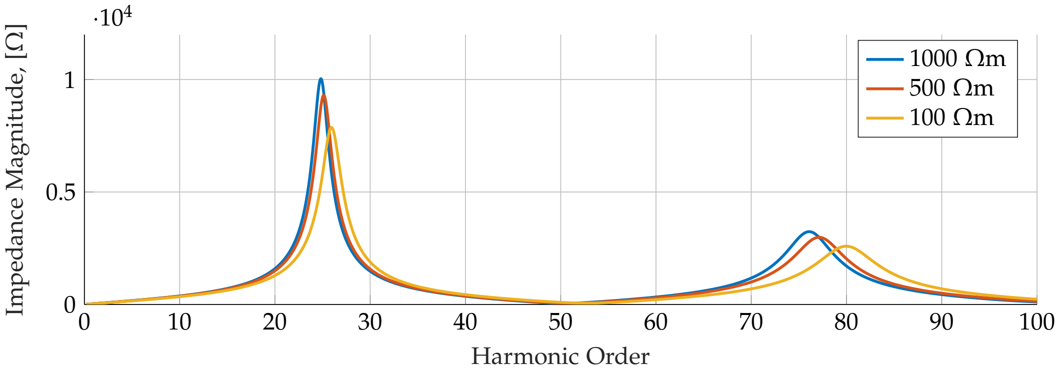


Figure 3.6: Change in zero-sequence impedance in an OHL when earth-resistivity is varied, [15].

The conductor height above ground of an OHL does not have a significant impact on harmonic impedance analysis, as it only causes an insignificant frequency shift in resonant point with a 20% height change around the average conductor height. However, the layout of the conductor with respect to each other can have a larger impact, and so does the layout of the cables, as seen in Figure 3.7. The layout of the UGC, meaning the formation and structure, affects the frequency, the magnitude and the number of resonances of the positive sequence impedance within a frequency range. The zero sequence impedance is though not affected.

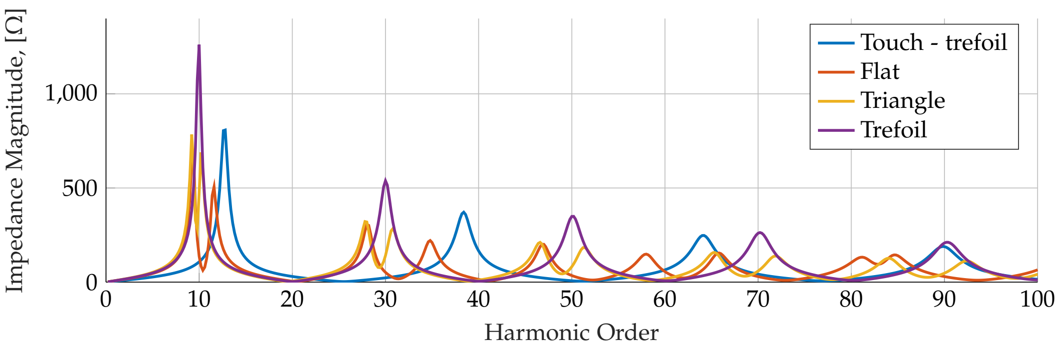


Figure 3.7: Positive sequence impedance of an UGC with varying cable layout, [15].

The conductor radius and the insulation thickness affects the capacitance of an UGC, and thus shifts the resonance points. An increase in radius will increase the capacitance which will cause a downshift in the resonant frequency. That is mainly regarding the positive sequence, as the zero sequence only slightly impacts the amplitude of the resonance points. Regarding the insulation, increased thickness decreases capacitance, which affects both amplitude and frequency of the positive sequence resonance, and only the amplitude of the zero sequence. The positive sequence harmonic impedance with different insulation thicknesses can be seen in Figure 3.8.

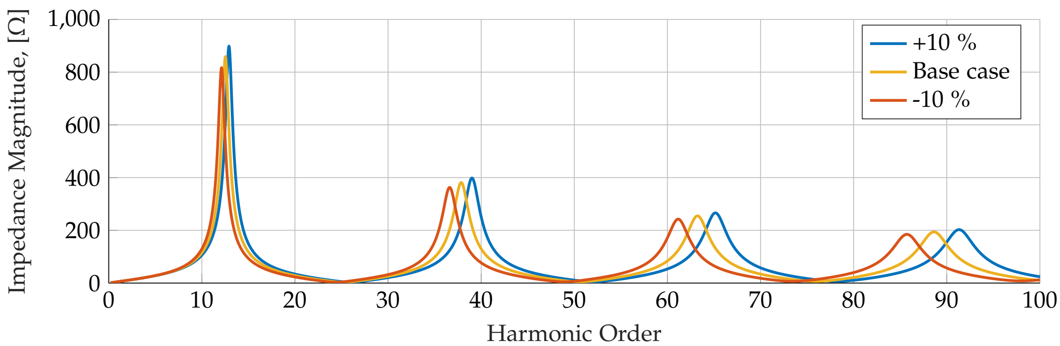


Figure 3.8: Positive-sequence harmonic impedance of UGC with varying insulation thickness, [15].

Summary

It has been seen that OHLs and UGCs should be modelled with distributed parameters, if a focus is led after the first resonance point, and it should be done with three-phase models if any unbalance is present. Skin effect should be included if the amplitude of the parallel resonance points are important and if reviewing the behaviour at high frequencies is relevant. An average value for the conductor height is sufficient, but cable layout needs to be accurately modelled.

3.3 Component Modelling for Harmonic Studies

In this section, the state of the art of the component modelling, relevant in this project is explained.

3.3.1 Equivalent Grid

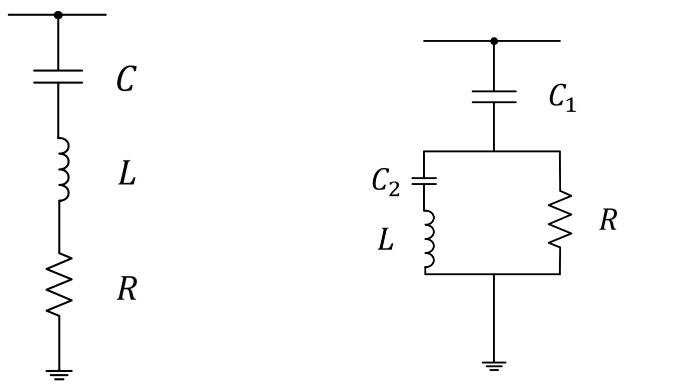
An equivalent grid can be used to reduce the computational burden and only include the area of interest. It should give an accurate representation of the existing grid and the amount of reduction can therefore be different from system to system. Equivalent grids are generally modelled as either a Thévenin or a Norton equivalent. They have effectively identical performance, and can be converted from one to another. The Thévenin equivalent consist of an ideal voltage sources in series with an impedance matrix and the Norton consists of current sources in parallel with an admittance matrix. Background harmonic distortion can be included in the equivalent grid based on the analyses conducted.

3.3.2 Harmonic Emission Source

Harmonic emission sources can be modelled as both Thévenin and Norton equivalents circuits. Traditionally harmonic emission sources have been modelled as Norton equivalents, without harmonic impedance, meaning an ideal current source. This was because the harmonic levels were low and dominated by LCCs and diode rectifiers, where a constant current source was a reasonable assumption. The increase of harmonics from converter-based devices has necessitated a more accurate representation including harmonic impedance. It will thereby include interactions between the harmonic emission source impedance and the system impedance, which can change resonances and the level of emissions to the system. The harmonic impedance in the equivalent circuit can be modelled depending on the device it is representing to obtain the best accuracy, and the complexity of the model will consequently increase as well.

3.3.3 Passive Harmonic Filter

Passive filters are the most common form of harmonic mitigation. They consists of resistive, inductive and capacitive components, which are combined to form a resonant circuit at the target frequency as well as being able to introduce resistive damping to the system. The components are modelled as lumped representations with linear susceptance or impedance, as any possible non-linearity like saturation, can be neglected for steady-state harmonic studies. Two commonly used filters can be seen in Figure 3.9, namely a single-tuned filter and a c-type filter.



(a) A single-tuned filter configuration.

(b) A c-type filter configuration.

Figure 3.9: Commonly used filter configurations.

The introduction of filters will affect the system impedance, which can be seen in Figure 3.10, where the previously mention filters are introduced to target the 5th harmonic order.

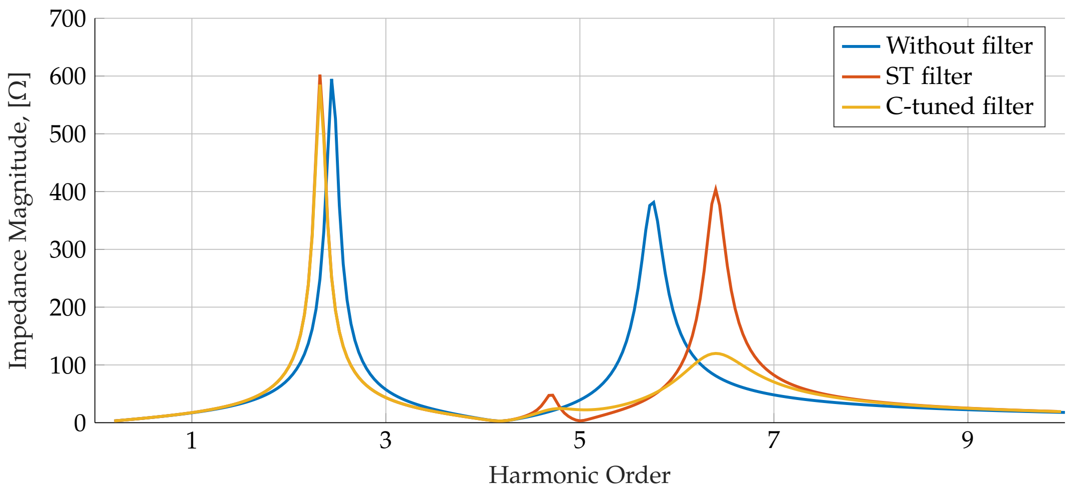


Figure 3.10: Impedance magnitude of a system with single-tuned and c-type filters implemented, [15].

It can be seen that the interaction between the single-tuned filter and the system causes a spike at a harmonic order a little lower than the 5th harmonic. This effect is seen to be reduced with a c-type filter, as the resistor in parallel with the reactor, have a dampening effect on the resonance points in the system around the target frequency. The filter configuration and the effect the filter has on the system impedance should be considered when introducing these to a system.

Chapter 4

System Modelling

This chapter introduces the system used in the analysis in this report, which is based on an example grid developed by Oscar Lennerhag. The model used is a simplified version of the mentioned example grid. The model, as well as the modelling detail required to conduct the analysis, is explained. Furthermore, the domain at which the analysis is chosen to be conducted in, is explained.

4.1 Example Model

The example grid used in the analysis is developed by Oscar Lennerhag, [16], and is, amongst others, developed for harmonic propagation studies. The system can be seen in Figure 4.1, and is characterised by a large share of UGCs at a 400 kV and 220 kV level. It has a first resonance frequency between 100 and 150 Hz.

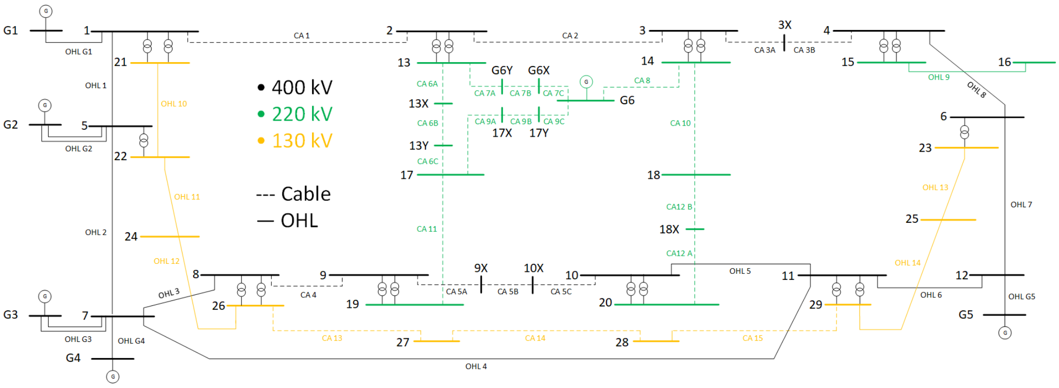


Figure 4.1: Single line diagram of example grid developed by Oscar Lennerhag, [16].

The grid is partially based on an existing grid, and the line types included, as well as the UGCs, the cable formation and tower types are based on a typical existing power systems. The system is fed by large generation units, representing hydro and nuclear generation, mainly implemented in the western part of the system through OHLs. They are modelled as network equivalents, at the buses G1 to G5. The loads in the system is implemented in radial systems at lower voltage levels, and are inductive with an angle of around 30 degrees. Details concerning the example grid can be found in the report written by Oscar Lennerhag, [16].

4.2 Modelling Approach

The system used in the analysis in this report is, as mentioned, a simplified part of the mentioned example grid, and it is adapted according to the analysis conducted. The focus of the report lies on anti-resonance phenomena and in relation to this, the system-wide harmonic levels in transmission systems, and harmonic propagation and amplifications. Therefore only the 400 kV system will be included in the analysis. Furthermore, no network equivalent for the lower voltage levels are implemented, which would be necessary if power flows at fundamental frequency was of interest. This implies that none of the loads or the distribution systems are included, as it is not of interest to review how harmonics propagate down to lower voltage levels or, vice versa, from lower voltage levels up to higher voltage levels. Furthermore, none of the shunt reactors that are included in the original model, are included in the model used in the analyses. They are originally implemented to compensate for the reactive power generated by the UGCs. Excluding the loads, the network equivalent for the lower voltage levels and the shunt reactors will affect the impedance, but not have a big impact on the harmonic propagation in the cables and OHLs at transmission level, which is the focus area. Furthermore, excluding the shunt reactors increases the fundamental voltage in the system. It is however not of importance that the fundamental voltage is maintained at 1 pu, as that does not affect the harmonic propagation.

The generation units in the model, meaning the network equivalents, implemented at the busses G1 to G5, are included and thus contributes to the short circuit power and affects the frequency dependent impedance of the system. The simplified system used in the analysis in this report can be seen in Figure 4.2.

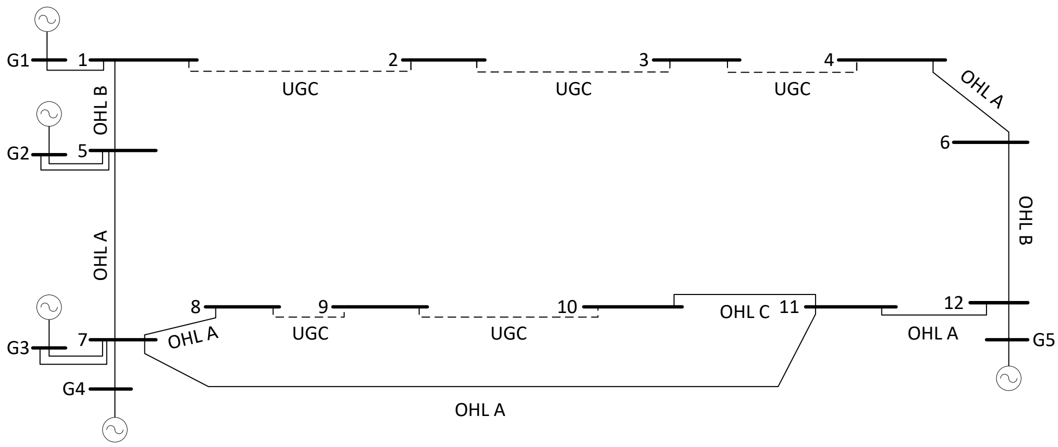


Figure 4.2: Single-line diagram of meshed example grid used in the simulations.

The analysis in this report is conducted in a balanced sequence domain, where the positive sequence is analysed. This will be an approximation of a real system, where information about coupling and unbalance is lost. That effects the impedance of the system and the harmonic levels. The principal of harmonic propagation and anti-resonance phenomena can however still be described, and the results and conclusion will not be affect and can be applied to more advanced systems. The focus of the report can therefore be carried out in a balanced sequence domain which would simplify the calculations and explanations.

4.3 Component Modelling

The system used in the analysis in this report, does, as explained in Section 4.2, consist of OHLs, UGCs, generation units, which represents the equivalent grid, and harmonic emission sources. The modelling, and the simplifications made, of those components, are explained in this section. Furthermore, the filters implemented, introduced to the system in Chapter 6, are explained.

4.3.1 Overhead Lines

The OHLs included in the system is built based on the data available from the example grid. Equivalent pi-models with distributed parameters are used. Parts of the model is approximated, such as the geometric mean radius (GMR) values required in the modelling in DIgSILENT PowerFactory. That value has been calculated based on the conductor diameter and the number of strands. As the number of strands in all the cases is 61, the GMR is calculated as seen in Equation 4.1, [18].

In the equation d is the conductor diameter, and the conductor is assumed to be solid and circular.

$$GMR = 0.772 \cdot \frac{d}{2} \tag{4.1}$$

The OHLs are all perfectly transposed as it is modelled in a balanced sequence domain. The earth wires will therefore not have any effect either. The OHLs that are included in the model have the impedance and admittance per km as defined in Table 4.1.

	Resistance [Ω/km]	Inductance [mH/km]	Conductance [μS/km]	Capacitance [μF/km]
OHL A	0.0186	0.9507	0	0.0123
OHL B	0.0144	0.8723	0	0.0133
OHL C	0.0272	1.0014	0	0.0116

Table 4.1: Overview of the parameters of the OHLs included in the model.

4.3.2 Underground Cables

The UGC are also modelled as equivalent pi-models with distributed parameters and the earth wires are neglected as well. The UGCs included in the model is simplified to be all of the same type and formation. This is done as they would have added complexity to the modelling, but they would not have changed the explanation for harmonic propagation or anti-resonance. Sheets has for the same reason been fully cross bonded and removed from the Z metrics in DIgSILENT PowerFactory with a built-in "reduce" function.

The formation of the UGCs used, can be seen in Figure 4.3. Each of the three foiled formations can be seen to be placed 1 m apart, and therefore have little impact on each other. The system is therefore modelled as three separate three foiled formations, and the earth wires are, as mentioned, not included.

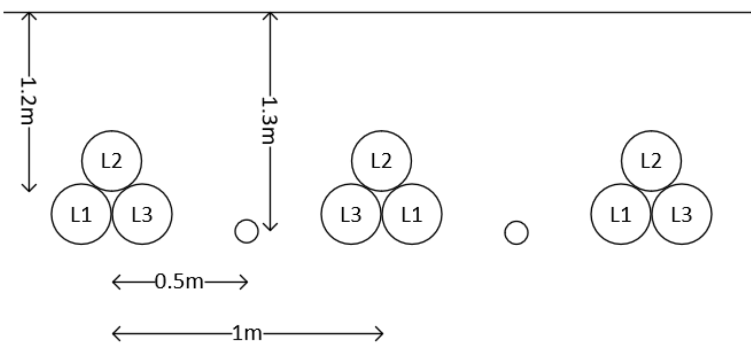


Figure 4.3: UGC formation with three cable grouped and two earth wires, [16].

The UGC included in the model have the impedance and admittance per km as defined in Table 4.2.

	Resistance [Ω/km]	Inductance [mH/km]	Conductance [μS/km]	Capacitance [μF/km]
UGC	0.0126	0.3196	1.5109	0.2109

Table 4.2: Overview of the parameters of the OHLs included in the model.

4.3.3 Generation units

The generation units, which represents the equivalent grid in the system, are modelled as Thévenin equivalents, based on the data provided about the example grid. They do not include background harmonic distortion, as it is not in the focus and would add further complexity.

4.3.4 Harmonic Emission Source

Harmonic emission sources are implemented in the model by the use of Norton equivalent circuits, injecting current harmonics of specific amplitudes and frequencies. They will not include a harmonic impedances, and can therefore be modelled as an ideal current source. This is done in order to reduce interactions in the system impedance and to reduce the complexity, which is outside the scope of the report. The locations and the number of sources, are implemented according to the analysis conducted. The harmonic load flow simulations conducted are, as mentioned, balanced harmonic load flows, and the harmonic current sources implemented are balanced. The sequence component of harmonic injections that then can be implemented is positive and negative odd integer harmonic orders. The magnitude of the output of the current source is 1 kA in the meshed system, which is defined as 1 p.u. This will give a high level of harmonic voltage, but will not affect the results and conclusions.

4.3.5 Filter Tuning of Single-Tuned Passive Filter

The filter used in the analysis in this report, is a single-tuned passive filter, as it is usually tuned to lower frequency harmonic orders and has an increased possibility of causing anti-resonance phenomena. It will therefore be ideal in the analysis of explaining the causes for the anti-resonance phenomena. The filter is implemented in DIgSILENT PowerFactory by the use of an R-L-C shunt element, where there are two input modes. Either the rated reactive power (L-C) and the quality factor can be adjusted, or the resistance, the capacitance and the inductance can be adjusted. The first mentioned method has been used in this report.

The rated reactive power at fundamental frequency, is related to the rated reactive power of the capacitor and the reactor as seen in Equation 4.2.

$$Q_{Rrea} = Q_{tot} \cdot \left(\left(\frac{f_{res}}{f_{nom}} \right)^2 - 1 \right) \quad , \quad Q_{cap} = Q_{tot} \cdot \left(1 - \left(\frac{f_{nom}}{f_{red}} \right)^2 \right) \tag{4.2}$$

The reactive power of the capacitor and the reactor is each defined as seen in Equation 4.3.

$$Q_{rea} = \frac{V^2}{X_{rea}} \quad , \quad Q_{cap} = \frac{B_{cap}}{V^2} \tag{4.3}$$

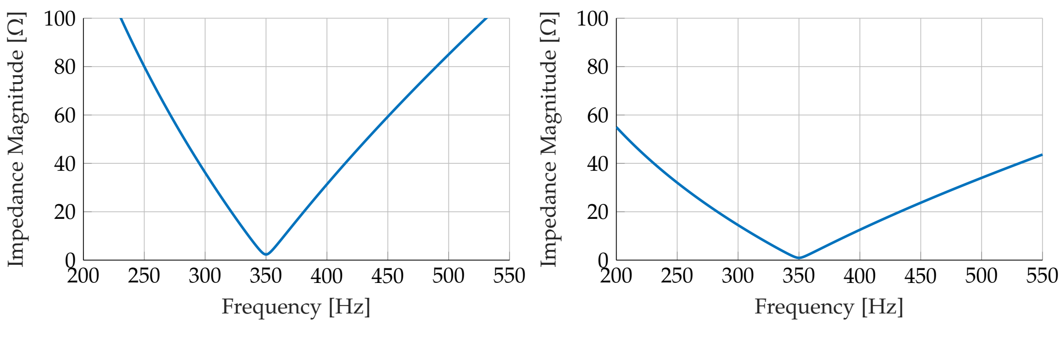
In the equation V^2 is the rated voltage in the system, and X_{rea} and B_{cap} is the reactance and suseptance of the filter respectively. The inductance and the capcitance of the filter is thereby defined as seen in equation 4.4.

$$L = \frac{X_{rea}}{2 \cdot \pi \cdot f_{nom}} \quad , \quad C = \frac{B_{cap}}{2 \cdot \pi \cdot f_{nom}} \tag{4.4}$$

It can thus be seen that increasing the rated reactive power increases the capacitance in the filter, while it reduces the inductance. Furthermore, it also reduces the resistance, which is defined as seen in Equation 4.5.

$$R = \frac{X_{rea}}{q} \tag{4.5}$$

It can be seen in the equation that when the reactance is reduced, which occurs when the reactive power is increased, the resistance is reduced as well, if the quality factor, q is maintained constant. Increasing the rated reactive power of the filter thus changes the impedance of the filter as seen in Figure 4.4.



(a) Impedance magnitude of filter with a rated reactive power of 200 MVA and a quality factor of 50.

(b) Impedance magnitude of filter with a rated reactive power of 500 MVA and a quality factor of 50.

Figure 4.4: The impact an increase in reactive power has on the impedance magnitude of a single-tuned filter.

It can be seen that if the reactive power of the filter is increased the impedance in close vicinity to the targeted frequency is reduced. The effect filter tuning, and changing the impedance of the filter, has on anti-resonance phenomena, is explained in Chapter 6.

4.3.6 Summary

The modelling approach chosen for the system, both the domain and the components have been described in this chapter. The analysis will be conducted in balanced sequence domain, which will change the impedance of the system and thereby the harmonic propagation and anti-resonance phenomena. The explanation of harmonic propagation and anti-resonance will however not be affected. Several simplifications have been done in order to reduce the complexity of the system at the cost of changing the system impedance. The resonance points at low frequencies between 100 and a 150 Hz have however not been affected in frequency as seen in Figure 4.5, which is an impedance scan seen from Bus 1 of the meshed system.

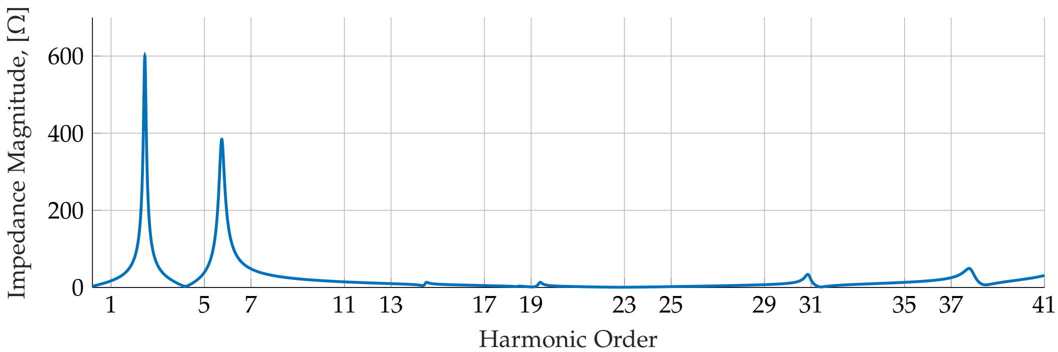


Figure 4.5: Impedance magnitude of the meshed system seen from Bus 1.

Chapter 5

Harmonic Propagation Studies

This chapter explains how harmonic currents and voltages propagate through a power system. Firstly harmonic propagation in a radial system is explained, and thereafter, the propagation in a meshed system is explained. The analysis of harmonic propagation not only focuses on the resulting harmonic levels in the busses in a system, but also on the levels within the OHLs and the UGCs. In that regards, a method to calculate the maximum harmonic levels in a system is presented in the end of this chapter.

More details on how the system impedance is affected by changing the system parameters, and how that affects the harmonic propagation, can be found in Appendix A. Furthermore, an analysis of how the resulting harmonic levels in the system are when several harmonic emission sources are present, or if the system itself is expanded, can be found in Appendix A. The simulations conducted for the analysis in this chapter is conducted in PowerFactory, and the models used are based on the mentioned example grid developed by Oscar Lennerhag, [16], explained in Chapter 4.

5.1 Harmonic Propagation in Radial Systems

A radial part of the meshed model, explained in Chapter 4, is in this section used to explain the basics of how harmonics propagate through a radial power system. How harmonics are reduced or amplified from one busto another, and what determines how big the amplification and reduction is, is explained in detail. Furthermore, the harmonic levels within a line is reviewed. Firstly the system used in the analysis is explained, and thereafter, the system impedance and the harmonic propagation is explained in detail.

5.1.1 Explanation of the Radial System

The radial part of the meshed system that is used in the analysis, can be seen in Figure 5.1, and includes the 400 kV Bus 1, 5 and 7, meaning the western part of the system explained in Chapter 4.

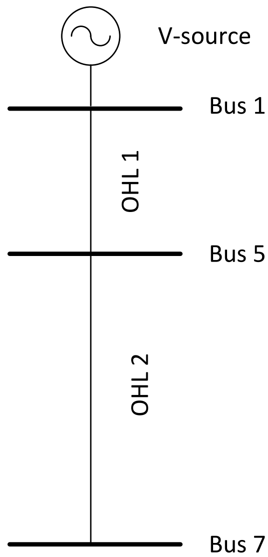


Figure 5.1: Single-line diagram of radial system.

The parameters of the two OHLs included in the radial system can be seen in Table 5.1. The two OHLs are of different types, and it can be seen that OHL 1 is shorter than OHL 2. It has a lower resistance, inductance and capacitance, but it should be noted that the capacitance is actually higher per km.

Table 5.1: Parameters of OHL 1 and 2.

	Type	Length [km]	Resistance [Ω]	Inductance [mH]	Capacitance [μF]
OHL 1	B	25.3	0.3643	22.07	0.3365
OHL 2	A	41.6	0.7738	39.55	0.5117

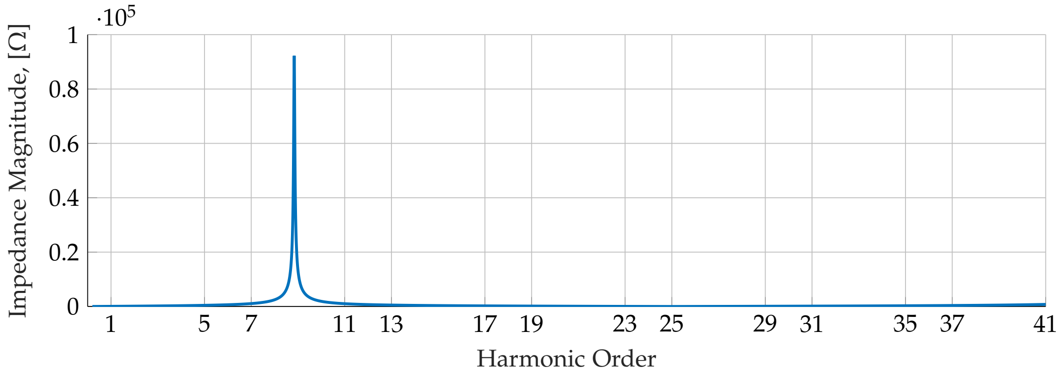
An equivalent grid is connected to Bus 1, and it is identical to the equivalent grid, connected to Bus G1, in the meshed system. That equivalent grid is set to 400 kV, and has a Thévenin equivalent impedance, which is inductive and results in a short circuit power of 3807 MVA. A harmonic emission source is implemented in model at Bus 7. It emits a harmonic currents at a magnitude of 0.72 kA, which is set to the current base for the radial system, and will therefore be equal to 1 p.u.

The harmonic orders injected in the system are positive sequence harmonics of odd integers, up to the 41st harmonic order. The range is chosen to give a good explanation in the variation of low and high order harmonics. Furthermore, only odd integers are included in order to give a good resemblance to the harmonics present in a power system, and the triplen harmonics are excluded as the power flow conducted is balanced.

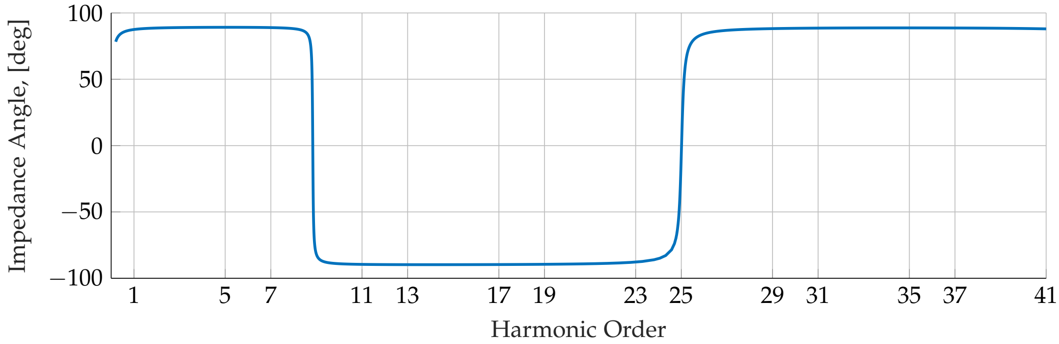
The contribution the impedance of the OHLs have on the total system impedance is in this case small compared to the contribution from the external grid, which is determined by the voltage level and the short circuit power. However, the impedance of the OHLs and the impedance of the external grid all contribute in the impedance profile, which affect harmonic propagation. The effect of changing the parameters of the OHLs, replacing them by cables, which are more associated with harmonic amplification, and changing the short circuit power are demonstrated in Appendix A. The propagation of the harmonic currents and voltages in the system, and how the impedance of the system affects the propagation, is explained below.

5.1.2 Explanation of Harmonic Propagation

Harmonic propagation depends on the system configuration and the system impedance. Both the magnitude and the angle of the impedance of the radial system seen from Bus 7, can be seen in Figure 5.2. The parallel resonant point can be seen to be a bit below the 9th harmonic and the series resonant point is at the 25th harmonic. The fact that the resonant points do not occur at the frequencies of the harmonic orders injected in the system is not of importance when explaining the concept of harmonic propagation. The points in vicinity to the resonant points, and the points at which the angle of the impedance are different, namely the inductive and capacitive region, will be shown to demonstrate the amplifying and reducing behaviour of the harmonics.



(a) Impedance magnitude seen form Bus 7.

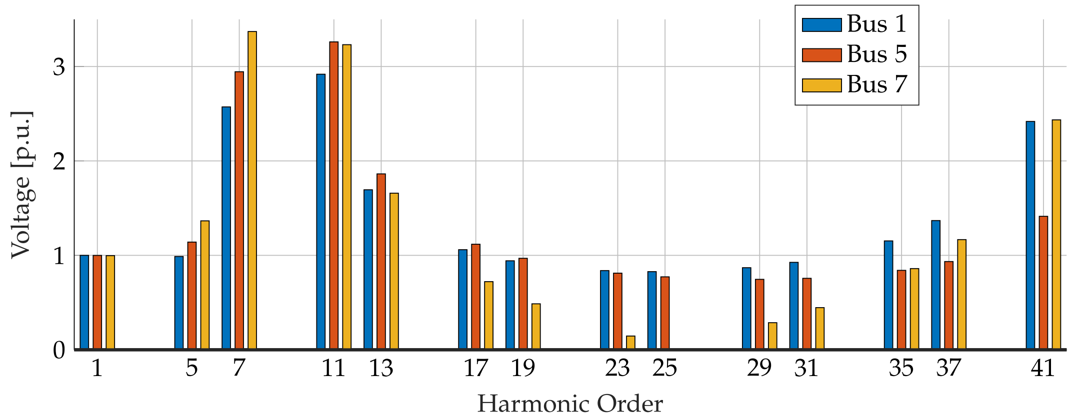


(b) Impedance angle seen from from Bus 7.

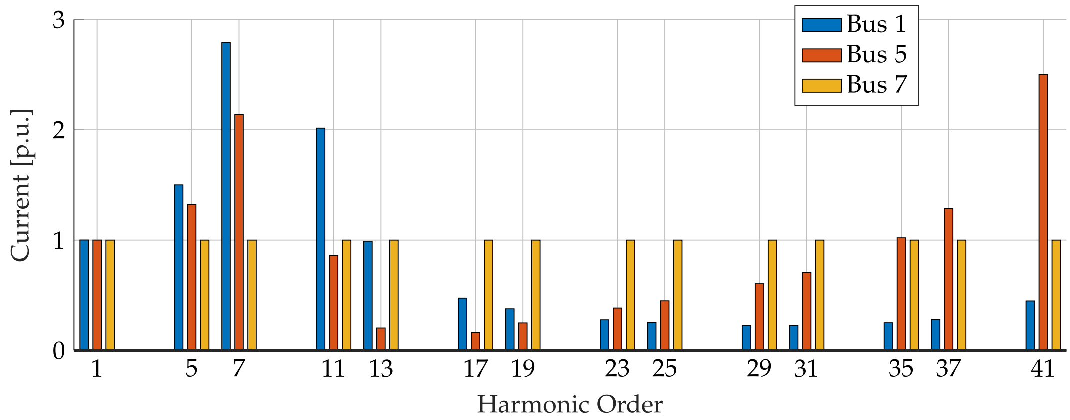
Figure 5.2: Impedance magnitude and angle seen from Bus 7 in the simple radial system.

It can be seen in Figure 5.2b that the impedance is inductive in the lower frequency range, prior to the parallel resonant point, and in the higher frequency range, after the series resonant point. Furthermore, it can be seen to be capacitive in between the two points.

The harmonic voltage in the three busses in the system can be seen in Figure 5.3a, where it is seen that the amplitude at Bus 7 increases and decreases with the impedance, as the current in Bus 7 is defined by the harmonic emission source and is constant. That can be seen in Figure 5.3b, as the harmonic current magnitude from Bus 7 is 1 p.u. for all the harmonic orders. At the frequencies where the impedance is larger, the voltage is thus also larger, and vice versa.



(a) 7th harmonic voltage magnitude at each bus in the system.

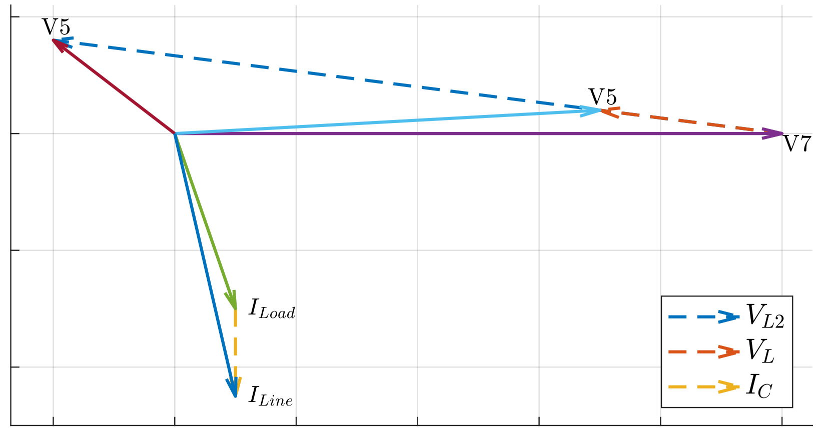


(b) 7th harmonic current magnitude through each bus in the system.

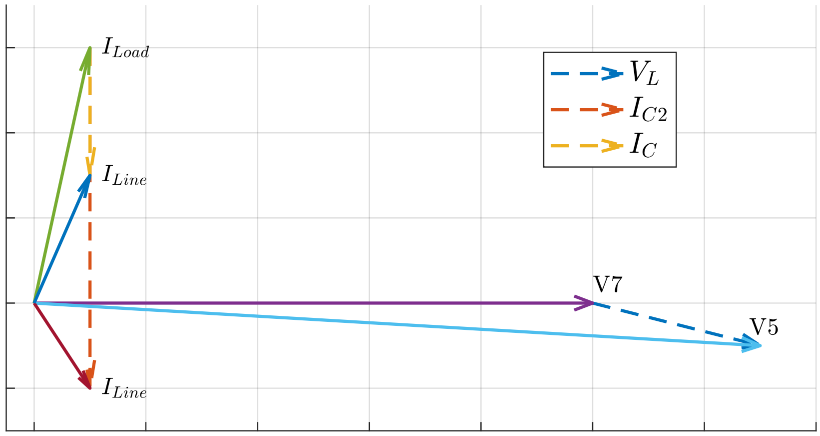
Figure 5.3: 7th harmonic voltage and current in the three busses in the simple radial system, when a harmonic emission source is implemented in Bus 7.

The harmonic propagation from Bus 7 to Bus 5 is dependent on the path between the two busses, meaning the impedance of OHL 2, and the magnitude and angle of the harmonic voltage in Bus 7. The voltage magnitude in Bus 7, and its angle compared to the current, depends solely on the impedance. It is proportional to the impedance magnitude, and it will lead the current in the inductive region, meaning that the power factor is inductive, and it will lag the current in the capacitive region, meaning that the power factor is capacitive. Furthermore, the voltage angle is proportional to the angle of the impedance. This results in the voltage at Bus 7 which has a great impact on the propagation.

The propagation through OHL 2, can be described as seen in Figure 5.4, which is a vector diagram of the voltage and current, with a inductive and capacitive power factor respectively.



(a) Vector diagram with inductive power factor.



(b) Vector diagram with capacitive power factor.

Figure 5.4: Vector diagrams demonstrating harmonic voltage and current amplifications and reductions.

I_C, seen in the figures, represents the change in current through a line, in this case through OHL 2, which depends on the voltage across capacitance in the OHL. V_L represents the voltage change throughout the OHL, which depends on the current through the inductive and restive part of the OHL. It can be seen that I_C increases the current flowing in the OHL when the power factor is inductive while it reduces the current when the power factor is capacitive. Likewise, V_L will increase the voltage across the OHL with capacitive power factor and reduce it with inductive power factor. It is seen that V_{L2}, which represents the voltage change when the voltage is low and close to zero, that a 180 degree phase shift can occur and the voltage will start to increase. That is because the voltage lags the current, meaning that the power factor is capacitive. It can similarly occur for the current, when the power factor is capacitive, as seen from I_{C2} where the current is low and a phase-shift occurs. To summarise;

- Voltage will decrease when the power factor is inductive, while the current will increase.
- Voltage will increase when the power factor is capacitive, while the current will decrease.
- Power factor can change from inductive to capacitive when voltage is low.
- Power factor can change from capacitive to inductive when current is low.

This regards the change in the RMS current and voltage through a line. The propagation gains of the harmonic voltage, meaning the gain from one bus to another, can thus be seen to be above 1, when the power factor is capacitive, in this case in Bus 7, and to be below 1, when the power factor is inductive. This is unless the power factor changes within the line. The explained change in the harmonic current and voltage, within a line, is demonstrated graphically in Figure 5.5, where a circle describes the waveform with regions defining if the power factor is inductive or capacitive.

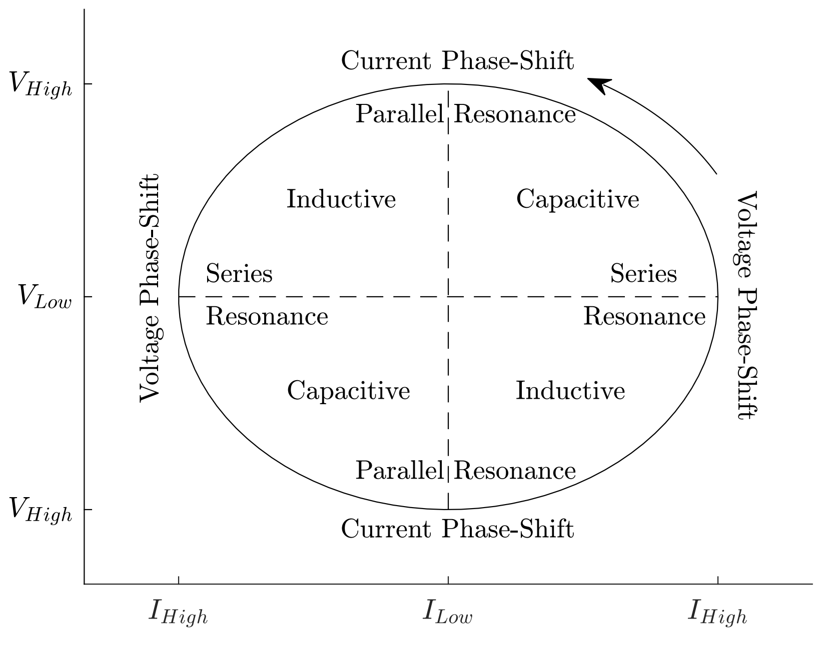


Figure 5.5: Graphical illustration of harmonic propagation through a line.

The initial point in the circle, meaning the harmonic signal in the beginning of a line, depends on the amplitude of the harmonic voltage and current, and whether the power factor is inductive or capacitive in that point. A harmonic voltage through a line will change, as demonstrated, anti-clockwise around the circle, changing in magnitude and angle. A phase-shift in the corresponding harmonic current will occur when the voltage is capacitive and at maximum magnitude. A voltage phase-shift, on the other hand, will occur when the harmonic current is at a maximum magnitude. The starting point of the line, connected to the harmonic emission source, will be, as mentioned, decided solely by the impedance seen from that bus. It can be seen in the figure, that parallel resonances will correspond to a voltage phase-shift as the voltage is at its maximum at this point. Series resonances will correspond to a phase-shift as voltage will be close to zero and current will be at its maximum.

The voltage propagation throughout an OHL can therefore be seen as a sinusoidal waveform. To illustrate this, a 150 km long line with the properties of OHL 2 is modelled and the harmonic voltage throughout the line can be seen in Figure 5.6, where the negative voltage values implies a phase shift in the voltage, namely from inductive to capacitive. Furthermore, the change in slope, indicates a current phase shift, from capacitive to inductive.

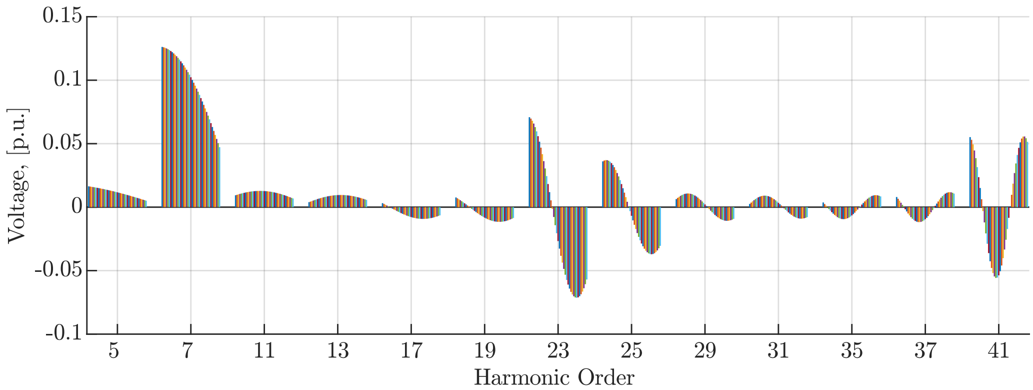


Figure 5.6: Voltage in a 150 km OHL corresponding to OHL 2 from Bus 7 to Bus 5. Negative voltage indicates a voltage phase-shift and a change in the slope indicates a current phase-shift.

The propagation of the voltage, meaning the change in the harmonic voltages through the line, is seen in the figure from Bus 7 which is the leftmost value at each harmonic, to Bus 5, which is the rightmost value at each harmonic. The values in between the busses represent measurements along the line which are 3.75 km apart. It can be seen to follow a sinusoidal waveform, where its wavelength can be calculated from Equation 5.1.

$$\lambda_h = \frac{v_s}{f_h} \tag{5.1}$$

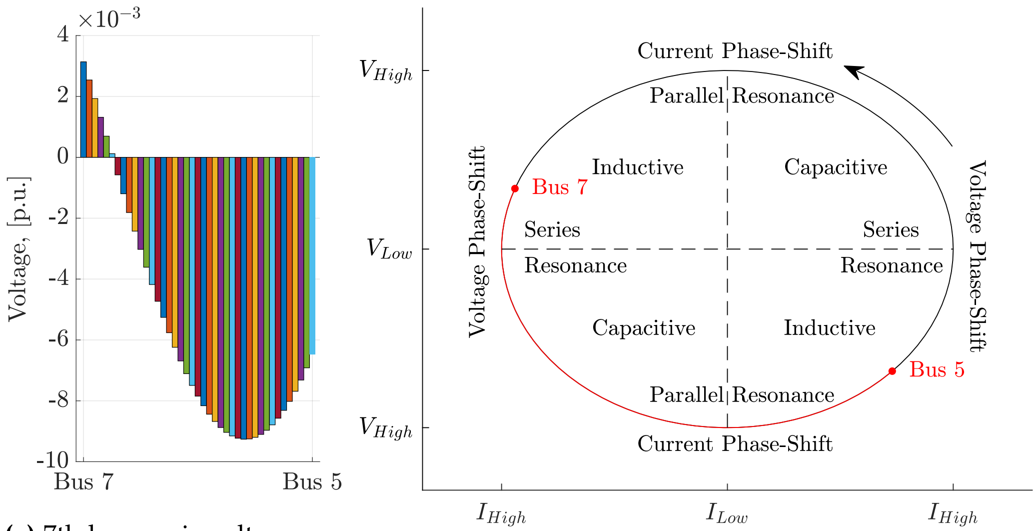
In the equation, λ_h is the wavelength for a specific harmonic, v_s is the velocity of the electric signal in the line, and f_h is the frequency of the harmonic order. The velocity v_s can be calculated for a loss-less line as seen in Equation 5.2.

$$v_s = \frac{1}{c_0 \cdot \sqrt{L \cdot C}} \tag{5.2}$$

In the equation, c_0 is the speed of light, L is the distributed inductance per unit length and C is the distributed capacitance per unit length. The wavelength and the length of the line thereby determines the degree of change occurring between the two busses. An example can be seen for the 5th and the 41st harmonic, which have a wavelength calculated to 1172 km and 143 km respectively. It is seen that the 41st harmonic completes a full period in the 150 km OHL, while the 5th harmonic completes one eighth of a period.

A significance difference can be seen between the voltage in the busses and through the line. The line can therefore be exposed to higher voltage and currents than the busses. The extra stress exerted on the line will be analysed further in Section 5.3, where a method to calculate the levels through the line is proposed.

A clearer review of the harmonic voltage level of the 17th order throughout the long line, can be seen in Figure 5.7, which is used as an example to explain, how the harmonic voltage varies, in more detail.



(a) 7th harmonic voltage variation throughout the long line.

(b) Graphical illustration of the change in the 17th harmonic voltage throughout the long line.

Figure 5.7: Variation in 17th harmonic voltage throughout the 150 km long OHL.

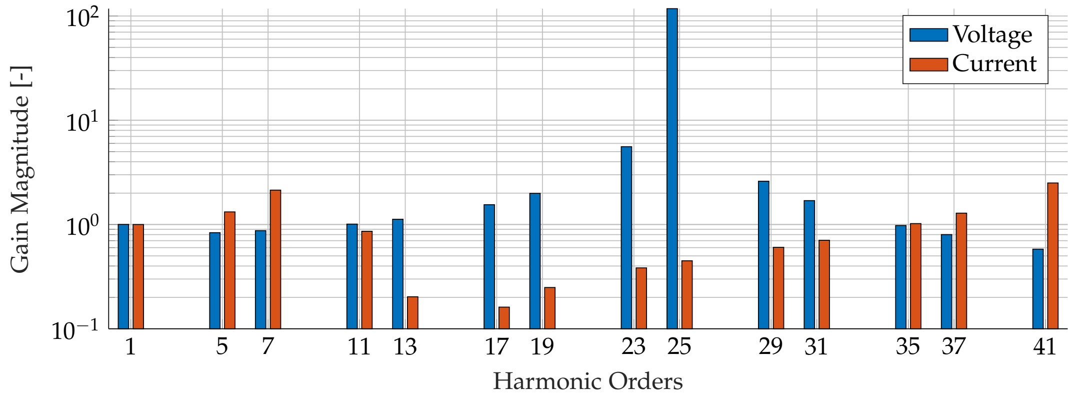
It can be seen in Figure 5.7a how the harmonic level is reduced and increased in magnitude, and how the angle shifts varies through the line. It can be seen to initially be inductive, and of relative low voltage magnitude. Thereafter, it can be seen that the harmonic voltage level is zero at a point in the line. It can also be seen that the voltage has phase shifted in the end of the line, and is significantly amplified in magnitude. In Figure 5.7b, it can be seen that the propagation follows the behaviour explained by the circle. It can be seen to initially be in the inductive region, reduce in amplitude, and then in the capacitive region, increasing in amplitude, and lastly in the inductive region, reducing in amplitude again. This sinusoidal amplification in magnitude demonstrates the importance of the measuring point at which the harmonic level is measured, as the RMS value of the harmonics are different at different locations throughout a line.

5.1.3 Analysis of Harmonic Propagation Gains

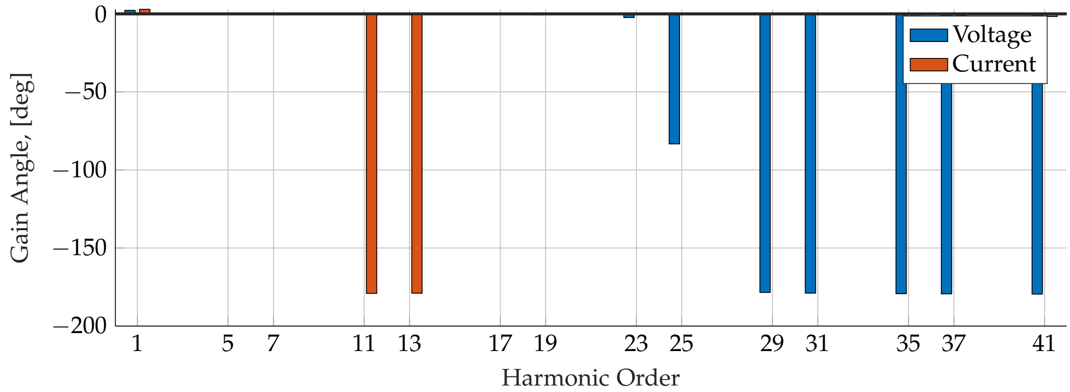
It has been seen that the voltage and current magnitudes in the three busses in the simple radial system, seen in Figure 5.3a and Figure 5.3b, can be analysed and explained with the theory of sinusoidal propagation. This can be done simpler from the gain and phase displacement between Bus 7 and Bus 5, for both voltage and current. This is defined in Equation 5.3 for voltage, and is similar for current.

$$GV_{75}\angle\Phi_{75} = \frac{V_5\angle\phi_5}{V_7\angle\phi_7} \tag{5.3}$$

In equation, GV_{75} is the voltage gain in magnitude from Bus 7 to Bus 5, and Φ_{75} is the phase displacement from Bus 7 to Bus 5. V_5 and V_7 is the voltage magnitude at the specific busses, namely Bus 5 and Bus 7 in this case, and ϕ_5 and ϕ_7 is the phase of the voltage at those busses. In Figure 5.8a and Figure 5.8b, the gain and phase displacement between Bus 7 and Bus 5, for both voltage and current, can be seen. It should be noted that Figure 5.8a is shown with a logarithmic y-axis.



(a) Gain magnitude for voltage and current from Bus 7 to Bus 5.



(b) Gain angle for voltage and current from Bus 7 to Bus 5.

Figure 5.8: Harmonic current and voltage gains from Bus 7 to Bus 5.

The 5th and the 7th harmonic voltage, which is at a lower frequency than the parallel resonant point, is seen to decrease from Bus 7. That is because they are in the inductive impedance region, and the power factor is therefore inductive. That can be seen as the voltage gain for those harmonic orders are below 1. There will not occur any phase-shift as the OHL is short compared to the wavelength of those frequencies. The 11th and 13th harmonic are seen to have a phase-shift in current as those frequencies are relatively close to the parallel resonant point. Those frequencies can therefore be placed close to the current phase-shift point, demonstrated in Figure 5.5.

The harmonic orders from the 17th to the 23rd, are seen to not have a phase-shift in current and are thus increased in voltage throughout OHL 2. After the series resonance, at the 25th harmonic, a phase-shift in voltage is seen for the rest of the harmonics. The 37th and the 41st harmonic is seen to have about the same voltage as the 5th harmonic, but a phase shift still occurs which demonstrates that the short wavelength of higher harmonics causes an increased number of phase shifts.

5.1.4 Summary

Harmonic voltage and current propagation have been described in this section. It is seen to follow a sinusoidal waveform, where the voltage is increasing in magnitude when the power factor is capacitive and reduce in magnitude when the power factor is inductive. A change in power factor is seen when the voltage or current crosses zero. The starting point of the waveform is defined by the magnitude and angle of the voltage and current in the starting bus. These can, for a radial line connected to a harmonic emission source, be determined by the output of the harmonic emission source and the impedance seen from the bus it is located at.

An analysis of the affect a change in the parameters in the system reviewed in this section has on harmonic propagation is explained in Appendix A. It can there be seen that the external grid has a large effect on the impedance in this small radial system. Furthermore, it can be seen that the increased capacitance introduced by replacing the OHLs in the system by UGCs, shifts the resonance points to lower frequencies and reduces the magnitude of the parallel resonance points.

An analysis of a more complex radial system, consisting of several radial paths, is explained in Appendix B. It can there be seen seen that several sources can be analysed using super position. The connection of an additional radial connection can also be seen to change the resonance points and cause a resonance circuit.

The method to analyse harmonic propagation will in the following section be applied in the meshed system introduced in Chapter 4.

5.2 Harmonic Propagation in a Meshed System

This section presents the analysis of harmonic propagation in the meshed system, explained in Chapter 4, and can be seen again in Figure 5.9. The voltage levels in the system when a single harmonic emission source is introduced, and implemented in Bus 1, is analysed. Furthermore, the analysis conducted on the harmonic propagation gains in the system is presented.

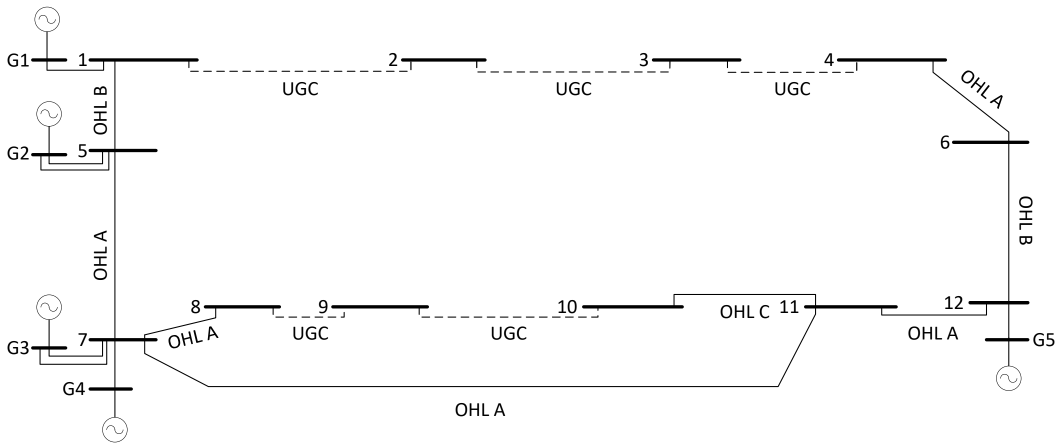


Figure 5.9: Single-line diagram of meshed example grid used in the analysis.

The system can be seen to have two loops, one including all busses apart from the generation busses, and one including the busses between Bus 7 and Bus 11. There are in total five buses that are connected to more than two other busses, like Bus 7 which has four connections. There are also five generation units creating a path to the ground for the harmonic currents. These factors all increase the complexity of the system as they affect the harmonic propagation.

The resulting harmonic voltage in the system, when the harmonic emission source, also explained in Chapter 4, is implemented in Bus 1, can be seen in Figure 5.10.

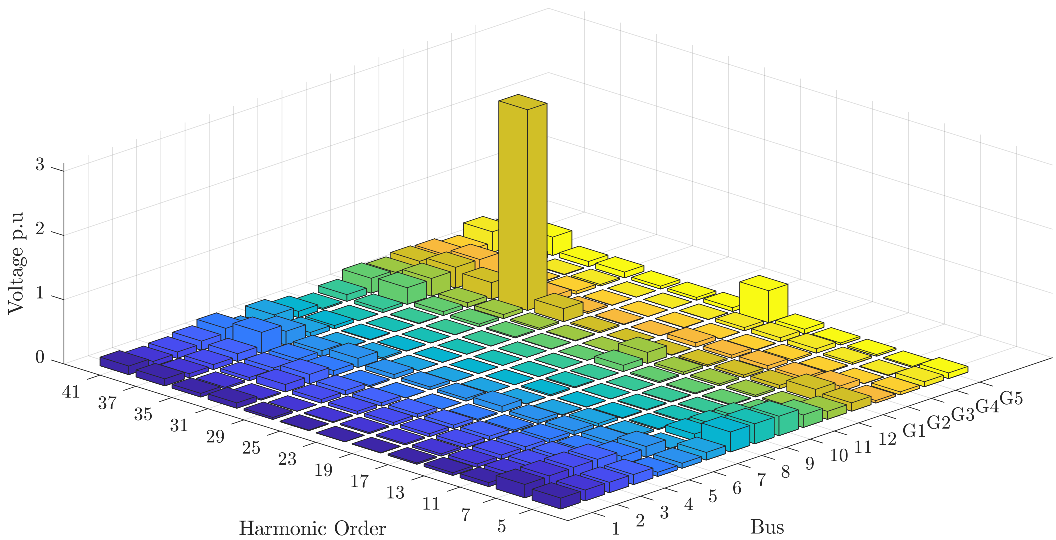


Figure 5.10: Harmonic voltage magnitudes in all the busses in the system, for all the harmonic order present, when a harmonic emission source located in Bus 1.

It can be seen in the figure that the harmonic voltage levels are very different in each bus and for the different harmonic orders, which emphasises the complexity of the system. The generation busses, G1 to G5 are radially connected to the system, and follows the theory presented in the previous section about harmonic propagation in radial systems. A further analysis on the harmonic levels in those busses, can be seen in Appendix C.3. That included the explanation of the 29th harmonic order in Bus G1, which is seen to be significantly higher than the other harmonic levels in the system.

In order to explain the harmonic propagation in the system, the focus is led on one single harmonic order, namely the 7th harmonic. That harmonic order is chosen as it is a low order harmonic, and it has the highest magnitude of the harmonic orders in Bus 1, where the harmonic emission source is located. The harmonic voltage in the system for the 7th harmonic order, when the harmonic emission source is located in Bus 1, can be seen in Figure 5.11.

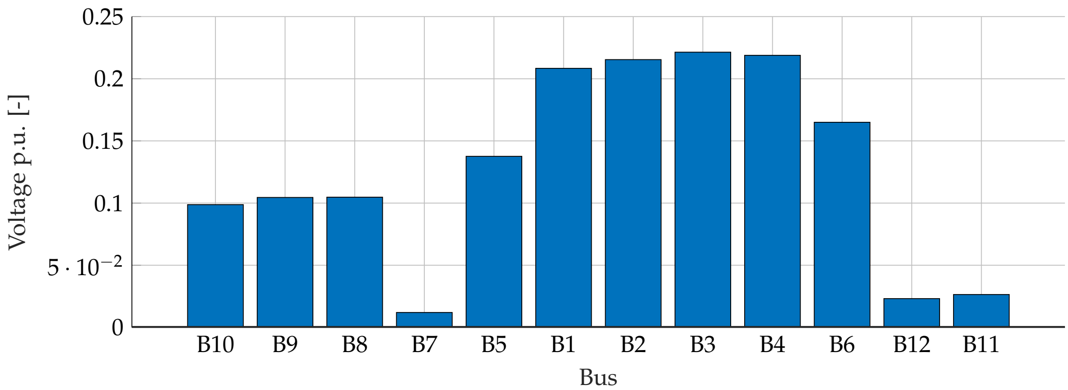


Figure 5.11: 7th order harmonic voltage magnitude in the meshed system when the harmonic emission source is located in Bus 1.

The busses are arranged so Bus 1 is located in the middle of the figure. The busses in the northern and eastern side of the large loop in the system can be seen to the right, while the busses in the southern and western side of the loop in the system can be seen to the left. All busses in the figure are located according to the electrical distance from Bus 1. This is done in order to easier visualise the harmonic voltage waveform, described in the previous section. The voltage level can be seen to increase form Bus 1 to Bus 2, and further increase to Bus 3, from which it starts to decrease, indicating a phase shift in current, to Bus 4 and further to Bus 6 and 12. The waveform can also be followed from Bus 1 to Bus 5 where it can be seen to decrease and further decrease to Bus 7, where it increases to Bus 8, indicating a phase-shift in voltage.

This is a simple example with a single harmonic emission source, where the waveform can be visualised from the voltage levels alone. This is however not the case for more complex configurations of harmonics and sources, as the current will split at the busses with more than two connections and that will change the waveform significantly. This makes system-wide harmonic propagation in complex meshed system difficult to describe in the same manner as for the radial system. The theory can however be applied to describe the voltage and current levels throughout the lines and thereby the propagation gains between busses, when the voltage and current magnitudes and angles for the busses are known.

A further analysis on the harmonic propagation gains can be found in Appendix C.1. They are seen to be dependent on the location of the harmonic emission source, as they depend on the propagation path and the impedance seen from the bus at which the harmonic emission source is located at. The gain between two busses is therefore not constant as it depends on the starting point of the waveform, which changes depend on the propagation path. The phase displacement through the line is however constant as it is based on the properties of the line and its length.

Furthermore, a detailed analysis on the harmonic propagation through UGCs compared to OHLs, can also be found in Appendix C.2

As explained in the previous section, the voltage and current levels through out the lines in a system varies significantly, causing a different stress to the line than at the busses. That can also be seen in this meshed system and a method to find the highest stress in a line is proposed in the following section.

5.3 Maximum Stress in a Line

It has been seen that the harmonic voltage at the busses in a system not always gives a good representation for the harmonic voltage levels in the system in general, as the levels might be higher within a the line, between the busses. This can be seen again in Figure 5.12, where the voltage levels for different harmonic orders through a 150 km long OHL can be seen. A further explanation of the figure can be found in Section 5.1.2.

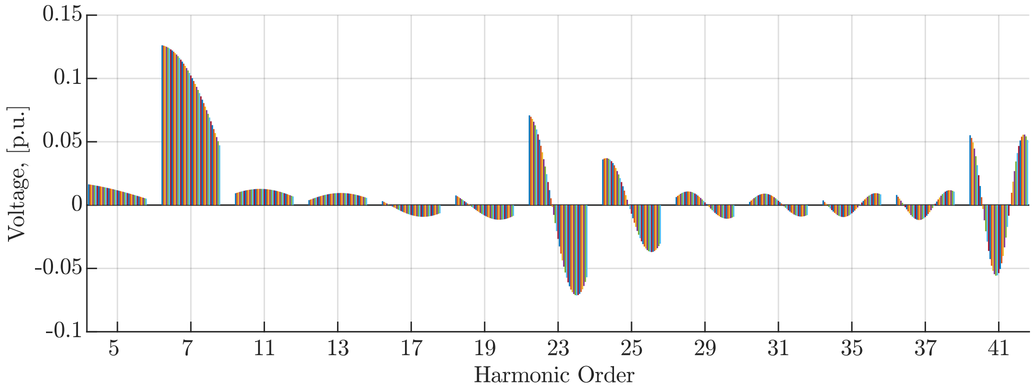


Figure 5.12: Voltage levels through a 150 km OHL at all harmonic orders. Negative voltage indicates a voltage phase-shift and a change in the slope indicates a current phase-shift.

The same behaviour occurs for current with a 90° shift compare to the voltage. This shows that the stress in the line can be higher than assumed from running a harmonic load flow, or measuring the harmonic levels in a system in the busses. The voltage and current levels within a line, and the maximum stress they are exposed to, can however be calculate based on the values in the busses.

An example will be explained in this section, where a method will be proposed to calculate the maximum stresses. In the example the harmonic emission source is located in Bus 1, in the meshed system explained in Chapter 4, and the maximum stress through OHL 1 will be calculated with the focus on the 7th harmonic order. The values needed from the harmonic load flow is then the voltage and current magnitudes and the angles at each side of the OHL, which is at Bus 1 and Bus 5. These can be seen in Table 5.2

	Bus 1	Bus 5
Voltage [kV]	83.355∠ 95.1°	55.039∠ 94.4°
Current [A]	324.06∠7.26°	353.66∠7.05°

Table 5.2: 7th order harmonic voltage and current at Bus 1 and Bus 5, when the harmonic emission source is located in Bus 1.

The waveform can, as shown in the previous sections, be described as a sinusoidal waveform as seen in Equation 5.4, which describe the voltage levels.

$$V_p = sin(\theta_p) \cdot V_{max} \tag{5.4}$$

In the equation, V_p is the voltage level at point p, θ_p is the corresponding angle at point p and V_{max} is the maximum amplitude of the waveform. If the wavelength of the harmonic being analysed, and the length of the line, is equal, a full period of the waveform will be seen between the busses like the 41st harmonic in Figure 5.12. However, if the length of the line is shorter, the waveform between the busses will only include a part of the full period. This part might include the V_{max}, but that will depend on the values at the busses.

The method will fit the calculated values to a pure sinusoidal waveform. The equations describing the voltage and current at Bus 1 can be seen in Equation 5.5 and Equation 5.8.

$$V_1 = sin(\alpha) \cdot V_{max}(OHL1) \tag{5.5}$$

$$I_1 = cos(\alpha) \cdot I_{max}(OHL1) \tag{5.6}$$

In the equations, α is the angle of the waveform at Bus 1, which has also been referred to as the starting point of the waveform. V_{max} and I_{max} is the maximum voltage and maximum current possible in the line, which are specific for OHL 1 and the harmonic order. It is dependent of the parameters of the line and the values of I_1 and V_1, which is the voltage and current at Bus 1. The voltage and current in Bus 2 can be seen described in Equation 5.7 and Equation 5.8.

$$V_2 = sin(\alpha + \beta \cdot h) \cdot V_{max}(OHL1) \tag{5.7}$$

$$I_2 = cos(\alpha + \beta \cdot h) \cdot I_{max}(OHL1) \tag{5.8}$$

In the equation, β is the phase displacement occurring for the fundamental waveform between the two busses. This is depended on the properties of the line and its length, which is constant. h is the harmonic order. There are in total four unknowns in the equations, namely V_{max}, I_{max}, α and β, and four equations, which can therefore be solved.

Equation 5.9 and 5.10 are the previous equations merged and rewritten to solve for β and α respectively.

$$\beta = \frac{1}{h} \cdot acos\left(\frac{I_1 \cdot V_1 + I_2 \cdot V_2}{I_1 \cdot V_2 + I_2 \cdot V_1}\right) \tag{5.9}$$

$$\alpha = atan\left(\frac{V_2 \cdot sin(\beta \cdot h)}{V_1 - V_2 \cdot cos(\beta \cdot h)}\right) \tag{5.10}$$

V_{max} and I_{max} can be calculated as seen in Equation 5.11 and Equation 5.12, respectively.

$$V_{max} = \frac{V_1}{sin(\alpha)} \tag{5.11}$$

$$I_{max} = \frac{I_1}{cos(\alpha)} \tag{5.12}$$

The values to describe the waveform for OHL1 can be seen in Table 5.3.

	OHL 1
Vmax [kV]	165.64
Imax [A]	374.90
α [°]	-30.21
β [°]	1.544

Table 5.3: Values to describe the waveform.

The maximum voltage amplitude of the waveform is about twice the magnitude of the voltage at Bus 1 and it is seen that the starting point at Bus 1 is -30.21°. A negative angle of α indicates an inductive power factor and that the voltage will decrease until the angle is positive. This will however not occur as β and h is low and the maximum voltage amplitude will not be achieved. The values and the movement of the waveform can be seen in the circle in Figure 5.13 from Section 5.1.2, in order to illustrate the levels through the line.

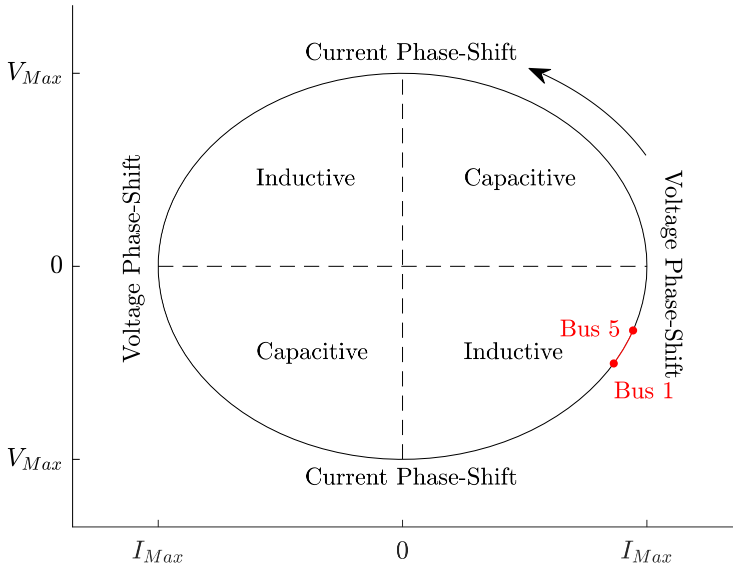


Figure 5.13: 7th order harmonic voltage level trough OHL 1.

It can be seen, for the given values at the busses and the given harmonic order, that the length of OHL 1 would need to be significantly longer to reach V_{max}. It can be calculated in Equation 5.13 how far from Bus 1 V_{max} will occur, given that OHL 1 was longer.

$$LtoMaxV = 90^{\circ} - \alpha \frac{L1}{\beta \cdot h} \tag{5.13}$$

In the equation $L1$ is the length of OHL 1 and is used to relate the degrees to a physical length. The length to the maximum current can be calculated as seen in

Equation 5.14.

$$LtoMaxI = -(\alpha)\frac{L1}{\beta \cdot h} \tag{5.14}$$

If the calculated length is longer than L1 or negative, it means that the part of the waveform which occurs between the busses, does not include V_{max} or I_{max}. The maximum stress in the line would therefore be at either of the two busses with the highest magnitude of voltage or current respectively. The length to V_{max} and to I_{max}, and the maximum stresses for OHL 1 can be in Table 5.4.

	OHL 1
LtoMV [km]	281.38
LtoMI [km]	70.706
MaxSV [kV]	83.555
MaxSI [A]	353.66

Table 5.4: Length to V_{max} and I_{max}, and the maximum stress from both voltage and current in the line.

It is seen that V_{max} and I_{max} did not, in the case of OHL 1 for the 7th harmonic order, occur in the line and the value at the busses will therefore give the maximum stress. In this case the maximum stress would be known from the harmonic load flow and would not be of interest. The phase-shift and maximum stresses, occur more often at higher order harmonics or at longer lines as the ratio between the length of the line and the wavelength of the harmonic would increase, and thereby the amount of the waveform occurring between two busses would increase. When the length of the line is a quarter or longer of the wavelength of the harmonic, it is certain that either V_{max} or I_{max} will occur. Both will occur when the length of the line is half of the wavelength of the harmonic or longer.

The highest gain between the values at the busses and the maximum values, when it occurs in the line, is for this system, occurring in OHL 4, which is the longest OHL in the system, when the radial connections to the generation units are excluded. It has a gain for voltage at 2.6 at the 35st harmonic order and a gain for current at 11.5 at the 41 st harmonic order. In Figure 5.14 the V_{max} and I_{max} for the system is seen when the harmonic emission source is at Bus 1. V_{max} and I_{max} is normalised by the maximum value in the system, respectively.

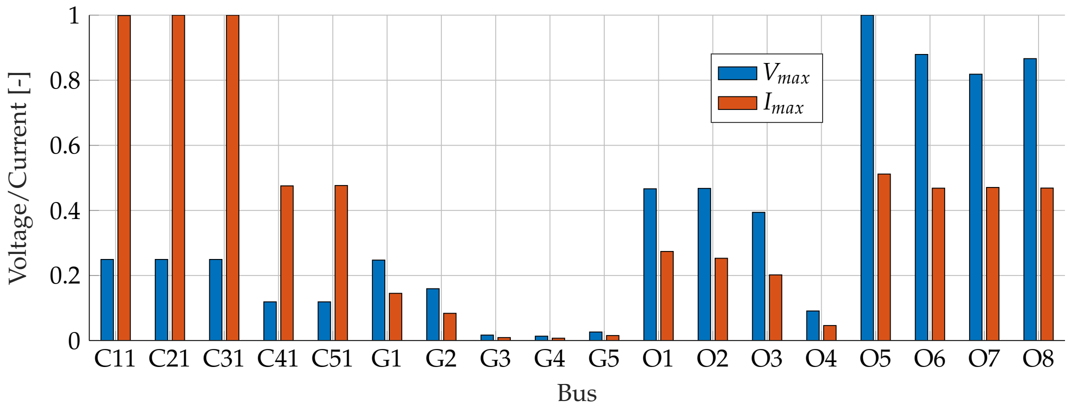


Figure 5.14: Normalised values for V_{max} and I_{max} of the 7th order, for every line when the harmonic emission source is located in Bus 1.

The difference between the parameters in the OHLs and UGCs can be seen as V_{max} is generally higher for OHL and I_{max} is generally higher for UGCs. This is related to the difference of the characteristic impedance in the lines. This also means that UGCs are more susceptible to over-currents, while OHLs are more susceptible for over-voltage.

The accuracy of the method presented in this section is decreased when a phase-shift occurs within a close vicinity of the bus defined as the starting point of the waveform. This can however be solved by switching the starting point to the opposite bus. The accuracy will therefore only decrease if phase-shift occurs at both busses, which is a special occurrence and a different method should be used.

5.4 Discussion and Recommendations

In this chapter, the system-wide harmonic levels, and how they propagate, both through radial systems, and meshed systems have been analysed. Furthermore, how the harmonic levels propagate through the lines in a system has been analysed. The results presented, will in this section be discussed.

When reviewing harmonic propagation gains in a system, meaning how the harmonic levels changes from one bus to another, the phase displacement between the busses is determined by the system parameters, and not the harmonic signal itself. It is thus not dependent on the location of the harmonic emission source. In the case of several harmonic signals, the phase displacement will still be the same. However, the magnitude of the mentioned gain in dependent on the location of the harmonic emission source, and the impedance of the system around. That is because it affects the path of the harmonic currents in a system, and does therefore also affect the waveforms through the lines, which have been seen to determine the magnitude of the mentioned propagation gains. That means that constant propagation gains are not very useful when analysing the harmonic propagation in a system with varying harmonic emission sources.

It has been seen that the change in the harmonic current and voltages through the lines in the system can be analysed in both radial and meshed systems. In a radial line, with a harmonic emission source in the end, only the impedance of the system seen from the bus at which the harmonic emission source is located at and the parameters of the line is required in order to analyse the waveform of the harmonic signals through the line. For a meshed system where the harmonic currents can flow in different paths, more information is required in order to analyse the waveforms, such as a harmonic load flow. The analysis of the waveform can be very useful in both cases.

The voltage and current levels has been seen to increase and decrease through a line. Sometimes both can occur and the voltage or current level at the bus will therefore not be the highest. An increase in voltage or current will be present at some points in the line, where it exerts more stress to the line than assumed from a harmonic load flow. The maximum stress can be calculated using a mix of the harmonic load flow and the knowledge that the levels will follow a sinusoidal waveform between the busses. This means that using only harmonic load flow will potentially loose the knowledge of the highest stresses in the lines. Significant increases for both current and voltage levels are seen in the lines compared to the busses, with a 2.6 times increase for the voltage and 11.5 times increase for the current, which can cause the total distortion in the line to increase and over-voltage and over-current can occur.

Over-voltage and over-current can lead to numerous issues in OHLs and UGCs, where UGCs are the most sensitive. An increase in voltage in an UGC, and especially around the joints between two sections of an UGC, can cause partial discharge which can lead to electrical treeing. This will permanently destroy the insulation and in turn the UGCs. Over-voltage in OHLs is not as severe, but it can cause corona and flash overs.

High currents can cause the temperature to increase in the conductors above the specified limits. Overheating can therefore occur, which in a UGC can damage the insulation and/or decrease its lifetime and thereby also the lifetime of the UGC, especially around weak point like bends, where the effect of heating is increased. UGC have a slow temperature constant, because of the high heating coefficient of the ground, and will therefore heat up slowly. It will therefore not be affected by transient harmonics, but harmonics which occurs from standard operation will increase the temperature. Overheating in OHLs can increase the sag, which can sag below legislation or beyond the elastic limit, which would cause permanent sag to the conductor.

It is therefore important to know the maximum stress through a line and be able to determine if it can cause damage to the lines. It is recommend to use the method proposed or similar methods to calculate the maximum stress of the lines. This can help improve limits and explain possible damages to lines.

Chapter 6

Harmonic Mitigation and Passive Filter Design

The analysis conducted on harmonic mitigation by the use of passive filters is explained in this section. Furthermore, a focus is led on anti-resonance phenomena, the causes and how that can be avoided when passive filters are implemented in a system. Several cases are presented, where the location of the harmonic emission sources and the filters implemented is varied. The filter of focus is single-tuned passive filters, as there is a high risk of anti-resonance phenomena when implementing those types of filters, as explained in Section 4.

Firstly, the filter and the harmonic emission source is implemented at the same bus, and the focus is on explaining how the anti-resonance phenomena occurs and how it is affected by the change in impedance due to the filter implementation. Thereafter a sensitivity analysis is presented, explaining how the location of the filter can affect anti-resonance phenomena. In that analysis the location of the filter is still maintained at the same bus as the harmonic emission source. Thereafter, an analysis of how the anti-resonance phenomena is affected when the location of the filter is not at the same bus as the harmonic emissions source. The focus is then led on anti-resonance phenomena, and its causes. Lastly a method to avoid anti-resonance phenomena is presented.

Only the busses 1 to 12 is included in the analysis in this chapter. The busses where the generation units are located are only linked directly to one bus in the system, and the propagation out to those busses follows the radial propagation theory explained in Section 5.1.2, in Chapter 5.

The anti-resonance phenomena to be investigated is reviewed as any amplification in the harmonic orders present in the system, after a filter is implemented in the system, compared to the levels before the filter is implemented. That includes the harmonics at the bus at which the filter is implemented, and at any of the other busses in the system. Mathematically it is defined as seen in Equation 6.1.

$$\forall h \quad and \quad \forall i \quad if \quad |V_{i,h}|_{HLFa} > |V_{i,h}|_{HLFb} \tag{6.1}$$

In the equation h and i are the harmonic orders and the busses that are present in the system, and $HLFb$ and $HLFa$ is the harmonic load flow before and after the implementation of the filter. The increase in voltage has been review by the use of an amplification gain, defined as seen in Equation 6.2.

$$V_{Gain(i,h)} = \frac{|V_{i,h}|_{HLFb}}{|V_{i,h}|_{HLFa}} \tag{6.2}$$

It can be seen that if the gain i larger than 1, anti-resonance phenomena has occurred, as the harmonic level at a given bus and a given order is larger after the filter implementation than before.

The system used in the analysis is the system explained in Section 4, which is also the meshed system used in Chapter 5, and can be seen, again, in Figure 6.1.

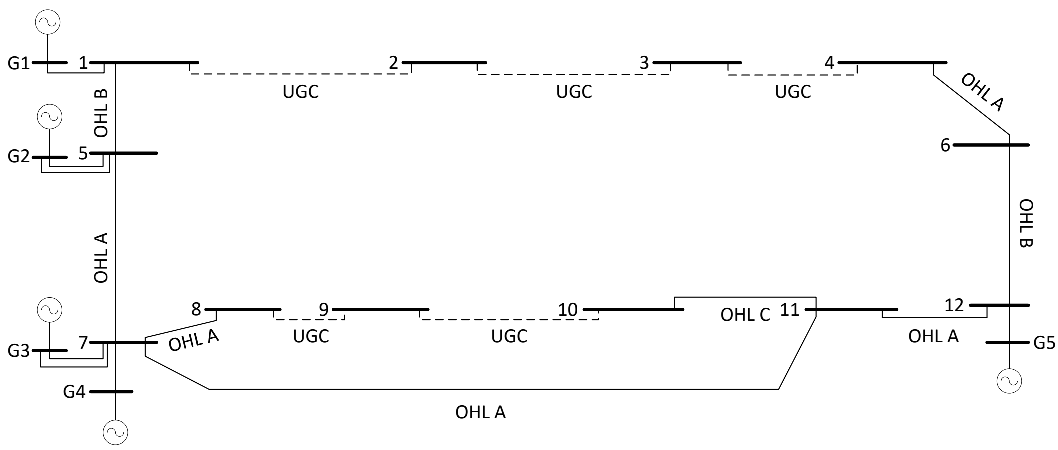
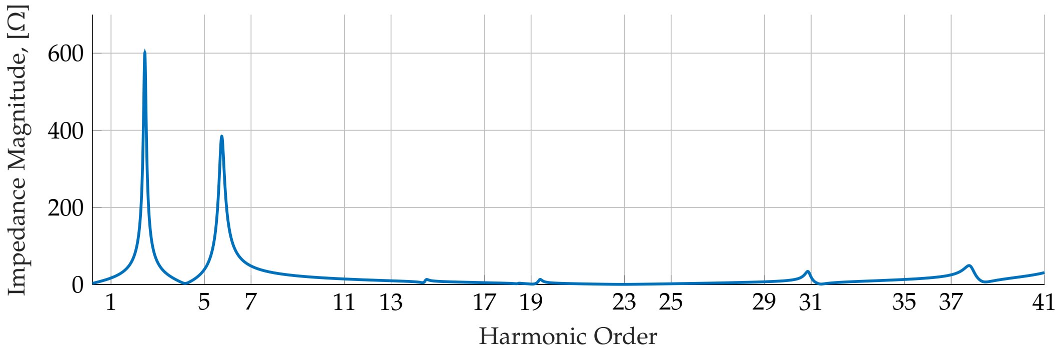


Figure 6.1: Single-line diagram of meshed example grid used in the analysis.

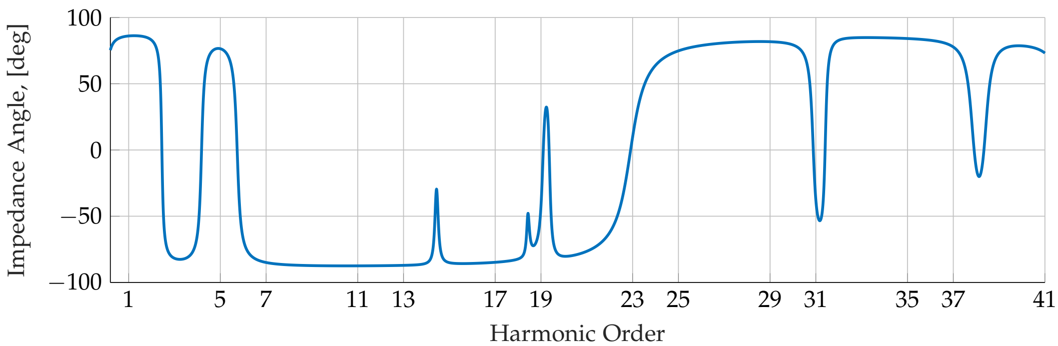
The harmonic emission source that is used in the analysis in this chapter, is the same harmonic emission source used in Chapter 5, which is explained in more detail in Chapter 4.

6.1 Harmonic Mitigation by the use of Single-Tuned Passive Filters

As mentioned single-tuned passive filters consists of a resistive, a capacitive and an inductive element placed in series. They are in the model implemented as an R-L-C typed shunt filter, as explained in Chapter 4. The filter is implemented in Bus 1 together with the harmonic emission source. The design parameters for the filter are chosen to be the rated reactive power, Q, the resonant frequency, f_r and the quality factor, q. The resonant frequency is chosen based on the impedance seen from the bus at which the filter is to be implemented. In this section, both the harmonic emission source and the filter is implemented in Bus 1. The impedance of the system, seen from Bus 1, can be seen in Figure 6.2.



(a) Impedance magnitude seen from Bus 1.



(b) Impedance angle seen from Bus 1.

Figure 6.2: Impedance magnitude and angle seen from Bus 1.

It can be seen in the figure that the first and highest parallel resonant points occur in the lower frequency range, more specifically it occurs at the harmonic order of 2.44 and 5.99. The harmonic voltage in Bus 1 is thus expected to be particularly high for the 5th and 7th harmonic order. That is because those are the harmonic orders, which are injected into the system, which are closest to the high resonance points, and the impedance is the highest in magnitude in those points, seen from Bus 1. The 5th and 7th harmonic orders in the system can be seen in Figure 6.3. The harmonic emission source is in this case implemented in Bus 1.

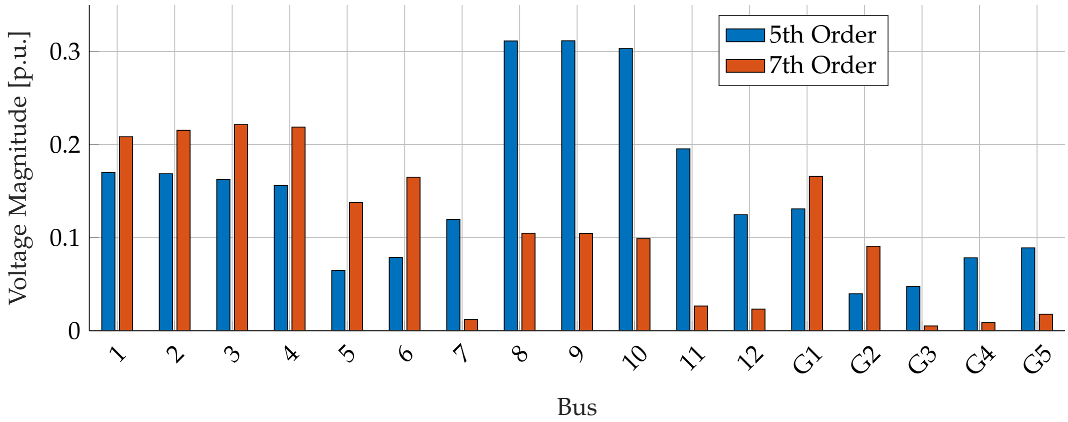
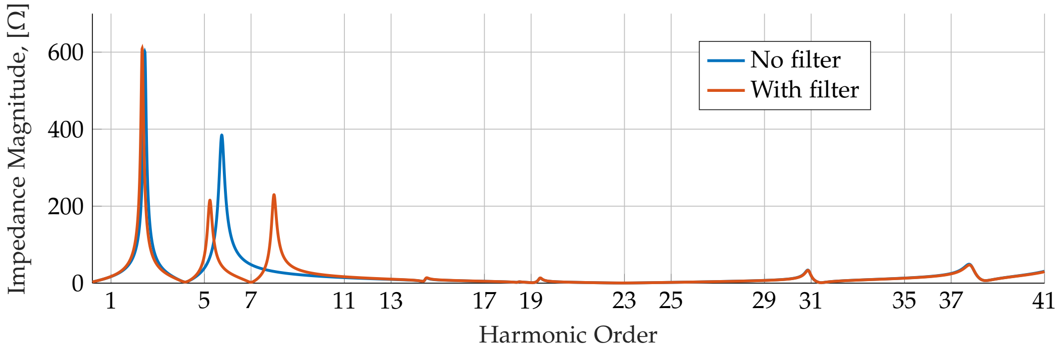
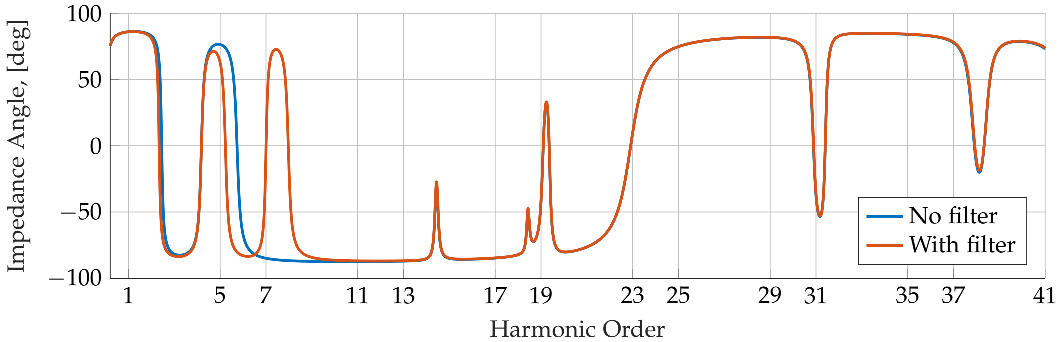


Figure 6.3: 5th and 7th order harmonic voltage levels in all the busses in the system when the harmonic emission source is located in Bus 1.

It can be seen in the figure that the 7th harmonic orders are of the highest magnitude at the local bus, namely Bus 1. Therefore, it is desirable to tune the filter to reduce the 7th order harmonic. It should though be mentioned that the 5th order harmonic voltage is generally high in the system. When a sharply tuned filter, with a quality factor of 50, and a rated reactive power of 200 MVA, aiming to reduce the 7th order harmonic in the system, is implemented in Bus 1, the impedance seen from Bus 1 changes. The impedance, seen from Bus 1, before and after the implementation of the mentioned filter, can be seen in Figure 6.4.



(a) Impedance magnitude seen from Bus 1.



(b) Impedance angle seen from from Bus 1.

Figure 6.4: Comparison of impedance magnitude and angle seen from Bus 1, before and after the filter implementation.

The impedance of the 7th order harmonic can be seen to be significantly reduced, more specifically it is reduced from 48.12 to 2.32 Ω. However, the impedance for the 5th order harmonic can be seen to be increased, from 39.24 to 72.35 Ω, which is a gain of 1.844. The impedance of the frequencies that are not close to resonant frequencies of the filter can be seen not be significantly affected in this case. The change in the impedance of the 7th order harmonic consequently reduces the harmonic voltage, as seen in Figure 6.5.

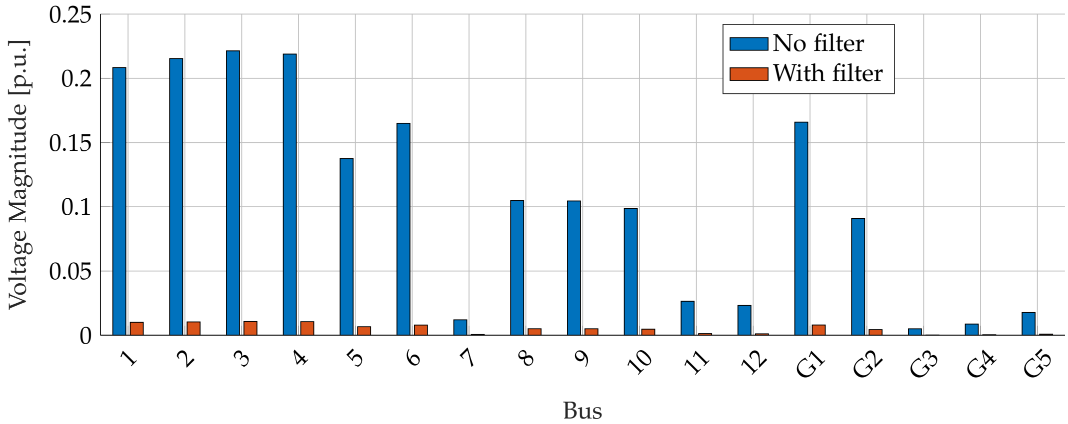


Figure 6.5: 7th order harmonic voltage levels in all the busses in the system, before and after the filter implementation.

It can be seen in the figure that the filter has reduced the 7th order harmonic voltage significantly. The impedance for the 5th order harmonic order was though seen to be increased after the implementation of the filter. The sharply tuned filter introduces new resonance points within a close vicinity to the target frequency. As a consequence, an amplification of the 5th order harmonic voltage in the system can be seen to occur, as seen in Figure 6.6.

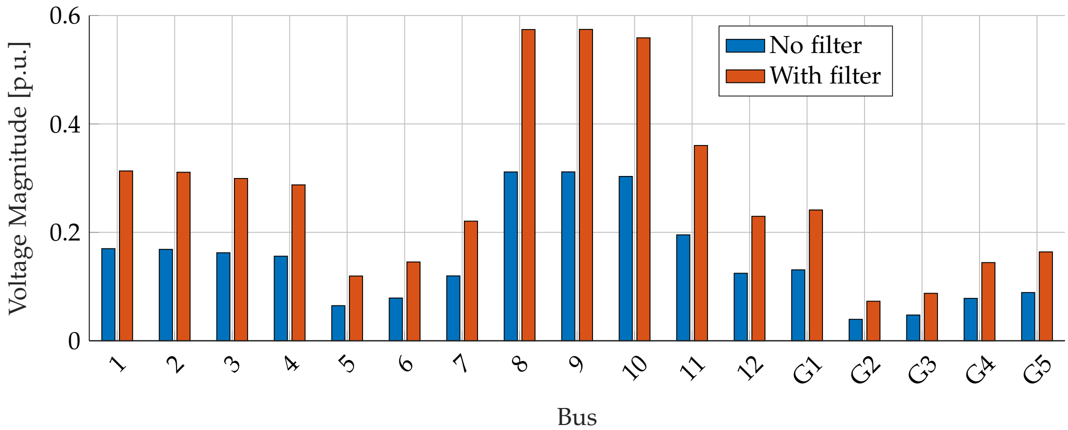


Figure 6.6: 5th order harmonic voltage levels in all the busses in the system, before and after the filter implementation.

The implementation of the filter can, in this case, be seen to not change the harmonic gains in the system. The 5th order harmonic is amplified by a factor of 1.844 in Bus 1, after the filter implementation, and therefore the same amplification can be seen for all the busses. The gains are constant only when the harmonic emission source and the filter is located at the same bus. It occurs as the parts of the current will, after the filter implementation, go a different path than before, namely down the filter. However, even though the current magnitude, running out in the system, is reduced, the impedance of the system is still the same. The propagation gains will therefore be the same in the system, but the voltage generated from the harmonic emission source will have changed as a consequence of the change in impedance seen from the bus at which the harmonic emission source is located at. However, as the location of the harmonic emission source is not always known, an analysis of having them located at different busses is also investigated, and explained in Section 6.3.

As the propagation factors in the system are constant in this case, it is sufficient to represent the change in the harmonic levels in the systems by reviewing the change in the local bus, namely Bus 1. An amplification of the harmonic voltage at a specific order in that bus, would consequently increase the harmonic voltage in the other busses as well, and the gains would be the same. The gains for all the harmonic orders in Bus 1 can be seen in Figure 6.7.

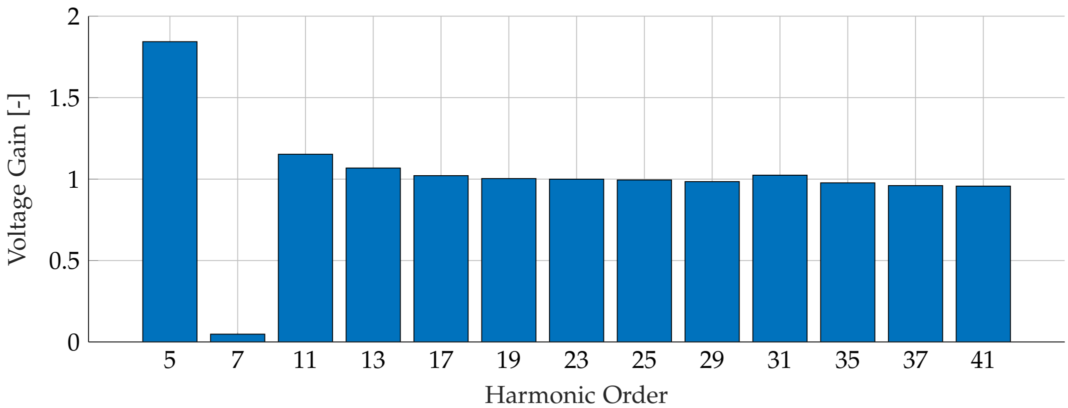


Figure 6.7: Harmonic voltage gains in Bus 1.

It can be seen in the figure that there is no significant change in the harmonics where no significant change were seen in the impedance. An amplification of 1.153 was seen for the 11th harmonic, which impedance was increased from 14.481 to 16.690.

The change in impedance that occurs when a filter is implemented aiming to reduce the 7th harmonic, is seen to cause amplification in other harmonic orders, most significantly in the 5th and the 11th order harmonics, meaning that anti resonance phenomena occurs. The phenomena can be reduced if the impedance is not significantly changed for any other harmonic orders present in the system. In this case when the harmonic filter and the harmonic emission source is placed in Bus

1, and the 5th order harmonic is present in the system, a reduction in the amplification of the 5th order harmonic order can be achieved if the impedance of the filter is changed, meaning that the filter is tuned differently.

6.2 Sensitivity Analysis of Location of Filter

In order to investigate how the harmonic amplifications are affected, when the filter and the harmonic emission source is located at the same bus, but the bus at which they are implemented is changed, a sensitivity analysis is conducted. In the analysis the filter is maintained constant, namely the sharply tuned single-tuned filter which aims to reduce the 7th harmonic order, explained in Section 6.1. There is then a risk to amplify especially the 5th order harmonic voltage, which also is present in the system. Furthermore, there is also a risk to amplify the 11th order harmonic and other harmonic orders present in the system. This amplification can change according to which bus the filter and harmonic emission source is connected to as the impedance seen from each bus is different, and therefore the impedance after filter implementation is also different. The impedance for the 5th, 7th and 11th order harmonic seen from each bus, after the filter implementation, can be seen in Figure 6.8.

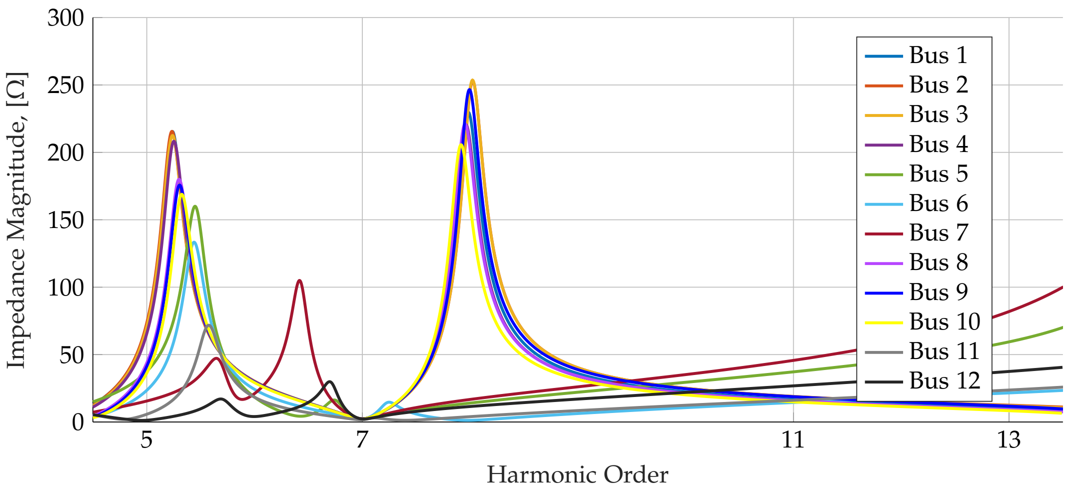


Figure 6.8: Harmonic impedance magnitude, seen from each bus in the system.

It can be seen in the figure that the impedance for the 7th harmonic is low, seen from all the busses. This is because the filter is aiming to reduce the mentioned harmonic order. Furthermore, it can be seen that the impedance for the 5th harmonic order varies significantly seen from each bus. Therefore, the harmonic voltage level for the 5th harmonic order in the bus at which the filter is implemented is also different. The amplification of the harmonic voltage, represented as a gain factor, for the 5th order harmonic, when the filter is implemented at each of the busses in the system, can be seen in Table 6.1. Furthermore, the voltage before and after the filter implementation can be seen. As mentioned in Section 6.1, the propagation factors in the system is not changed as the system impedance is constant. Therefore, only the local amplification in the harmonic voltage, meaning at the bus at which the filter is implemented, is analysed.

Table 6.1: 5th order harmonic voltage before and after the filter implementation in the bus at which the filter is implemented at, and the resulting harmonic amplification factor.

Bus	Local voltage before filter implementation [pu]	Local voltage after filter implementation [pu]	Amplification factor
1	0.170	0.313	1.844
2	0.172	0.318	1.856
3	0.168	0.306	1.823
4	0.161	0.284	1.765
5	0.111	0.163	1.459
6	0.080	0.102	1.279
7	0.057	0.067	1.192
8	0.126	0.190	1.508
9	0.121	0.178	1.476
10	0.111	0.157	1.420
11	0.023	0.025	1.061
12	0.006	0.006	1.007

It can be seen in the table, that an amplification of the 5th order harmonic voltage is expected, when the filter is located in all the busses. However, the expected amplification when the filter is implemented in Bus 12 is close to zero, meaning that the gain is approximately 1. It can however also be seen in Figure 6.8 that, when the filter is implemented in Bus 12, the impedance for the 11th order harmonic is higher than the impedance seen from most of the other busses. When the filter is implemented in Bus 3 an amplification of the 5th order harmonic of 1.823 is expected, however the 11th order impedance is not as high as when the filter is implemented in Bus 12. The impedance magnitude before and after the filter implementation, seen from Bus 3 and Bus 12 can be seen in Figure 6.9.

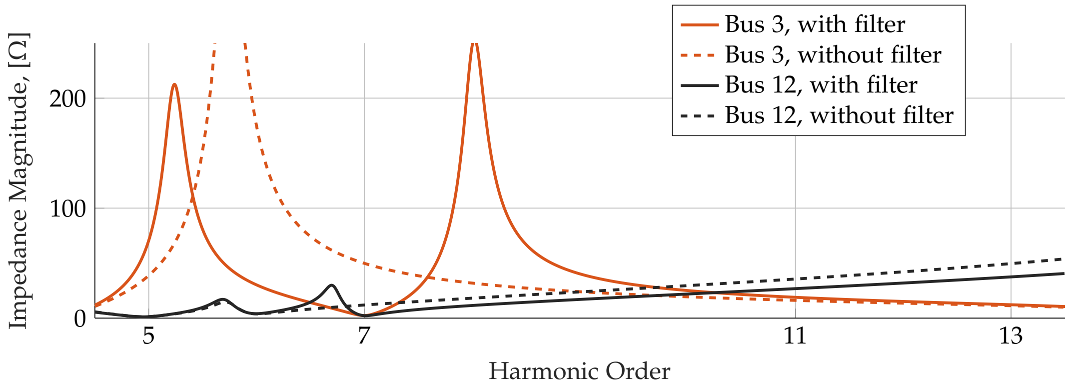


Figure 6.9: Harmonic impedance magnitude, seen from Bus 3 and Bus 12 before and after the implementation of the filter. The dashed lines illustrates impedance before the filter implementation, while the solid lines illustrates it after the implementation of the filter.

It can be seen in the Figure that the impedance seen from Bus 3 increases for the 5th order harmonic and slightly increases for the 11th order harmonic, after the filter is implemented. The impedance seen from Bus 12 can be seen to not change significantly for the 5th order harmonic, and to be reduced for the 11th order harmonic. Furthermore, it can be seen that the impedance for the 7th order harmonic, seen from Bus 12, is low even before the filter implementation, so it would not make much sense to implement the filter here, unless it was an issue that some of the propagation gains for that harmonic order was very high, so the harmonic voltage in some of the other busses was an issue. If it then was known that the harmonic emission source is located in Bus 12, a filter to fully mitigate the harmonic could be implemented. That is however, not the case in this system, where the highest harmonic voltage of the 7th order occurs in Bus 12 itself, when the harmonic emission source is located there.

It can be seen that the expected harmonic amplification of the other harmonic orders than the targeted, meaning a situation where the anti-resonance phenomena is expected to occur, is highly dependent on the bus at which the filter is located, in the case when the harmonic emission source is located at the same bus. That is because the impedance seen from each bus is different, and the effect the impedance of the filter has on the total impedance seen from that bus affects the change in the total harmonic levels. The amplification factor for each of the harmonic orders that are present in the model, when the location of the filter is changed, can be seen in Figure 6.10. The amplification also represents the change in impedance at each harmonic levels.

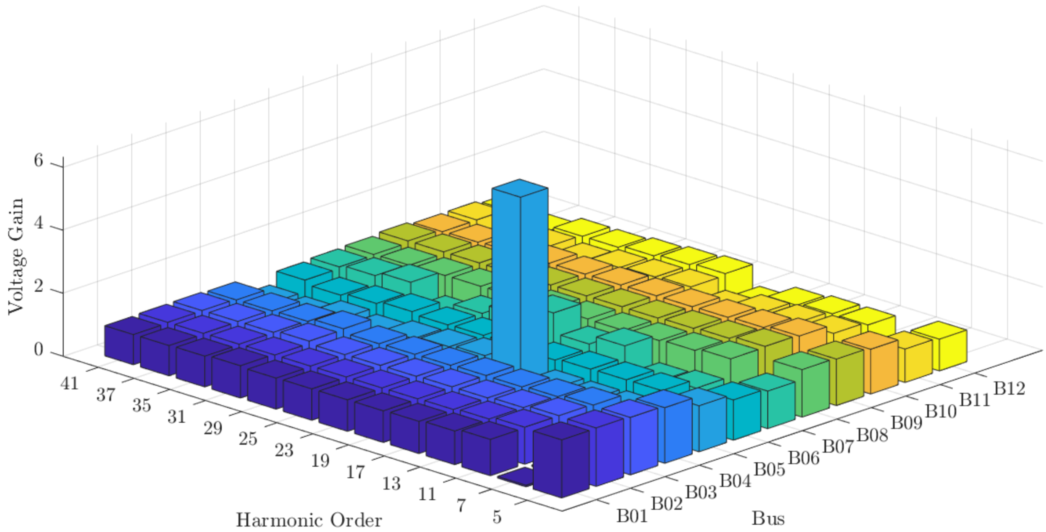


Figure 6.10: Harmonic voltage gain factor for each harmonic order when the filter is located at different busses in the system.

It can be seen in the figure that there are not many amplification factors that is exactly one. The impedance can thus been seen to be slightly affected in all harmonic orders in most of the cases. Furthermore, it can be seen that the 5th harmonic is amplified the most in most of the cases, which is the harmonic order closest to the targeted harmonic order, namely the 7th. The change in harmonic voltages can be seen to be positive in some cases, and negative in others, so a reduction in some harmonic levels other than the targeted can also be expected to occur in some of the cases. It can though be seen that the 5th and 11th order amplification factor generally are above one, resulting in an increase in the harmonic voltage.

A slight change in the impedance can shift a resonance point so that a specific harmonic order is increased drastically. That can be seen to occur when the filter is located in Bus 5. The 19 order harmonic can there be seen to be increased drastically compared to the others, more specifically by a factor of 5.00. The change in the impedance seen from Bus 5 when a filter is implemented, can be seen in Figure 6.11.

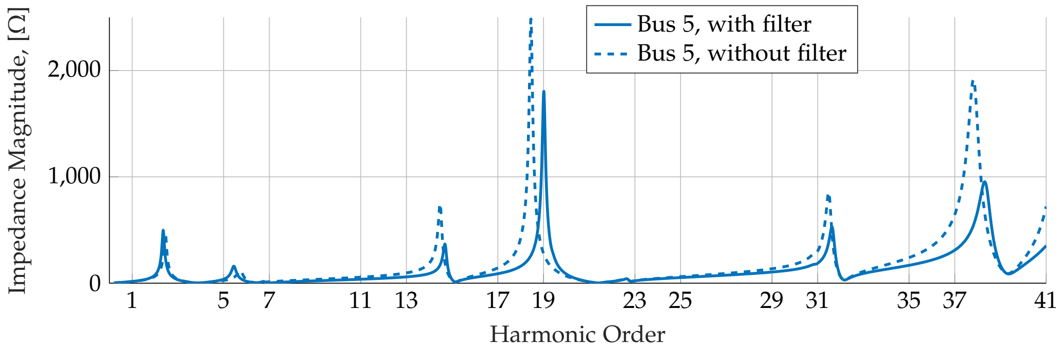


Figure 6.11: Harmonic impedance magnitude, seen from Bus 5, before and after the implementation of the filter. The dashed line illustrates before the implementation, while the solid line illustrate after the implementation.

It can be seen in the figure that the resonance point, that before the filter implementation was at the 18.44 harmonic order, is shifted to the 19.01 harmonic order, and thus a significant amplification in the 19th harmonic order can be expected.

The anti-resonance phenomena after a filter implementation is seen to be highly dependent on the impedance seen from the bus at which the filter is implemented, and thus also the system itself. There is a higher risk for the phenomena in some cases than others, namely the cases where the increase in impedance at the frequency at which harmonic orders are present in the system, is significantly high. It can be seen that an analysis of the impedance seen from the bus at which the harmonic emission source is located, before and after the filter implementation, can predict the amplifications that are to be expected. Tuning of the filter implemented is thus of great importance in order to avoid anti-resonance phenomena.

As the location of the harmonic emission source is not always know, an analysis of anti-resonance phenomena when the filter and the harmonic emission source is not located in the same bus is presented in the following section.

6.3 Analysis of Anti-Resonance Phenomena

An analysis of the anti-resonance phenomena where the location of the harmonic emission source and the filter not necessarily are implemented in the same bus, is presented in this section. The filter is in the analysis placed in all the busses, from Bus 1 to Bus 12, and the same is done for the harmonic emission source. The amplification of each harmonic order in all the cases has been reviewed in the analysis, where it was seen that the main issue is regarding the 5th harmonic order, as the filter implemented targets the 7th harmonic order, as explained in Section 6.1.

A more thorough presentation of the analysis, can be found in Appendix D. In the analysis the presentation of the anti-resonance phenomena is divided into three sections. Firstly, the amplification that occurs in the bus at which the harmonic emission source is implemented, is explained, namely in Appendix D.1. Thereafter, the change in the propagation gains in a system, that the implementation of filters can cause, is explained. That includes how a filter implementation changes how harmonics propagate through a system, and is explained in Appendix D.2. Lastly, the change in the harmonic levels that occurs in the bus at which the filter is implemented, is explained in Appendix D.3.

The anti-resonance phenomena is dependent on the location of the harmonic emission source, as that determines the harmonic levels before a filter implementation. As mentioned, the impedance seen from each bus in a system is different, and consequently the harmonic levels in the system change dependent on the location of the source. After a filter implementation the impedance seen from the bus at which the harmonic emission source is located at changes. Furthermore, it changes differently dependent on the location and the impedance of the filter, as that affect the impedance differently. The change in impedance, as a result of a filter implementation, seen from the bus at which the harmonic emission source is located in, also consequently effects the harmonic propagation gains in the system. That is because it affects the path the harmonic current flows in the system. As a result, the harmonic levels in each bus in the system is different.

The 5th harmonic order, is, as explained, at a higher risk of amplification when a filter targeting the 7th harmonic voltage is implemented in the system. When both the location of the filter, and the location of the harmonic emission source is varied, the amplification of the 5th harmonic order in the bus at which the harmonic emission source is located in, varies as well. That can be seen in Figure 6.12.

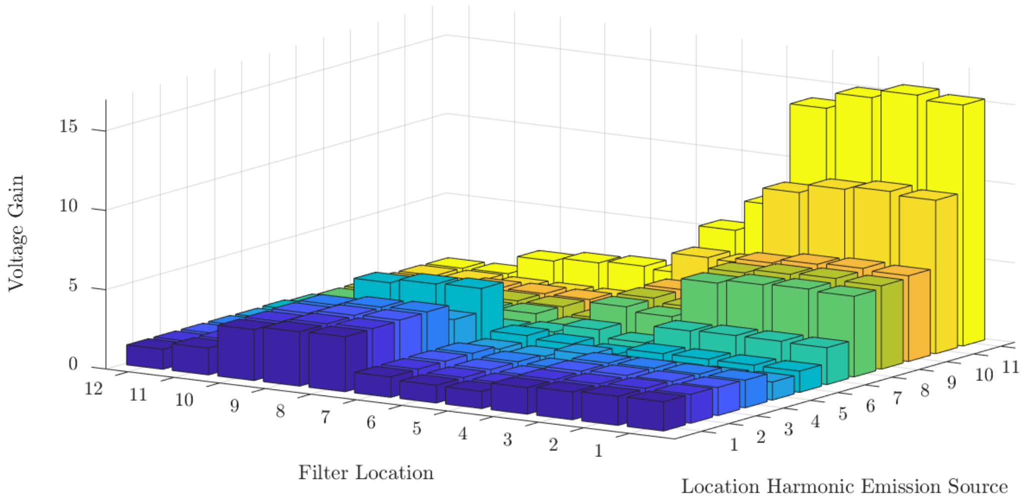


Figure 6.12: 5th order harmonic voltage gain factor at the bus at which the harmonic emission source is located, when the location varies for both the harmonic emission source and the filter.

In addition to the change in the amplification in the 5th harmonic order in the bus at which the harmonic emission source is located at, seen in the figure, the resulting 5th harmonic order in the rest of the system also changes. So does the the amplification of the other harmonic orders. An example is when the harmonic emission source is located in Bus 1 and the filter is implemented in Bus 5. The resulting harmonic voltage gains in the system can be seen in Figure 6.13.

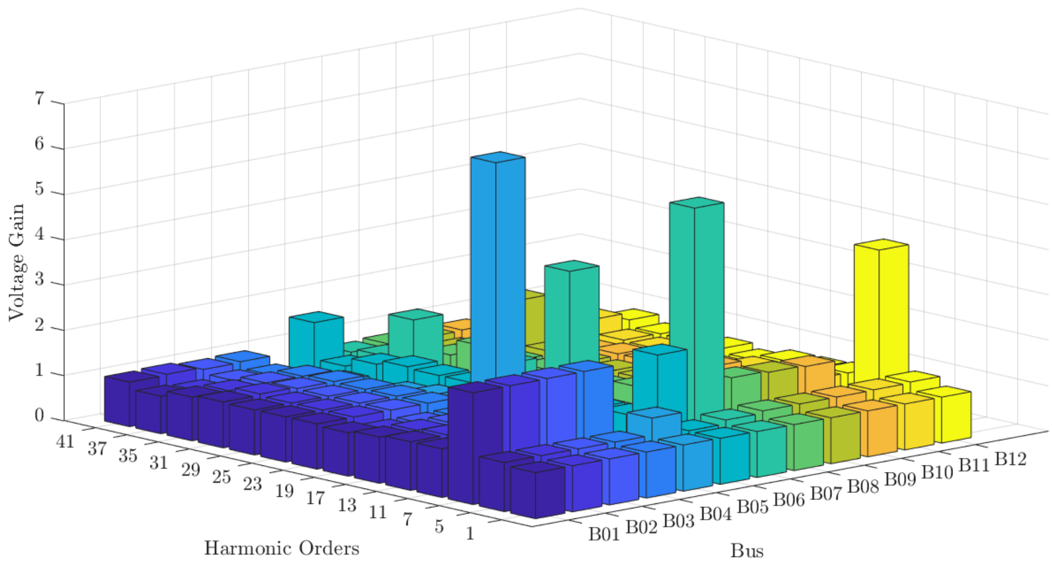


Figure 6.13: Voltage gain at all busses in the system, for all harmonic order, when the harmonic emission source is located in Bus 1, and the filter is implemented in Bus 5.

A further explanation of the harmonic levels seen in the figures can be found in the mentioned appendix, namely Appendix D.

In general, the anti-resonance phenomena is dependent on the impedance of the filter that is introduced to a system, seen from the bus at which the harmonic emission source is implemented in. Furthermore, it is dependent on the location of both the harmonic emission source and the location of the filter. It can though be difficult to predict the amplifications based on the harmonic levels in a system before the filter implementation. Especially if the location of all the harmonic emission sources in a system are not know. An alternative way to reduce the anti-resonance phenomena is to iteratively review the harmonic voltage on a system-wide level after the filter implementation, and adapting the impedance of the filter, aiming to avoid significant amplifications. In other words, tuning the filter, with a focus on the system-wide harmonic levels. Such a method is explained in the following section.

6.4 Filter Tuning with a Focus on Anti-Resonance Phenomena

The cause of the anti-resonance phenomena is the change in impedance after a filter implementation. Therefore, changing the impedance of the filter can reduce the amplifications that occur for the other harmonic orders than the targeted frequency in the bus at which the filter is implemented. Furthermore, it can reduce the amplifications that occur on a system-wide level. That can be done in an iterative manner, by adjusting the filter and reviewing the harmonic voltage levels system-wide until some requirements are met.

An analysis of how filter tuning can reduce anti-resonance phenomena is presented in this section. In the analysis the filter is tuned by adjusting the rated reactive power of the filter, Q, as well as the quality factor, q. Firstly, how the tuning affects the reduction of the target frequency and the amplifications of the other harmonic orders present in the system, is presented. Thereafter, a general optimisation algorithm, using a search function, namely a BOBYQA algorithm for bound constrained optimisation without derivatives, [19], which aims to minimise an adjustable cost function, will be presented. And lastly, several cases will be presented, in order to enlighten the flexibility of the algorithm that is used, and investigate the effectiveness.

6.4.1 Anti-Resonance Phenomena Versus Targeted Reduction

When tuning a single-tuned filter by adjusting the rated reactive power, Q, and the quality factor q, the reduction of the target frequency in the bus at which the filter is implemented, and the anti-resonance phenomena, can be adjusted as well. Whether a filter that effectively reduces the target frequency at a given bus, causes an increased risk of anti-resonance phenomena will be analysed in this section.

In Section 6.1, the changes in the harmonic voltage levels after a filter implementation in Bus 1, when the harmonic emission source was located in the same bus, was presented. The filter, aiming to reduce the 7th harmonic voltage, with a Q of 200 and a q of 50, was seen to effectively reduce the 7th harmonic voltage. However, it was also seen to cause anti-resonance phenomena. The 5th harmonic voltage was seen to be significantly amplified.

By maintaining the quality factor, q, of the filter at 50, and adjusting the rated reactive power Q a change in both the amplification of the 5th harmonic order, and the reduction of the 7th harmonic order occurs. That can be seen in Figure 6.14. The filter and the harmonic emission source is both maintained at Bus 1 in this case.

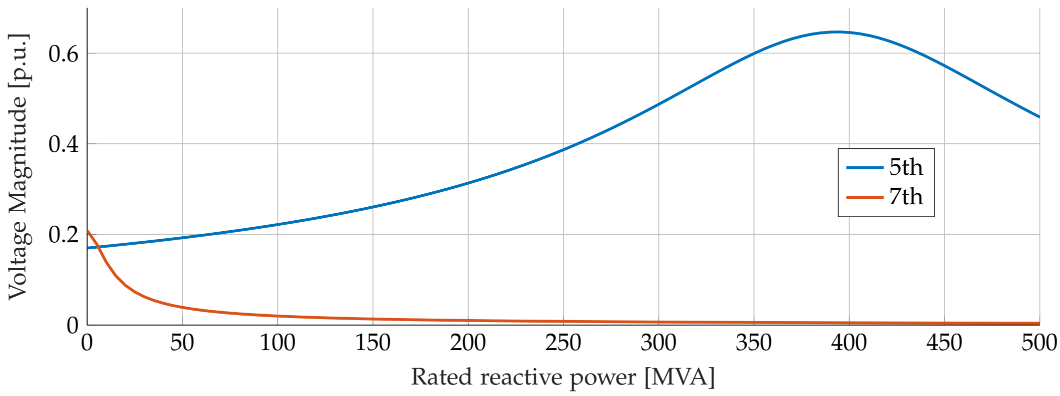


Figure 6.14: 7th and 5th harmonic voltage level in Bus 1, when adjusting the rated reactive power, Q, of the filter, and maintaining the quality factor, q, at 50.

It can be seen in the figure that the amplification and the reduction in the 5th and 7th order harmonic voltage respectively, do not change linearly when adjusting the rated reactive power of the filter. A more effective reduction occurs when the Q is adjusted from 0 to 100 MVA. The slope of the curve is thereafter reduced, and will not cause a significantly improved reduction. Furthermore, it will cause an even higher increase in the 5th harmonic voltage.

The slope of the 5th harmonic voltage can be seen to increase until the voltage level reaches a maximum, in this case when Q is 395 MVA. Then, if the rated reactive power of the filter is increased, the voltage level can be seen to decrease. That is because the parallel resonance point around the 5th harmonic, is then shifted to a lower frequency than the 5th order, instead of being shifted closer to the 5th order. That increases the risk to significantly impact the fundamental frequency. The rated reactive power of the filter is also a expression for the size of the filter at fundamental frequency, meaning the amount of reactive power generated to the system. It thus has an impact on the magnitude of the fundamental voltage. Furthermore, it should be kept in mind that the reactive power also takes up the power capacity in system. The impact the increase in Q has on the other harmonic orders present in the system, and the fundamental voltage level, in Bus 1, can be seen in Figure 6.15.

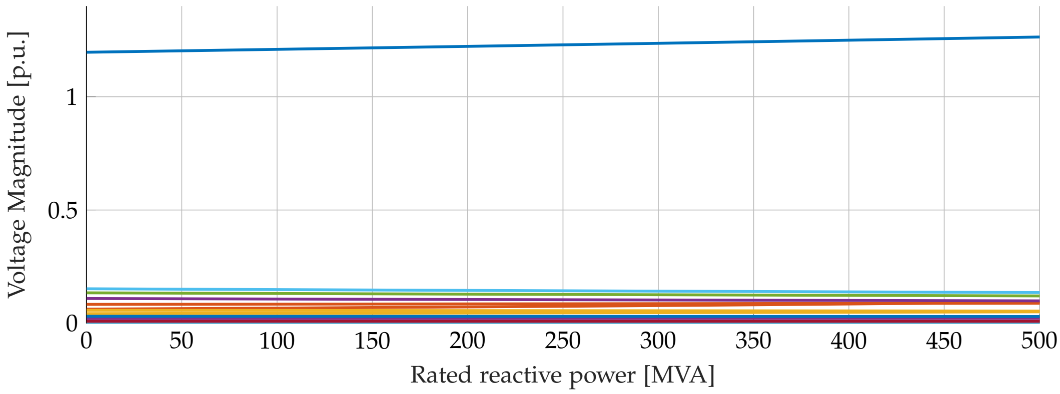


Figure 6.15: Fundamental and harmonic voltage levels in Bus 1, when adjusting the rated reactive power, Q, of the filter, and maintaining the quality factor, q, at 50. All the harmonic orders present in the system, except the 7th and 5th, are displayed in the figure. The blue line in the top of the figure, indicates the magnitude of the fundamental voltage.

The blue line in the top of the figure indicates the fundamental voltage, which can be seen to increase with the increased Q-value, as explained. It is more difficult to see the change in the harmonic voltage levels at other orders in the figure, and more details can be seen in Figure 6.16.

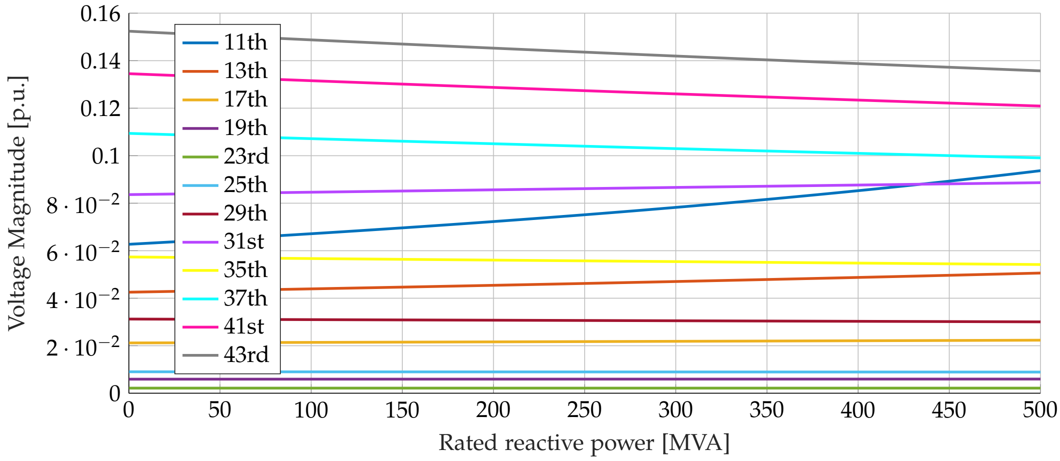


Figure 6.16: Harmonic voltage levels in Bus 1, when adjusting the rated reactive power, Q, of the filter, and maintaining the quality factor, q, at 50.

It can be seen in the figure that the high harmonic order decreases, when the Q increases, while the lower order harmonics increases. That is because of the change in impedance, the filter introduces to the total system impedance seen from Bus 1, in this specific case. It should though be noted that the impact on the different harmonic orders are system dependent. The change in impedance, seen from Bus 1, can be seen in Figure 6.17.

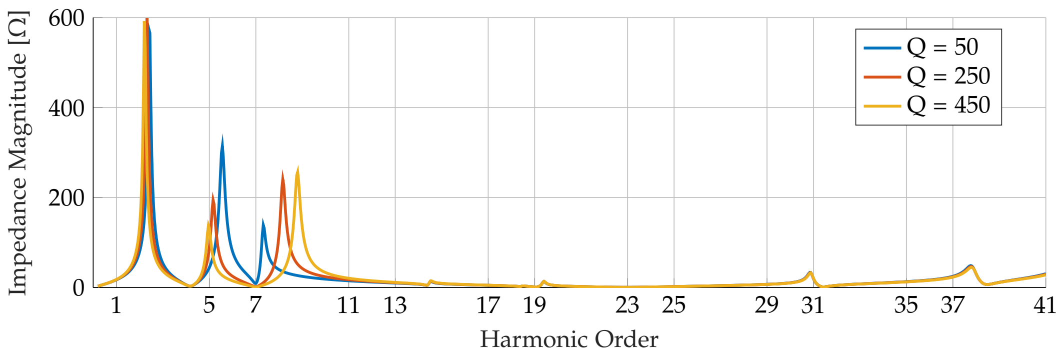
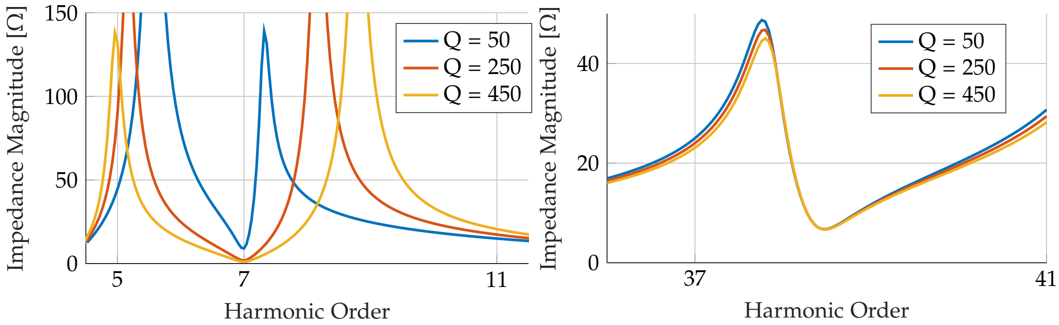


Figure 6.17: Impedance magnitude seen from Bus 1, when q is maintained at 50, and Q is set to 50, 250 and 450 MVA.

It can be seen in the figure that increase in Q has more significantly impact on the impedance in the frequency range within a close vicinity to the target frequency, rather than the frequency range further away. A more detail view of the impact the low and high frequency range can be seen in Figure 6.18a and 6.18b respectively.



(a) Impedance magnitude seen from Bus 1, in a lower frequency range.

(b) Impedance magnitude seen from Bus 1, in a higher frequency range.

Figure 6.18: Impedance magnitude seen from Bus 1, in the low and high frequency range, when q is maintained at 50, and Q is set to 50, 250 and 450 MVA.

It can be seen in Figure 6.18a that the increase in Q shifts the parallel resonance points away from the target frequency toward the 5th and 11th harmonic order, which increases the impedance at those harmonic orders. However, the parallel resonant point around the 5th harmonic order can be seen to be shifted to a lower frequency range when the Q becomes excessively high. The impedance of the 5th harmonic order then reduces again. In Figure 6.18b it can be seen that at higher frequencies there is only a slight reduction in the magnitude of the impedance, as the Q increases. The change in Q thus impacts the different harmonic orders differently, as previously seen in Figure 6.16. Furthermore, it can be seen that the increase in Q increases the reduction of the impedance at the target frequency.

The non-linear behaviour that the reduction and amplification can be seen to have, also applies when adjusting the quality factor q. The resulting 5th, 7th and 11th order harmonic voltage in Bus 1, when both the Q and the q is adjusted, can be seen in Figure 6.19.

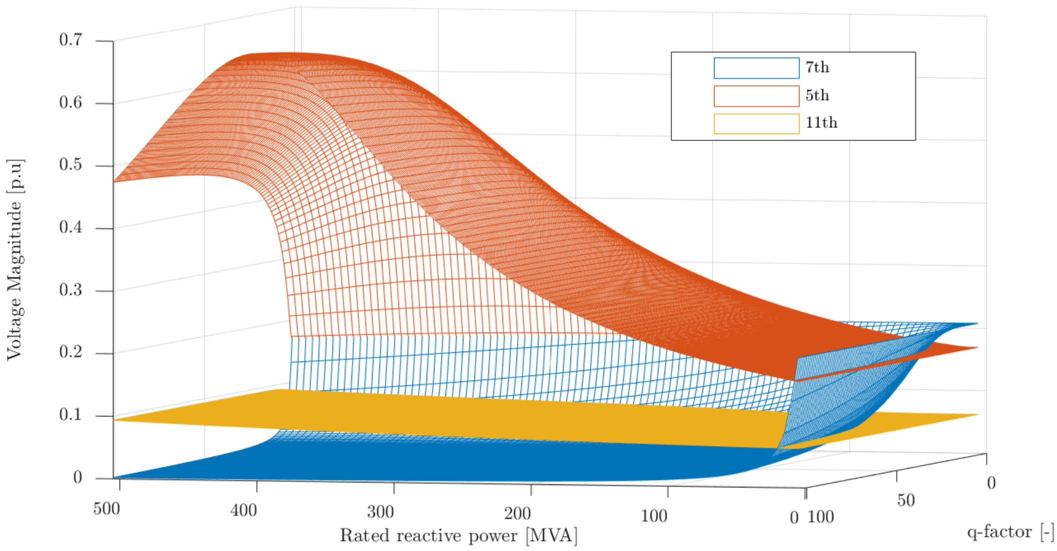


Figure 6.19: 5th, 7th and 11th harmonic voltage levels in Bus 1, when the rated reactive power, Q, and the quality factor, q, is adjusted.

It can be seen in the figure that the impedance of the 11th order harmonic is not as affected by the filter. When both the Q and the q are high, the 11th harmonic is amplified by a factor of 1.5, which is the highest gain of that harmonic order seen to occur for the given adjustments. Furthermore, it can be seen that an effective reduction in the 7th harmonic can not be achieved with a excessively low q-factor.

An optimisation algorithm, striving to find a Q and q of the single-tuned filter, in order to adjust the reduction of the target frequency and the level of amplification, is presented in the following section. Weight factors are used to adjust the focus of the reduction of the target frequency, and the anti-resonance phenomena on a system-wide level.

6.4.2 Optimisation Algorithm

A general optimisation algorithm, used to adjust the anti-resonance phenomena and the reduction in the target frequency, by tuning the filter, is presented in this section. The filter is adjusted according to the algorithm which aims to minimise the cost function, which is defined as seen in Equation 6.3.

$$g_{minimise}(Q, q) = A(Q, q) + B(Q, q) + C(Q, q) \tag{6.3}$$

In the equation, Q and q is the mentioned rated reactive power and the quality-factor of the filter. The algorithm is, as mentioned, based on the BOBYQA algorithm for bound constrained optimisation without derivatives, [19]. It is set to measure the voltage levels in the system, including all the harmonic voltage levels present, in all the busses in the system, for each given Q and q. It then adjusts the mentioned values, with the aim to minimises the defined cost-function. The A-, B- and C-term in the cost-function, seen in Equation 6.3, are defined as seen in Equation 6.4, 6.5 and 6.6 respectively.

$$A(Q,q) = w_h \cdot \Big(\Delta V_h(Q,q) \text{ if } \Delta V_h(Q,q) > 0\Big) \tag{6.4}$$

$$B(Q,q) = w_t \cdot \Big(V_{h,target}(Q,q)\Big) \tag{6.5}$$

$$C(Q,q) = w_f \cdot \Big(|\Delta V_{fundamental}(Q,q)|\Big) \tag{6.6}$$

In the Equation 6.4, h is all the harmonic orders that are present in the system with the exception of the targeted harmonic in the bus at which the filter is implemented. So the algorithm is aiming to reduce anti-resonance. ΔV_h, seen in the equation, is defined as seen in Equation 6.7.

$$\Delta V_h = V_{h,filter} - V_{h,nofilter} \tag{6.7}$$

The cost function thus only minimises the change in the harmonic voltage, if the change corresponds to anti-resonance, meaning that the voltage levels after the filter implementation is larger than it was before the filter implementation.

$V_{h,target}$, seen in Equation 6.5, is the target frequency in the bus at which the filter is implemented, and the aim is naturally to minimise it.

In equation 6.6 it can be seen that the cost function also can be set to minimise any change in the fundamental voltage.

Each of the harmonic orders can be weighted differently, by adjusting w_h for each harmonic order, h. So can the minimisation of the voltage of the target frequency, which is done by adjusting the weight w_t, and the weight of the change in the fundamental voltage, by adjusting the weight w_f. So, if the 7th order harmonic is targeted, and equipment in the bus is also sensitive to 5th harmonic voltage, it would make sense to put more weight on the 7th and 5th harmonic orders, than the other harmonic orders.

The algorithm could be more advanced by including the target frequency as a parameter, which is further discussed in Section 6.5. Furthermore, the economical price of the filter could be included, and the harmonic limits in the system, which also is discusses in the mentioned section.

The reactive power of the filter Q and the quality factor q is then adjusted in order to minimise the cost function. The limits set for the filter is as follows;

- Q_{min} = 0.1
- Q_{max} = 500
- q_{min} = 0.1
- q_{max} = 100

Excessively low and high Q and q values are not realistic when implementing a single-tuned filter in a power system. The limits has though been set to extreme values in order to enlighten the effect it has on the harmonic levels.

6.4.3 Optimisation of Local Single-Tuned Filter

The implementation of a single-tuned filter, aiming to reduce the 7th harmonic order in the system, when a harmonic emission source is located in Bus 1, was seen to reduce the 7th order harmonic voltage, but also to amplify other harmonic orders, as explained in detail in Section 6.1. The 5th harmonic order was seen to increase from 0.17 p.u to 0.31 p.u, meaning by factor of 1.844, and was the harmonic order that was amplified the most on a system-wide level.

If the algorithm, explained in Section 6.4.2, is only set to minimise the 7th order harmonic voltage, the resulting rated reactive power, Q, and quality factor, q, is maximised, and thereby set to 500 MVA and 100. However, if an equal weight is set to minimise the positive change in the 5th order harmonic voltage, the resulting Q and q is 44.18 and 100 respectively. The description of the resulting filters, and their respective Q and q can be seen in Table 6.2.

Table 6.2: The parameters of the filter with different aims.

Filter	Q [MVA]	q [-]	Description
Filter 1	200	50	Filter from Section 6.1.
Filter 2	500	100	Optimised to minimise the 7th order harmonic voltage.
Filter 3	44.18	100	Optimised to minimise the 7th order harmonic voltage, and to minimise the positive change the 5th order harmonic voltage.

The resulting harmonic voltage in the two cases, compared to the values with no filter, and with the filter introduced in Section 6.1 can be seen in Figure 6.20.

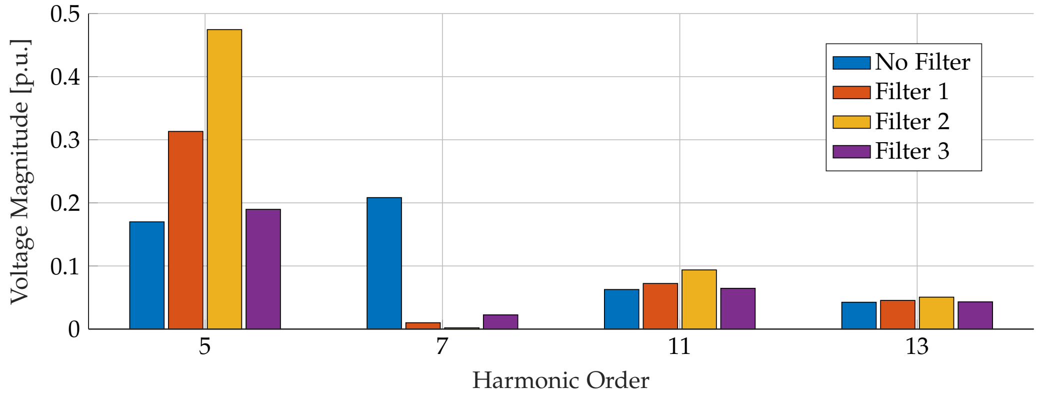


Figure 6.20: Harmonic voltage level in Bus 1 without filter, with the initial filter (Filter 1), and with the optimised filters (Filter 2 and Filter 3).

It can be seen in the figure that the 7th harmonic voltage is significantly reduced by all the filters. However, the 7th order harmonic voltage is the lowest when the filter that is optimised only to reduce that particular voltage, is implemented. Furthermore, it can be seen that the 5th order harmonic voltage is amplified the most by the same filter, namely Filter 2. Filter 3 can be seen to reduce the 7th harmonic voltage the least, however, it is still a significant reduction. Furthermore, it can be seen to not increase the 5th harmonic voltage as much as the other two filters.

It can be seen that the filter that is optimised to minimise the anti-resonance phenomena, in this case the amplification of the 5th harmonic order in the bus at which the filter and the harmonic emission source is located, while still minimise the 7th order harmonic voltage in the same bus, does that effectively. However, this is a simplified case, where the harmonic propagation gains do not change as a result of the filter implementation. Therefore, no other significant amplifications occur is the system. A more complex case, where the filter and the harmonic emission source is located in different busses, so the system-wide harmonic levels need to be considered, is explained in the following section.

6.4.4 Optimisation of Single-Tuned Filter on a system-wide Level

When the location of a harmonic emission source in a system is not known, the filter might be implemented in a different bus than the harmonic emission source, due to a high level of the harmonic voltage of a specific frequency. The analysis of such a case is presented in this section. The harmonic emission source is located in Bus 1, while the filter is located in Bus 6, aiming to reduce the 7th order harmonic voltage.

A reduction of the 7th order harmonic voltage can be achieved by setting the cost function to tune the filter with the aim to minimise the 7th order harmonic voltage in Bus 6, and nothing more. However, that might not reduce the 7th order harmonic voltage on a system-wide level, or even amplify it, as the propagation gains in the system changes as a result of the filter implementation.

The cost function can then be adjusted to minimise the 7th order harmonic on a system-wide level, with an equal weight on each bus. Furthermore, in order to reduce the amplifications of the other harmonic orders in the system, the change in those harmonic voltage magnitudes, as well as minimising the 7th, can be included in the cost functions. The parameters of the different filters implemented, with different aims can be seen in Table 6.3.

Table 6.3: The parameters of the filters with different cost-functions.

Filter	Q [MVA]	q [-]	Description of cost-function
Filter 1	500	100	Minimise 7th order harmonic voltage in Bus 6.
Filter 2	500	0,532	Minimise 7th order harmonic voltage on a system-wide level.
Filter 3	110,5	100	Minimise 7th order harmonic voltage, and the change in the other harmonic orders, in Bus 6.
Filter 4	100	1,95	Minimise 7th order harmonic voltage, and the change in the other harmonic orders, on a system-wide level.

It can be seen in the table that when the only aim is to reduce the 7th harmonic voltage in Bus 6, the Q and the q is maximised. If the aim is to reduce the 7th harmonic order on a system-wide level, it can be seen that the q is reduced significantly, which increases the resistance of the filter and provides damping. Filter 2 has a resistance of 87.72 Ω, while filter 1 has a resistance of 0.47 Ω.

Furthermore, it can be seen that Filter 3 and Filter 4 has a significant reduced Q-value, compared to Filter 1 and Filter 2, where the aim is to reduce the amplifications in the system. It can again be seen that when the harmonic levels on a system-wide level is of interest, the resistance in the filter is increased.

The resulting 7th harmonic voltage in the system after the filter implementations, compared to the levels before the implementations, can be seen in Figure 6.21.

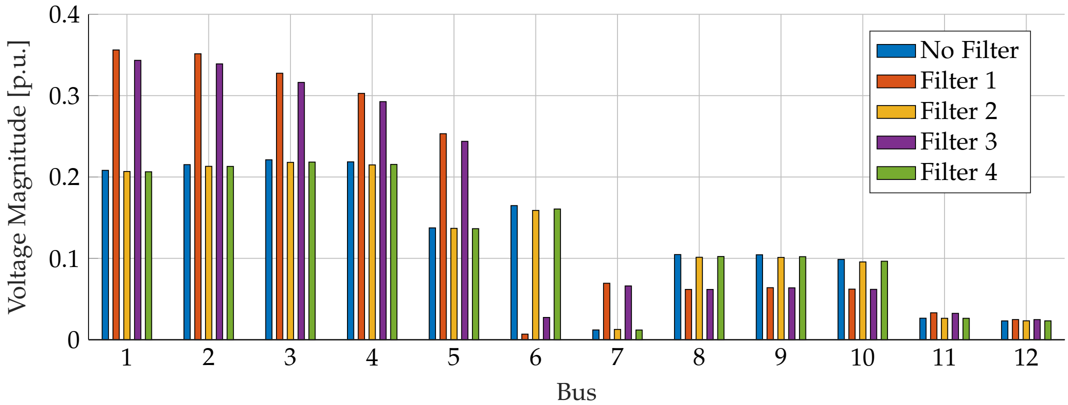


Figure 6.21: 7th order harmonic voltage level in the system without filter, compared to the levels after the implementation of the of the different filters in Bus 6.

It can be seen in the figure that when the aim is to reduce the 7th harmonic voltage in Bus 6, and in Bus 6 only, meaning Filter 1, the reduction in that bus is effective. However, it can be seen that the 7th harmonic voltage levels are increased significantly in the other busses in the system. Furthermore, it can also be seen that the reduction of the 7th harmonic voltage in Bus 6, also is effective when the aim is to reduce the 7th order harmonic voltage in Bus 6, as well as minimising the amplifications of the other harmonic voltage levels in the same bus, namely Filter 3. It can though be seen, that also in that case the 7th harmonic voltage is significantly amplified on a system-wide level.

A minimisation of the amplification of the 7th order harmonic on a system-wide level is seen to be low, when that is weighed as much as minimising it in Bus 6, namely Filter 2 and Filter 4. However, the general reduction, compared to the levels when there is no filter in the system, is small.

Filter 4, can be seen not to reduce the 7th harmonic voltage in Bus 6, namely the bus at which the filter is implemented, much at all. Furthermore, it can be seen not to effect the 7th order harmonic voltage much on a system-wide level. It is set to weight the amplifications of the other harmonic orders, as much as the 7th, on a system-wide level, which results in a small reduction of the 7th harmonic voltage. The resulting 5th order harmonic levels, on a system-wide level, can be seen in Figure 6.22.

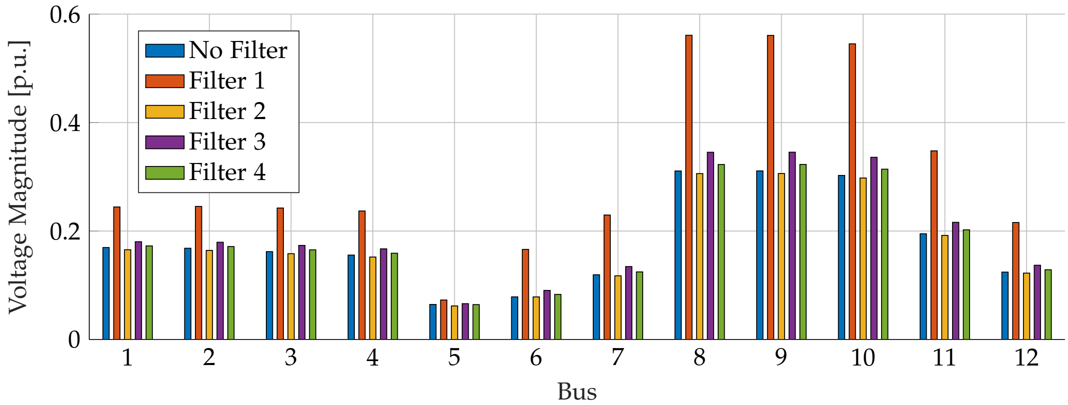


Figure 6.22: 5th order harmonic voltage level in the system without filter, compared to the levels after the implementation of the of the different filters in Bus 6.

It can be seen in the figure that Filter 1 causes amplifications of the 5th harmonic voltage in all the busses in the system. Furthermore, it can be seen that the Filter 3 also causes slight amplifications in all the busses. Those are the filters that are set to minimise the 7th harmonic voltage in Bus 6, and with and without a focus on anti-resonance in that bus. Filter 3, can be seen to only slightly amplify the 5th harmonic, in addition to an effective reduction of the 7th harmonic voltage in Bus 6. However, the 5th harmonic voltage levels in the other busses are amplified. Filter 2 and Filter 4, which focuses on the harmonic levels on a system-wide level, can be seen to not affect the harmonic level much at all, so significant amplifications are avoided.

The weight on the reduction of the target frequency, and the weight of the minimisation of the anti-resonance phenomena needs to be well considered when tuning a filter. It can be seen that if the reduction of the target frequency is weighted heavily, it is a big risk of anti-resonance on a system-wide level. On the contrary, if anti-resonance on a system-wide level is heavily weighted, the resulting filter might not make much difference in the system. That is further discussed in the following section.

6.5 Discussion and Recommendations

Anti-resonance phenomena is a consequence of the change in impedance as a result of a filter implementation. The focus of this chapter has been on reviewing the amplifications that occurs on a system-wide level after the implementation of a single-tuned filter. The impedance that a single-tuned filter introduces, increases the risk of amplifying other harmonic orders, compared to more common filter types, and has therefore been of focus.

A difference has been seen in the change of the voltage magnitude of the harmonic orders present in the bus at which the harmonic emission source is located in, in the bus at which the harmonic filter is implemented in, and the change that occurs in the propagation gains, after a filter implementation. When a harmonic emission source is located in Bus A in a meshed n-bus system, and a filter is implemented in Bus B, the impedance seen from bus A, changes. As the analysis has been conducted with a harmonic emission source that is modelled as a current source, emitting several harmonic currents, with a specific, and constant, magnitude, the voltage in bus A adapts according to the change in impedance, as seen in Equation 6.8.

$$V(h)_{BusA} = I(h)_{HES} \cdot Z(h)_{BusA} \tag{6.8}$$

In the equation $I(h)_{HES}$ is the current that the harmonic emission source emits, and it is constant, as explained in Section 4. The change in impedance, $Z(h)_{BusA}$, is dependent on the impedance the filter implemented is introducing to the system, seen from Bus A, namely the bus at which the harmonic emission source is implemented in. Adjusting the impedance of the filter, by tuning it, can thus also adjust the amplifications of the other harmonic orders than the targeted frequency, namely the level of anti-resonance.

The impedance seen from each bus in the system is different. The harmonic voltage levels, in the bus at which the harmonic emission source is located, does therefore vary dependent on the location of the harmonic emission source. That is because the level of the voltage harmonics, in that bus, are dependent on the mentioned system impedance. Furthermore, the change in impedance that the filter introduce, changes dependent on the location of the filter with respect to the location of the harmonic emission source. The propagation gains in the system also changes accordingly, and the total harmonic levels does therefore also change.

The change in the harmonic voltage in the Bus B, namely the bus at which the filter is implemented in, is also dependent on the impedance of the filter. It has been seen in the analysis not to be dependent on the location of the harmonic emission source, if the filter impedance is constant. However, it is dependent on the location of the filter, as that determines the impedance seen from that bus before the filter implementation, and therefore also affects the change in impedance, and the resulting anti-resonance.

The harmonic levels system-wide therefore change after the implementation of a filter, dependent on the location and the impedance. An optimisation algorithm has therefore been presented, with the aim of still achieving an effective single-tuned filter, while reducing the levels of anti-resonance. It has been seen that there is a high risk to amplify the harmonic order in close vicinity to the target frequency. In the case when the 7th harmonic is the target, and the 5th harmonic is present in the system, there is a large risk to amplify that harmonic order.

The non-linear relation of the filter tuning, and the anti-resonance and the reduction in the target frequency can result in filter with a heavy reduction in the target frequency, and large levels of anti-resonance. A small adjustment can then reduce the anti-resonance without affecting the reduction of the target frequency significantly. That is an important relation to take into account in filter tuning.

The optimisation algorithm was seen to be able to reduce the amplification in the 5th harmonic significantly, while still reducing the 7th harmonic effectively. That is when the cost function equally weights those two. If the 11 th harmonic also is present in the system, that can also be included in the cost function. And so can an undesirable change in the fundamental voltage. It was also seen that when the weights are sized badly, it resulted in filter parameters that correspond to a filter with hardly any impact on any harmonics, even the target frequency. Furthermore, it should be mentioned if harmonic orders that are not of high risk to be amplified is weighted, it will not affect the resulting filter significantly.

However, the weights in the algorithm are essential. They should be carefully considered, according to the risk of amplifications. It was seen that the risk of amplifying the high order harmonics was small when implementing a filter targeting the 7th harmonic. The weight of impacting the fundamental voltage should also be considered, according to the risk of amplification. In the cases analysed in this report it was seen that an significant risk of amplifying the fundamental was occurring in the region when the reduction of the target frequency was excessive, and anti-resonance phenomena was extreme. That was when the rated reactive power of the filter was unrealistically large.

Furthermore, the weights can be adjusted according to different busses. It has been seen that the risk of amplifications are not the same in all busses, especially if the harmonic emission source and the filter is implemented in the same bus. That is because the filter implementation then does not effect the harmonic propagation gains in the system. A reduction in the bus at which the harmonic emission source is located in would then be sufficient. Furthermore, it should be kept in mind that when the harmonic emission source and the filter are located in different busses, a slight change in the system impedance of a specific order, can cause large changes in the propagation gains in the system, which can cause large harmonic amplifications.

Another parameter that can be included in the algorithm is the target frequency. It was though seen in the analysis conducted that including it, did not change it. It was therefore not included in the explanations. However, in some cases, it might be effective to slightly vary the target frequency, in order to achieve a filter complying with the requirements. Furthermore, one can exclude either the q or Q value from the algorithm, as it was seen that if one is set to a reasonable value, the cost function can still result in an effective filter. The mentioned reasonable value can be found based on a simple analysis, as explained in Section 6.4.1. In regards of the limits of the Q and the q they naturally affect the price of the filter, and the limits can be set accordingly. Furthermore, implementing several single-tuned filters, or a filter with lower risk of anti-resonance phenomena, such as a C-type filter, which include a dampening effect, could also be an option for reducing anti-resonance, further discussed in Chapter 8.

It can, on the bases of the results explained in this chapter, be recommended to only review the harmonic levels in the bus at which the filter is implemented at, if that is at the same bus as the harmonic emission source. However, in the case of several harmonic emission sources, or if the location of the harmonic emission source is not known, it is recommended to review the system-wide harmonic levels when implementing filters. That can be done by the use of the algorithm presented, or similar approaches.

Chapter 7

Conclusion

In the analysis of this report an investigation of system-wide harmonic propagation, including the harmonic levels in the busses in a system, and the levels within the overhead lines and the underground cables, has been presented.

The impact the different system parameters has on the system impedance has been analysed, where it has seen that the increased susceptance in underground cables compared to overhead lines reduces the frequency of the resonance points, which can increase the possibility to amplify harmonics of lower order.

The harmonic propagation has firstly been analysed in a radial system, and thereafter in a meshed system. The harmonic levels has been seen to be both affected by the location of the harmonic emission source, and the system impedance seen from that bus. Furthermore, the system impedance has been seen to be affect the harmonic propagation gains from the bus at which the harmonic emission source is located at, to the other busses in the system. The harmonic levels in the overhead lines and underground cables are seen to follow a sinusoidal waveform which could, together with a harmonic load flow, be used to describe the gains.

It has been seen that the harmonic levels throughout a line can be higher than the levels measured in the busses it is connected to, which means that the lines can be exposed to a higher stress than initially assumed from a harmonic load flow. This can cause damage to the lines like partial discharge, insulation degradation, flash over and excessive sagging.

A method is proposed to calculate the maximum stresses and to find the location at which it occurs. It can be used in conjunction with a harmonic load flow, as it needs the values for the harmonic current and the harmonic voltage at both of the ends of the line. The method has been seen to have sufficient accuracy, if the voltage and current waveform follows a sinusoidal curve. The accuracy has been seen to be reduced if a phase-shift occurs within a close vicinity of the bus defined as the starting point of the waveform. This can however be solved by switching the starting point to the opposite bus. The accuracy will therefore only decrease if phase-shift occurs at both busses, which is a special occurrence and a different method should be used.

The anti-resonance phenomena is caused by the change in impedance that occurs after a filter implementation. The change in impedance that occurs at the bus at which the harmonic emission source is implemented, can cause a change in the path the harmonic current flows in the system, and thus also changes the propagation gains. That results in different harmonic levels in the entire system, where large amplification in the harmonic voltage can occur at some busses, for some specific harmonic orders.

The harmonic orders that are amplified the most, and the bus at which the large amplification occurs, is determined by the change in impedance, seen from the bus at which the harmonic emission source(s) are located, and the resulting change in the harmonic propagation gains in the system. When implementing a single-tuned filter, it is a higher risk to amplify the harmonic orders within a close vicinity to the target frequency. That can occur in the bus at which the harmonic emission source is located in. Moreover, it can be further amplified in some of the other busses in the system, as a result of the changed harmonic propagation gains.

In the analysis conducted, the harmonic voltage amplification that can occur at the bus at which the harmonic filter is implemented at, is solely determined by the change in impedance seen from that bus, given that the system impedance is not changed. Therefore, if the harmonic emission source was modelled with an impedance, the location would affect the amplifications in the mentioned bus.

The anti-resonance phenomena, caused by a single-tuned filter, can thus be reduced on a system-wide level, by adjusting the impedance of the implemented filter while focusing on the harmonic levels system-wide. A method which tunes a single-tuned filter, with a focus on reducing the target frequency, and the anti-resonance phenomena, has been presented. The method uses an optimisation algorithm, where the aim is to minimise a defined cost function that can be adjusted according to the aim. It is thus an iterative process where the the harmonic levels on a system-wide level, is analysed, while the impedance of the filter is adjusted.

The introduced method, has been seen to be able to significantly reduce the anti-resonance phenomena, while still effectively reducing the magnitude of the targeted frequency. However, a case where an equal weight was put on minimising the anti-resonance phenomena, and minimising the target frequency, was seen to result in no significant change in any of the harmonic orders, in order to enlighten the importance of adjusting the weights in the cost function.

It can thus be concluded that it is possible to reduce the anti-resonance phenomena by carefully choosing the impedance of the filter that is to be implemented in a system. Furthermore, the location of the filter should also be considered, if possible.

Chapter 8

Further Work

In this chapter, different topics which can be investigated further will be presented. This includes more advanced analysis and different approaches.

The system impedance in a meshed system and its effect on the propagation should be investigated further as a change in the propagation has been seen to cause significant amplifications. It has also been seen to significantly affect anti-resonance phenomena and being able to accurately describe this change in the propagation gains could contribute in preventing the phenomena.

The method used to calculate the maximum stress within a line in a system, due to the harmonic level, can be expanded, to include a method to correct the error, if the phase shift occurs at both busses. This could be done by including a virtual bus in the line, and get a third measurement point, which could be used to find a possible offset. An addition could also include validation of the calculations by adding a virtual bus in all lines, and run a second harmonic load flow.

A further analysis can also be conducted on the discussed constant phase displacement for each harmonic order, through specific lines in a system. The propagation gains have been seen to vary dependent on the harmonic emission source, however, the phase displacement has been seen to be constant.

The focus of the report has also been on anti-resonance phenomena caused by the implementation of single-tuned filters. This focus can be broadened to the amplification that occurs due to the implementation of other filter types, and the effect they have on the system impedance seen from the bus at which the harmonic emission source is located at. The c-type filter is a damped filter which could reduce the effect of anti-resonance phenomena. The implementation of several single-tuned filters can also be an option to reduce anti-resonance phenomena, by reducing a harmonic order in close vicinity to the target frequency, like the 5th and 7th.

The focus of the report could be broadened in what regards the harmonic propagation. Lower voltage levels can be included, so the harmonic propagation through transformers between voltage levels can be analysed. A more realistic analysis could also be conducted including both loads, shunt reactors, and properly modelled harmonic emission sources. Furthermore, realistic harmonic limits, and realistically emitted levels could be analysed.

The algorithm used to iterativley adjust the impedance of the filter could be expanded, and include filter costs. Furthermore, more restrictive limits can be set to the possible variables of the filter. That can be done according to availability and cost. Furthermore, the target frequency of the filter can be adjusted, as an adjusted target frequency can in some case improve the reduction. Harmonic limits for each harmonic order can be included, which can give a more effective cost function.

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Appendix A

Harmonic Propagation in Simple Radial Systems

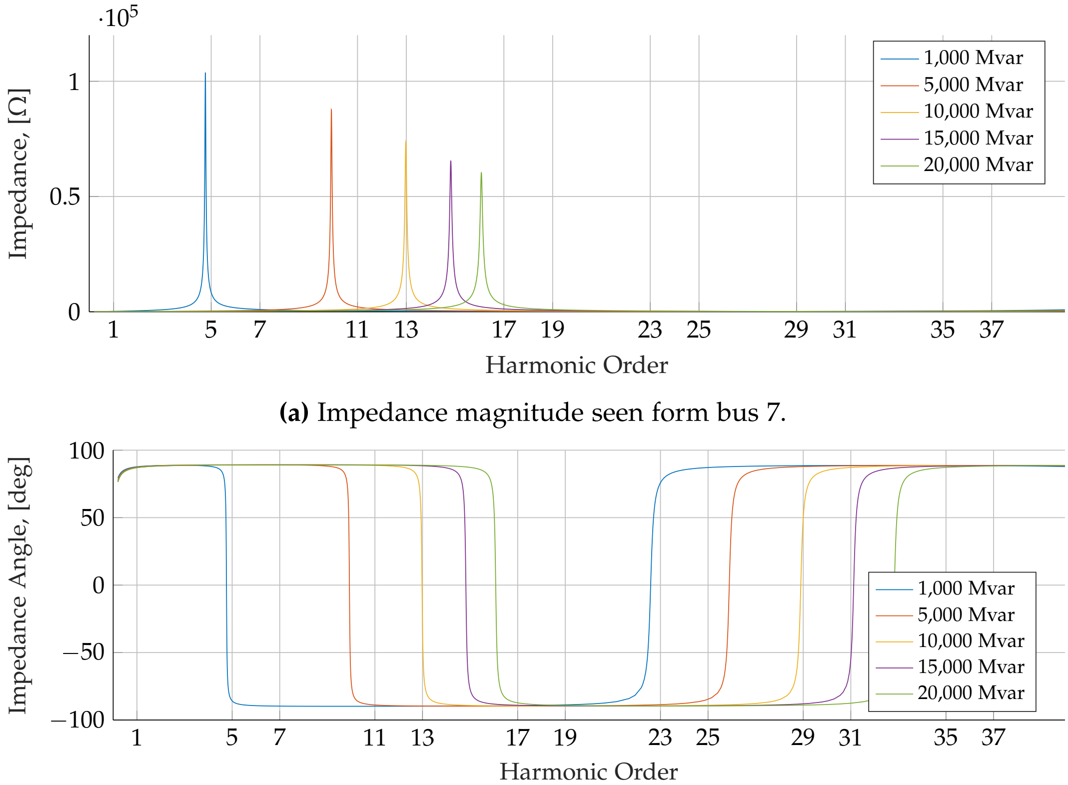
In this Appendix several radial system scenarios is introduced in order to explain how changes in a system can affect the system impedance, and how that affects the harmonic propagation though the system. The scenarios are explained in individual sections and they are compared to the simple case explained in detail in Chapter 5. The cases explained are the following;

- Short circuit power in external grid, while the system voltage is maintained constant. That consequently affect the impedance in the system, which also affect the harmonic propagation gains.
- Replacing the OHLs in the system with UGCs, which as explained in Section 3.2 significantly shifts the resonant points in the system to lower frequencies and therefore also has a significant impact on the harmonic propagation.

A.1 Change in External Grid

The contribution the external grid has on the total system impedance is large in a small radial system. Therefore a change in the short circuit power, while the voltage level is maintained constant, results in a significant change in the system impedance. As seen in Equation A.1, reducing the short circuit power results in an increase in the system impedance, and vice versa. The system impedance with varying short circuit power can be seen in Figure A.1.

$$S_{sc} = \frac{V^2}{Z_{External}} \tag{A.1}$$



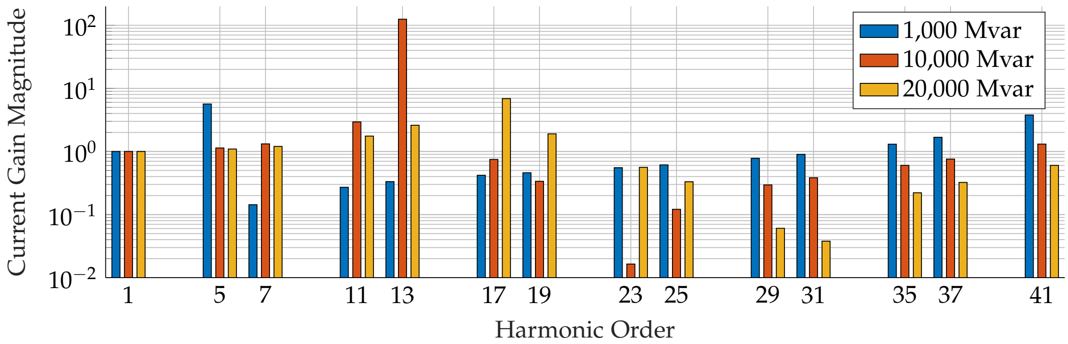
(a) Impedance magnitude seen form bus 7.

(b) Impedance angle seen form bus 7.

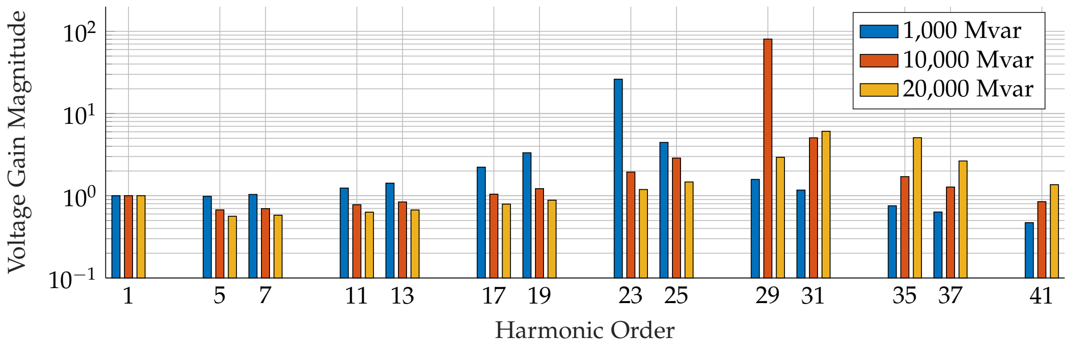
Figure A.1: Harmonics impedance scan from bus 7 in cases with different short circuit power.

Significantly reducing the short circuit power increases the system impedance, which is highly inductive. So the inductance in the system is significantly increased, which increases the magnitude of the parallel resonance points and shifts them to a lower frequency. The angle of the impedance are in these case maintained constant, and highly inductive with an angle of approximately 90 degrees. If the angle was to be reduced towards zero, and more resistive, the total system impedance would also become more resisitve as, as mentioned, the impedance of the external grid is so dominant. A more resisitve grid reduces the resonance peaks, and as the inductance is decreased it will shifts the peaks to higher frequencies.

Higher resonance peaks can cause significantly higher current gains in the system. It can be seen in the case with the lowest level of short circuit power, and thus also the higher resonant peak, that the current gain does not reach an as high level as the case with 10 times as high short circuit power. The reason for this is the frequency at which it occurs. The highest resonance point is seen to occur at 4.7 where the impedance is 1 e5, while at the 5th harmonic order the impedance is reduced to 8 e3. The current gain is thus not as high as it would be if the angle of the system impedance was adjusted and had become slightly more resistive.



(a) Harmonic current gain form Bus 7 to bus 5.

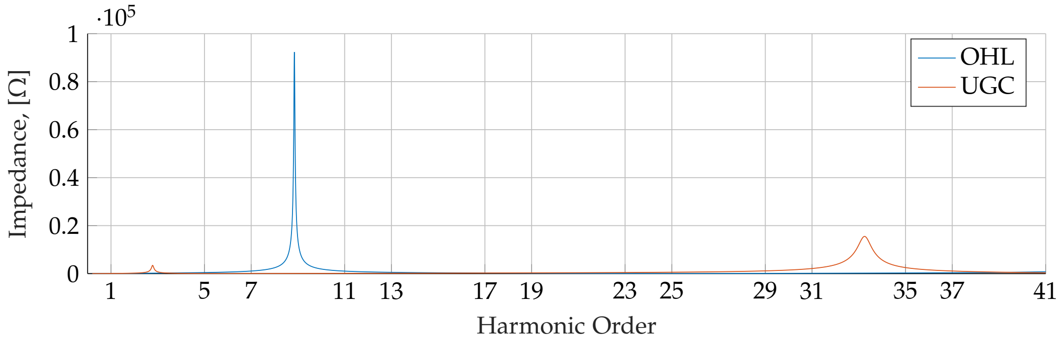


(b) Harmonic voltage gain form Bus 7 to bus 5.

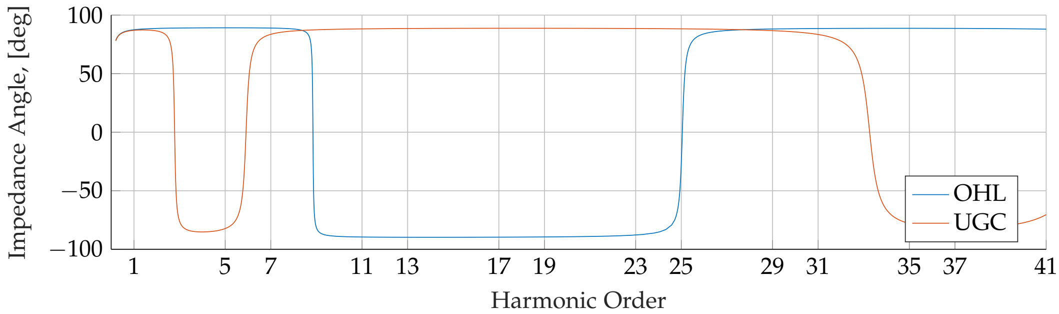
Figure A.2: Harmonic gain magnitudes with varying short circuit power.

A.2 Replacing Overhead Lines by Underground Cables

A comparison of the impedance diagram in the simple radial system when the lines are consisting of OHLs and UGCs, can be seen in Figure A.3. The UGCs implemented are of equivalent length and rating as the OHLs, and are perfectly cross bonded as the OHLs are perfectly transposed. It can be seen that the large capacitance the UGCs introduce is shifting the resonance point to lower frequencies, and it is reducing the magnitude significantly. Therefore two of the resonance point can be seen within the set frequency range, while only one is visible for the OHL as the next appears outside the frequency range.



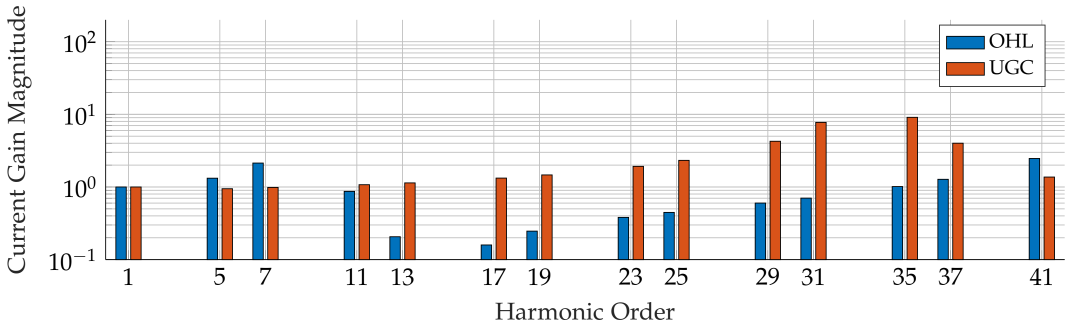
(a) Impedance magnitude seen form bus 7.



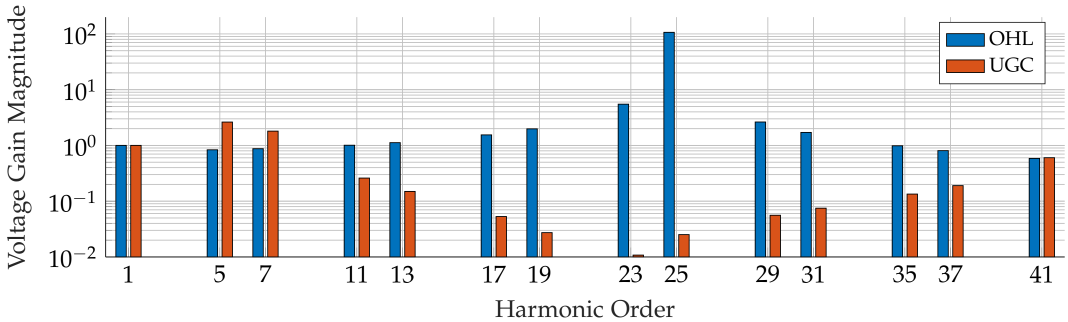
(b) Impedance angle seen form bus 7.

Figure A.3: Harmonics impedance scan from bus 7, comparison of radial system consisting of an OHL and an UGC of equivalent length.

It can be seen in Figure A.4 that the significant change in the impedance is also significantly changing the harmonic gains. It can be seen that the current gains in the region from the 11th harmonic to the 41st harmonic are increased in the case with the UGCs. The impedance of the lines in that region are seen to be inductive in the case with the UGCs and capacitive in the case with the OHLs. It is also seen that the corresponding harmonic voltage gains are reduced in the same range. The phase of the impedance has a significant impact on the gains, as explained in Section 5.1.



(a) Harmonic current gain form Bus 7 to bus 5.



(b) Harmonic voltage gain form Bus 7 to bus 5.

Figure A.4: Harmonic gain magnitudes, comparison of radial system consisting of an OHL and UGC of equivalent length.

Appendix B

Harmonic Propagation in more Complex Radial Systems

Harmonic propagation in a more complex radial system with several radial paths, and in a radial system with several harmonic emission sources, will be explained in this section. An expanded version of the radial system explained in Section 5.1.1, is used in the analysis. Firstly the propagation in a radial system with one harmonic emission source, and several paths, will be explained. Thereafter the propagation in a system with two harmonic emission sources will be explained.

B.1 Explanation of the Expanded Radial System

An expanded version of the radial system, which is explained in Section 5.1.1, is in the following analysis used to explain how harmonics propagate in a system with several paths. A single line diagram of the expanded radial system can be seen in Figure B.1, and the system is referred to as Radial 2. The equivalent grid, which in the diagram is represented by a thévenin equivalent, is the same as the one explained in Section 5.1.1, used in the simple radial system, hereafter referred to as Radial 1. OHL 2a and 2b seen in the figure, are equal to each other, and equal to OHL 2, also explained in the mentioned section. The harmonic emission source implemented, is also the same source as explained in the previous section. The two radial systems are thus referred to as Radial 1, and Radial 2, as seen below;

- Radial 1: Simple radial system explained in Section 5.1.1.
- Radial 2: Expanded radial system, seen in Figure B.1.

The impedance profile in the radial system Radial 2, can be seen compared to the impedance profile in the simple radial system explained in Section 5.1.1, Radial 1, in Figure B.2. As mentioned, Radial 2, is equal to Radial 1, with the exception that

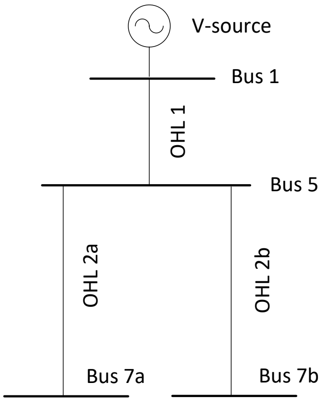
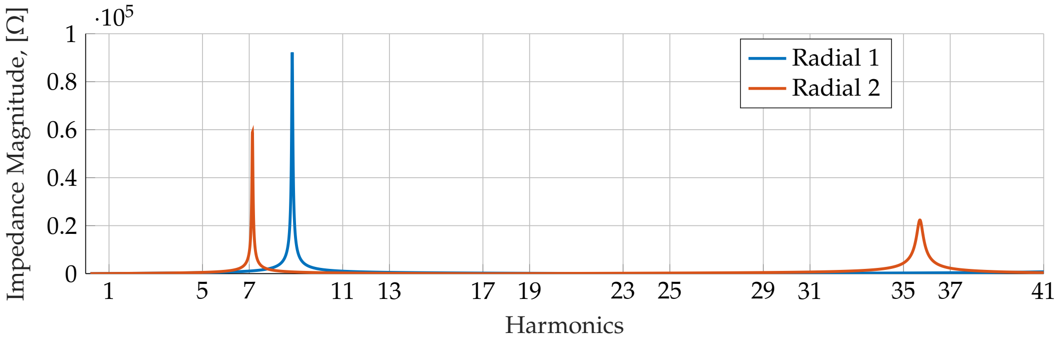
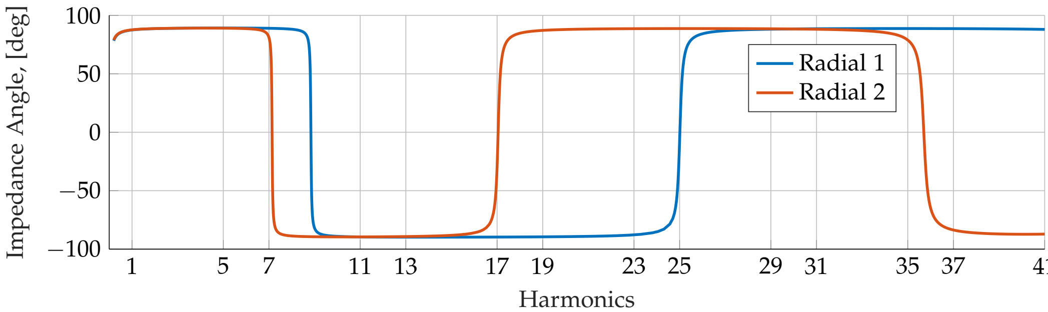


Figure B.1: Single-line diagram of expanded radial test case, Radial 2.

it has an extra branch, that is placed in parallel to an equal branch, namely the branches going from Bus 5 to Bus 7a and 7b.



(a) Impedance magnitude seen form Bus 7 in Radial 1, and seen from Bus 7b in Radial 2.



(b) Impedance angle seen from from Bus 7 in Radial 1, and seen from Bus 7b in Radial 2.

Figure B.2: Impedance magnitude and angle seen from Bus 7 in Radial 1, and seen from Bus 7b in Radial 2.

It can be seen in the figure, that the change in the system changes the impedance seen from Bus 7b, and the impedance has become more capacitive. The resonance points are shifted to lower frequencies, in addition to the fact that they are reduced in magnitude.

The impedance has become more capacitive, seen from Bus 7b, as two OHLs, namely OHL 1 and 2a, are placed in parallel. The equivalent susceptance of the lines are therefore increased, while the equivalent impedance is reduced. The second parallel resonance point is introduced at a frequency, where half the wavelength of the electric signal is equal to the total length of OHL2a and OHL2b. The two lines therefore form a resonance circuit, introducing a resonance point as a half wavelength introduces an impedance equal to that at the end of the OHL2a, as seen in Section 1.2.4. In this case the OHL2a is open circuit and a parallel resonance point is seen.

B.2 Harmonic Propagation in the Expanded Radial System

A change in a system changes the harmonic levels in the system, as it changes the propagation, meaning the harmonic gains. The harmonic voltage gains from the bus at which the harmonic source is located at, namely Bus 7b, to Bus 5, is defined as G75. Furthermore, the harmonic voltage gain from Bus 5 to Bus 1, is defined as G51, and the two gains, in Radial 1 and Radial 2 can be seen in Figure B.3.

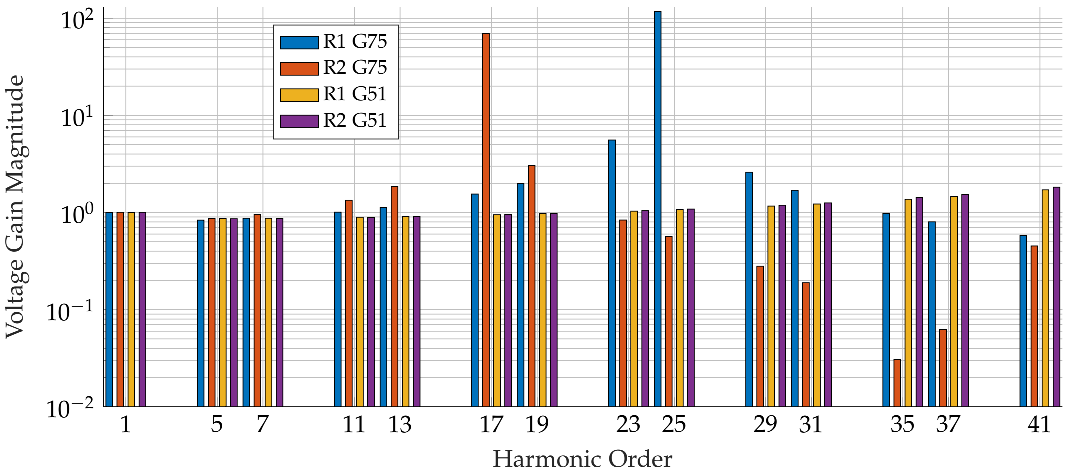


Figure B.3: Comparison between the voltage gains, from Bus 7 to Bus 5 and from Bus 5 to Bus 1, in Radial 1 (Radial 1) and Radial 2 (R2).

It can be seen in the figure that there is not a significant change in the gains of the harmonic orders below the series resonant points. There, a peak in the gains can be seen in the two system, namely at the 17th harmonic order in Radial 2 and the 25th harmonic order in Radial 2. Furthermore, a significant reduction in the gains can be seen to occur in Radial 2 in the inductive region at the frequency range after the series resonant point. The same reduction can be seen in Radial 1, but at a higher frequency range, due to the difference in the impedance. The propagation can be seen to comply with the theory explained in Section 5.1.2.

The harmonic voltage gains from Bus 5 to Bus 7a in Radial 2 can be seen in Figure B.4, and it can be seen that the harmonic voltage is, at all the frequencies, amplified from Bus 5 to Bus 7, as all the gains are above 1.

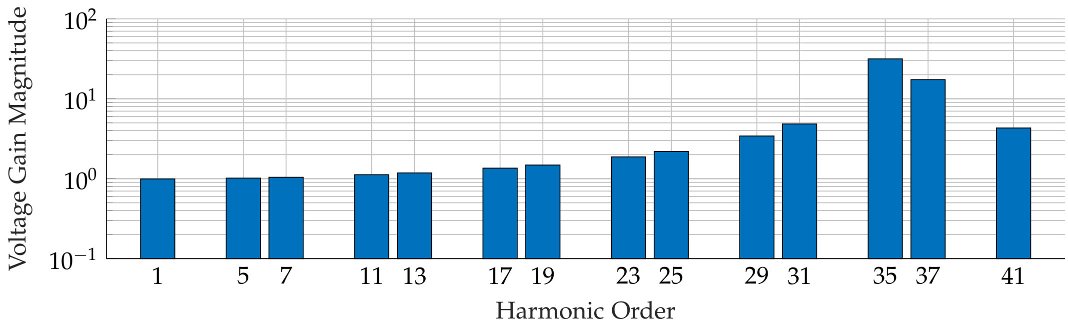


Figure B.4: Voltage gain from Bus 5 to Bus 7a in Radial 2.

The amplification, seen in the figure, occurs as OHL 2a is an open circuit so no current will be present at the end of the line. It will therefore always be at its maximum voltage at the end of the line. The highest gain will therefore be at the frequency, where the quarter wavelength is equal to the length of the OHL 2a. This occurs slightly above the 35th harmonic and the gain around that point can be seen to be the highest in magnitude. This is even more apparent when the OHL 2a and OHL 2b are equal, as they will have the same length, and combined they will appear as a half wavelength line, which is the cause of the 2nd parallel resonance point is present. As OHL 1 is connected in the middle between the two lines it will have little impact on the half wavelength line close the 35th harmonic, as there will be close to zero voltage in Bus 5 and a series resonance impedance in both directions.

B.3 Radial System with Several Harmonic Emission Sources

The resulting harmonic levels in a system with several harmonic emission sources, is explained in this section. The system used in the analysis is Radial 2, namely the system explained in Section B.1. An additional harmonic emission source is implemented in Bus 7a. The angle of the harmonic currents emitted by the two sources are varied, in order to enlighten the effect the initial angle of the harmonic emitted can have on harmonic amplification.

The harmonic emission source in Bus 7b is in all the cases set to 0 degrees, while the angle of the current in the source in Bus 7a is varied, and it is set to 0 degrees, 90 degrees and 180 degrees. The resulting harmonic voltage level in Bus 5 can be seen in Figure B.5.

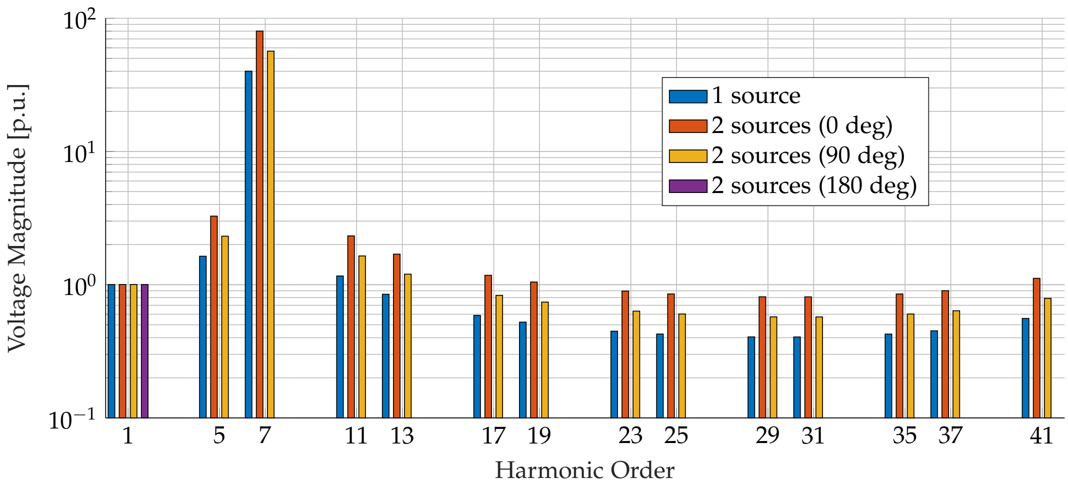


Figure B.5: Voltage magnitude in Bus 5.

It can be seen in the figure that when the two sources are of the same angle the harmonic voltage level in Bus 5 is doubled, while when they are of the opposite angle the harmonic level is fully mitigated. When there is a 90 degree phase shift between the two sources, the total harmonic level in Bus 5 is amplified by a factor equal to the $\sqrt{2}$. If OHL2a was of a different length than OHL2b, it would not be either doubled or fully mitigated, as the voltage from each source would have propagated a different length before they meet and would have different magnitudes and even phase angles. An cancelling effect can therefore occur even when the sources are in phase. These results are consistent with superposition, and it can be seen that different sources can have both an amplifying effect on the total harmonic level, and a reducing effect where the harmonic level actually can be fully mitigated.

Appendix C

Supplementary Analysis of Harmonic Propagation in a Meshed system

Several analysis of the meshed system, explained in Chapter 4, will in this appendix be introduced to give a better understanding of harmonic propagation in a meshed system. The analysis presented is a supplement to the explanations in Section 5.2 in Chapter 5.

C.1 Location of Harmonic Emission Source

The harmonic voltage in the system for the 7th harmonic order, when the harmonic emission source is located in Bus 1, can be seen in Figure C.1 and the mentioned voltage when the harmonic emission source is located at Bus 11 can be seen in Figure C.2.

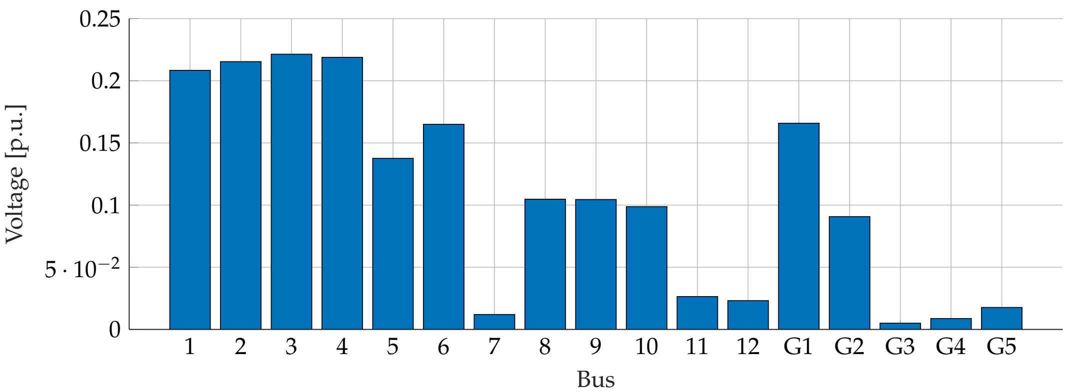


Figure C.1: Voltage magnitude in the system with harmonic emission source at Bus 1 for the 7th harmonic.

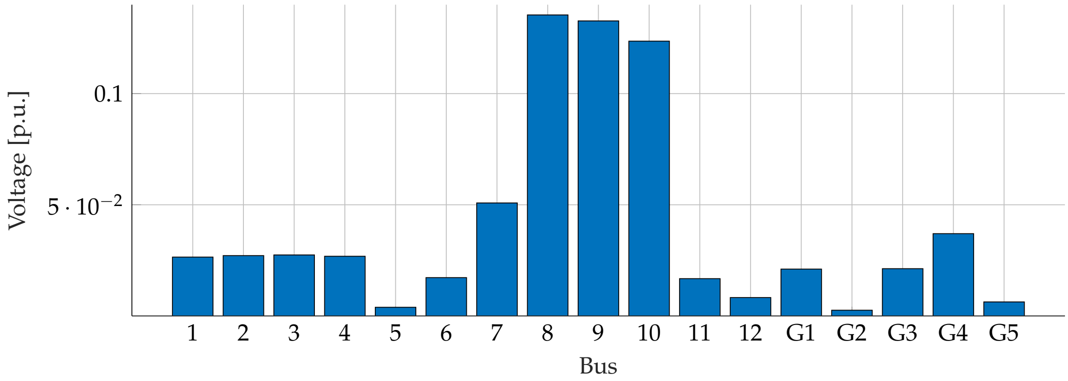


Figure C.2: Voltage magnitude in the system with harmonic emission source at Bus 11 for the 7th harmonic.

The 7th order harmonic voltage levels can be seen to be very different from the voltage level when the emission source is located in Bus 1, both in magnitude at the source bus and regarding the harmonic distribution. This is because the impedance is different seen from Bus 11 compared to Bus 1, which results in a different voltage levels. Furthermore, the impedance of the propagation paths are different which changes the system-wide harmonic levels. The gain between Bus 1 and Bus 2 when the harmonic emission source location is changed, can be seen in Figure C.3,.

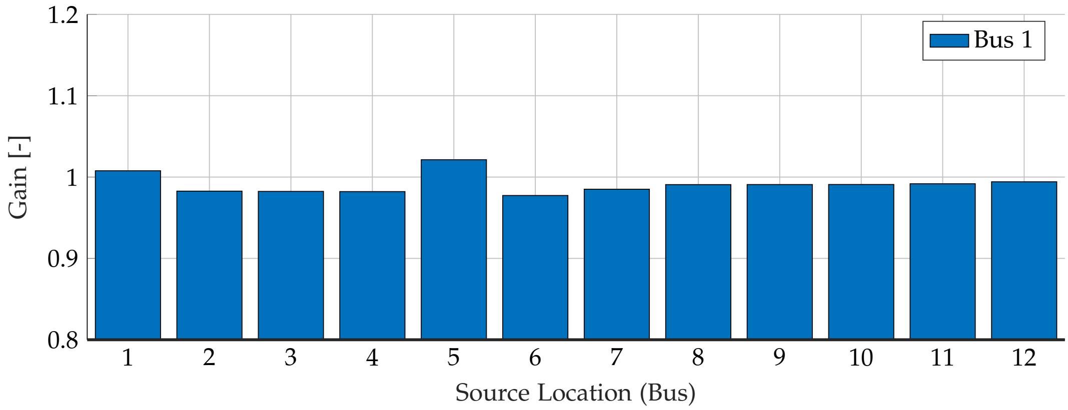


Figure C.3: Gains from Bus 1 to Bus 2, when the harmonic emission source is located at different locations.

The gains can be seen to be different for each source location, which can be explained the the waveforms through the lines. The starting point in Bus 1 will be different for each source location as the harmonics have propagated a different length. As the the phase displacement in the line is constant the gain is defined from the starting point.

C.2 Harmonic Propagation in Underground Cables and Overhead Lines

As seen in the previous section, in Figure C.1 and Figure C.2, the voltage levels between the busses from Bus 1 to Bus 4 and Bus 8 to Bus 10, which are busses connected with UGCs, stand out. It can be seen that the difference in the voltage in those busses are significantly lower than the difference between the busses in the rest of the system. This is because they are connected with UGCs.

Firstly, UGCs in a system are often of shorter length than OHLs, which is the case in this example grid. That reduces the ratio between the length of the line and the wavelength of the harmonic which reduces the part of the waveform occurring in UGC and thereby the gain. Secondly, UGCs have a lower characteristic impedance, because of the increased capacitance and reduced inductance. As the UGCs in the system are modelled as three separate UGCs in parallel, resulting an equivalent characteristic impedance a third of the size of each separate UGCs characteristic impedance. This will reduce the maximum voltage occurring the UGC but increase the maximum current. As the series thereby also is low, the voltage will change less than in anOHL, while the current will change more. It can be seen in Figure C.4 where the current magnitude of each line in the system from both ends is seen.

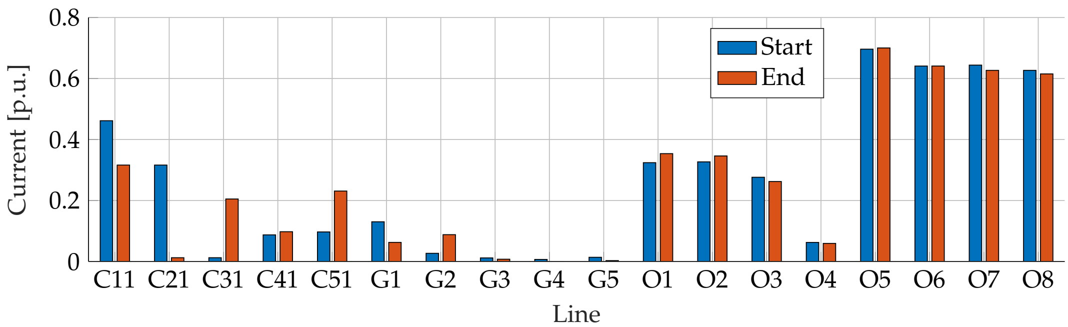


Figure C.4: Current magnitudes in the system with harmonic emission source at Bus 1.

In the axis in the figure, C11-C51 is the UGC corresponding to one of the three separate UGC, which makes up CA1-CA5, respectively. G1-G5 is the OHLs connected to the generation busses of same name. O1-O8 is the OHLs in the system. It is seen in the figure that UGCs have a significantly higher difference between the start and the end compared to the OHLs, meaning a larger change in current has occurred.

C.3 Radial Connections

The generation units are in the system radially connected to a bus in the meshed system, usually by relatively long OHLs. The harmonic voltage level in the busses at which the generation units are connected, are therefore highly affected by the level in buses they are connected to in the meshed system. Two cases will be highlighted, where the length of the radial line is close to the length of a quarter wavelength and the length of a half wavelength for two given harmonic orders respectively.

The length of the radial OHL connected between Bus 1 and Bus G1 corresponds to almost a quarter wavelength of the 29th and the 31st harmonic order, as it is 52.8 km. The quarter wavelength of the 29th and the 31st harmonic order in the line is around 50.6 km and 47.4 km, respectively. As explained in Chapter 1, Section 1.2.4, it can cause the voltage level to change from a very low level close to a voltage phase-shift to a high level close to a current phase-shift and vice versa. The voltage levels in all busses in the system, when the harmonic emission source is located in Bus 1, for the 29th and the 31st harmonic order, can be seen In Figure C.5.

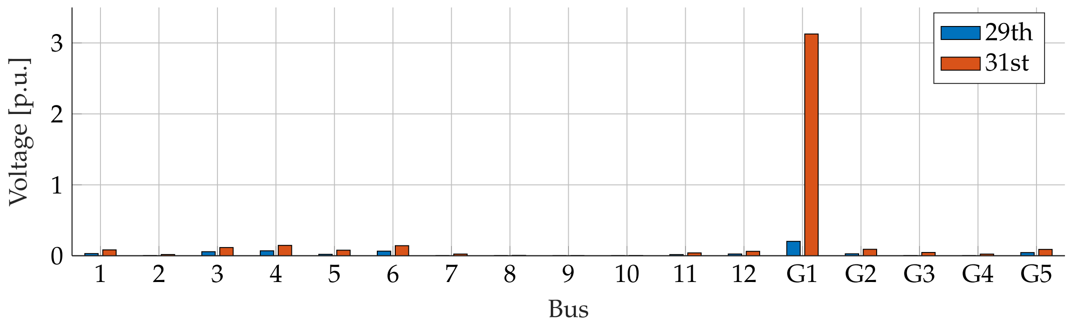


Figure C.5: Voltage magnitude in the system with harmonic emission source at Bus 1 for the 29th and 31st harmonic order.

It can be seen that the voltage level in Bus 1 is low in both cases, which would result in a high levels in Bus G1, according to the presented theory. The voltage level in Bus G1 is high for both harmonic orders, but significantly higher for the 31st order even though the 29th harmonic is closer to the quarter wavelength. This is because the current flowing through the line between the Bus 1 and G1 is of different magnitudes for the two harmonic orders because of the several paths from Bus 1. Furthermore, it is because the impedance in the system, seen from Bus 1, is different for the two harmonic orders.

The second case is the radial line between Bus 5 and Bus G2 which is close to the length of a half wavelength of the 41st harmonic order. The line is 85.3 km long and the half wavelength of the 41st harmonic order in the line is 94 km The voltage levels of the 41st harmonic when the harmonic emission source is located at Bus 7 and Bus 4, can be seen in Figure C.6.

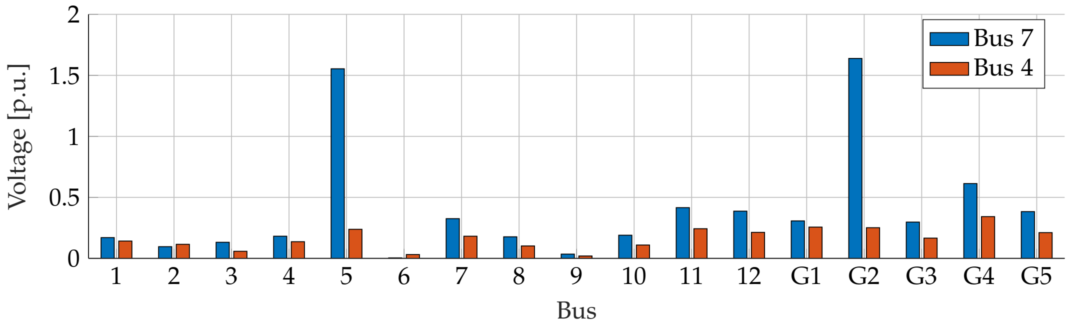


Figure C.6: Voltage magnitude in the system for the 41st harmonic when the harmonic emission source is located in Bus 7 and Bus 3.

As explained in Section 1.2.4, the voltage level in the busses which are connected by a radial line with a length corresponding to half a wavelength, would have close to the same magnitude. That can be seen in the figure, in Bus 5 and Bus G2, even when the location of the harmonic emission source is varied. The radial connections, as shown have a different behaviour than the meshed system and it is seen to cause higher harmonic voltage levels in this case.

Appendix D

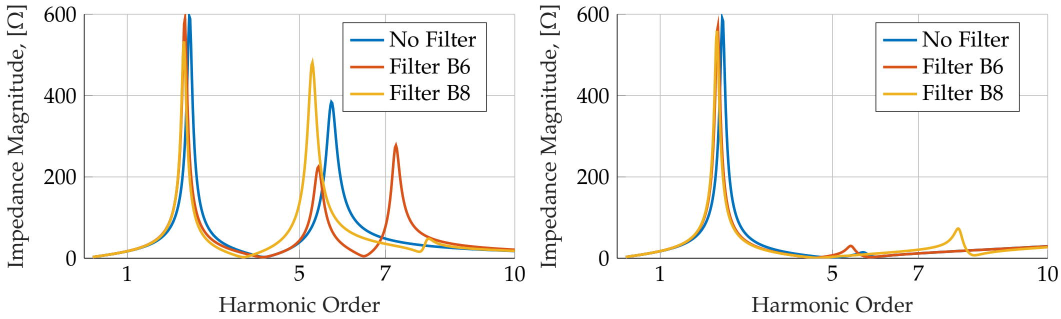
Supplementary Analysis of Anti-Resonance Phenomena

A more detailed explanation of of the analysis presented in Section 6.3, in Chapter 6, can be found in this Appendix.

D.1 Anti-Resonance Phenomena at Harmonic Source Location

The impedance seen from each bus in a system is different, and, as explained in Chapter 5, the impedance seen from the bus at which the harmonic emission source is located, affects the levels in the rest of the system. More specifically, the impedance seen from that bus determines the harmonic voltage levels that are generated in that bus, and the system impedance determines the propagation of the harmonic levels to the rest of the system. Therefore, the harmonic levels in a system will be different depending on the bus at which the harmonic emission source is located.

When a filter is implemented into a system, the impedance seen form the bus at which the harmonic emission source is located will change, and it will change differently if the location of the filter is changed. Furthermore, as the impedance seen from each bus is different, the change will also be different and depend on the location of the harmonic emission source. As an example, the impedance seen from Bus 1 and Bus 12 are different, and the change in impedance after a filter implementation in Bus 6, will be different in the two cases. Furthermore the change in both cases will be different if a filter is implemented in Bus 8 instead. The impedance seen from Bus 1 and Bus 12 is all the mentioned cases, can be seen in Figure D.1. The frequency range is limited to be 0-500 Hz, meaning that it goes from 0 to the 10th harmonic order, as the most significant difference in the impedance is seen in that range.



(a) Impedance magnitude seen from Bus 1. **(b)** Impedance magnitude seen from Bus 12.

Figure D.1: Impedance magnitude seen from Bus 1 and Bus 12, before and after a filter implementation in Bus 6 and Bus 8.

It can be seen in the figures that the impedance seen from Bus 1 and Bus 12 are different, and that the change in the impedance at the 7th and 5th harmonic orders, due to filter implementations, are significantly different in the two cases. Consequently the change in the harmonic voltage in the location of the harmonic emission source, namely Bus 1 and Bus 12 in this case, will be different. The 5th and 7th order harmonic voltage gains in Bus 1 and Bus 12, meaning the busses at which the harmonic emission sources are located, can be seen in Table D.1. The gains also represent the change in the impedance, seen the Figure D.1, as the harmonic voltage gains and the impedance gains in the bus at which the harmonic emissions sources are located are equal.

Table D.1: Impedance gain in the bus at which the harmonic emission source is located, namely Bus 1 and Bus 12, when a filter is implemented in Bus 6 and Bus 8.

Impedance seen from	Bus 1		Bus 12	
Harmonic Order	5th	7th	5th	7th
Filter in Bus 6	1.1160	1.6434	5.5228	1.001
Filter in Bus 8	3.4740	0.7343	2.5509	1.7665

It can be seen in Figure D.1 that the impedance at the 5th and 7th harmonic order is significantly higher seen from Bus 1 than Bus 12. Furthermore, it can be seen in Table D.1 that the filter implementations amplifies both the 5th and 7th harmonic voltage in the bus at which the harmonic emission source is located, in some of the cases. The amplifications are different because the impedance seen from Bus 1 and Bus 12 are different. Furthermore, it can be seen that the filter location has a large impact on the change in the harmonic voltage in the bus at which the harmonic emission source is located, as the change in impedance is then different.

The voltage gain of the 7th order harmonic voltage, meaning the target frequency of the filter, in the bus at which the harmonic emission source is located, when the location of the filter, and the location of the harmonic emission source is varied, can be seen in Figure D.2.

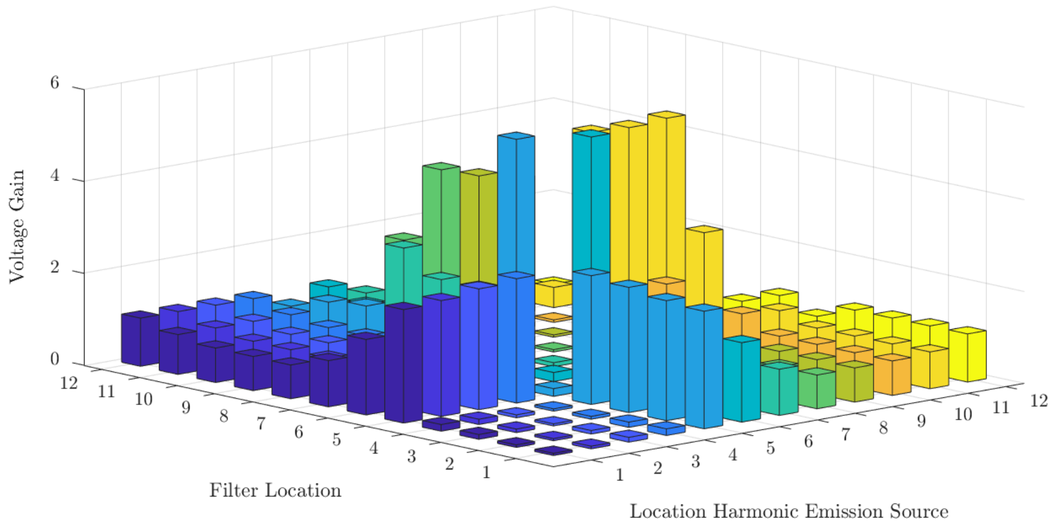


Figure D.2: 7th order harmonic voltage gain factor at bus at which the harmonic emission source is located, when the location varies for both the harmonic emission source and the filter.

It can be seen in the figure that the diagonal entries are all close to zero. That implies that when the filter, and the harmonic emission source is located in the same bus, the 7th harmonic order is almost fully mitigated in that bus. Furthermore, as explained in Section 6.1, when the filter and the harmonic emission source is located in the same bus, the propagation gains in the system are constant, meaning that the 7th harmonic voltage would be almost fully mitigated in the entire system in those cases.

In Figure D.2 it can also be seen that the 7th harmonic voltage in amplified in the bus at which the harmonic emission source is located, in many of the cases. That is because, even though the impedance for the targeted frequency seen from the bus at which the filter is implemented in can decrease, which consequently decreases the harmonic voltage at that bus, the impedance seen from the bus at which the harmonic emission source is located in, can increase. Consequently the harmonic voltage in that bus increases. That can be, amongst others, be seen to occur when the harmonic emission source is located in Bus 7. The impedance seen from that bus, is low for the 7th harmonic, and the 7th harmonic voltage in that bus, before any filter implementation is 0.02 p.u. The resulting gain after a filter implementation in i.e. Bus 8 is 4.65 in that bus. However the gain in Bus 8, namely the bus at which the filter is implemented in is 0.05.

More severe amplifications can be seen to occur for the 5th harmonic order, which can be seen in Figure D.3. In the figure the 5th harmonic amplification gain in the bus at which the harmonic emission source is located can be seen.

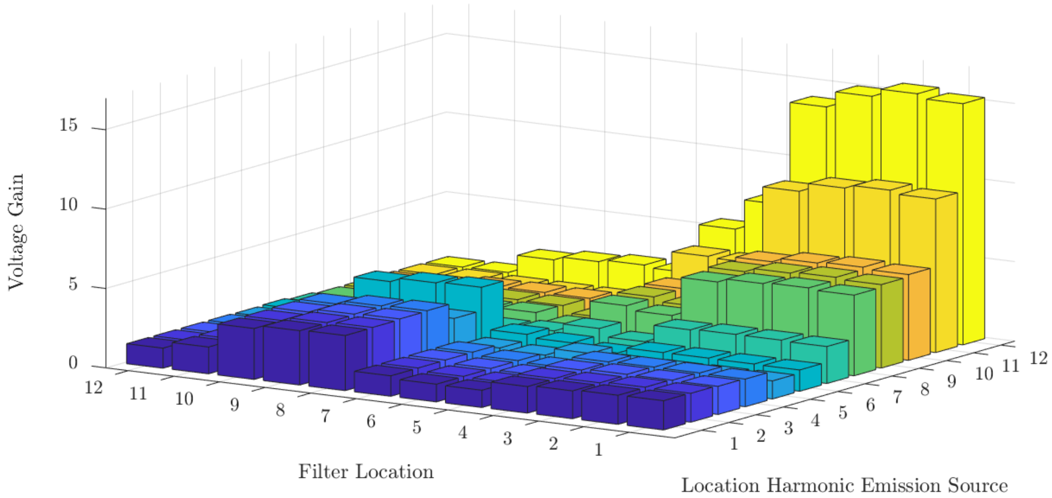


Figure D.3: 5th order harmonic voltage gain factor at bus at which the harmonic emission source is located, when the location varies for both the harmonic emission source and the filter.

As explained, the impedance seen from each bus in the system is different. Furthermore, the change in the impedance is a specific bus is different, dependent on the location of the filer. It can be seen that the voltage gains in the 5th order harmonic is high in some cases and significantly lower in others. And that is because of the change in impedance. The gains can be seen to be the highest when the harmonic emission source is located in Bus 12, and the filter is located in Bus 1, 2, 3 or 4. That is because of the impedance seen from Bus 12 before the filter implementation, which is low for the 5th order harmonic. It is then significantly amplified after the filter implementation.

D.2 Filter Implementations Impact on Propagation Gains

The propagation gains in a system, is determined by the system itself and the impedance of the system, as explained in Chapter 5. A change in the system, such as a filter implementation, changes the system impedance seen from a given bus.

That might affect the propagation gains in the system significantly, as the harmonic currents might flow in different directions. That can be seen to occur in Figure D.4, where the amplification gains for all the harmonic orders in all the busses can be seen, when a filter is implemented in Bus 5, and the harmonic emission source is located in Bus 1.

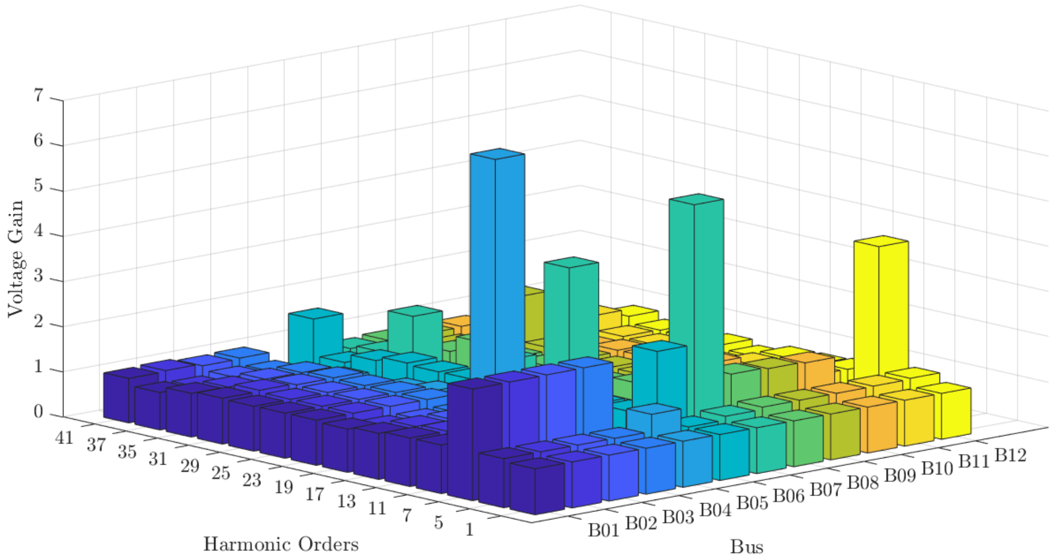


Figure D.4: Voltage gain at all busses in the system, for all harmonic order, when the harmonic emission source is located in Bus 1, and the filter is implemented in Bus 5.

The 5th harmonic is amplified in all the busses in the system, when the harmonic emission source is located in Bus 1. However, a bigger issue can be seen in the figure to be the amplification that occurs in the 7th harmonic, namely the target frequency. It can be seen that the 7th harmonic is reduced in the bus at which the filter is implemented. However, as the impedance of the 7th order harmonic is amplified seen from the Bus 1, namely the bus at which the harmonic emission source is located, it can be seen that the 7th harmonic voltage also is increased in many of the other busses in the system. The largest amplification can be seen to occur in Bus 7. The propagation gains in the system has changed, as a consequence of the change in impedance, and the result can be seen to increase the issue regarding the 7th harmonic on a system-wide level, even though it is reduced in the bus at which the filter is implemented. The 7th order harmonic voltage in the system, before and after the filter implementation, can be seen in Figure D.5.

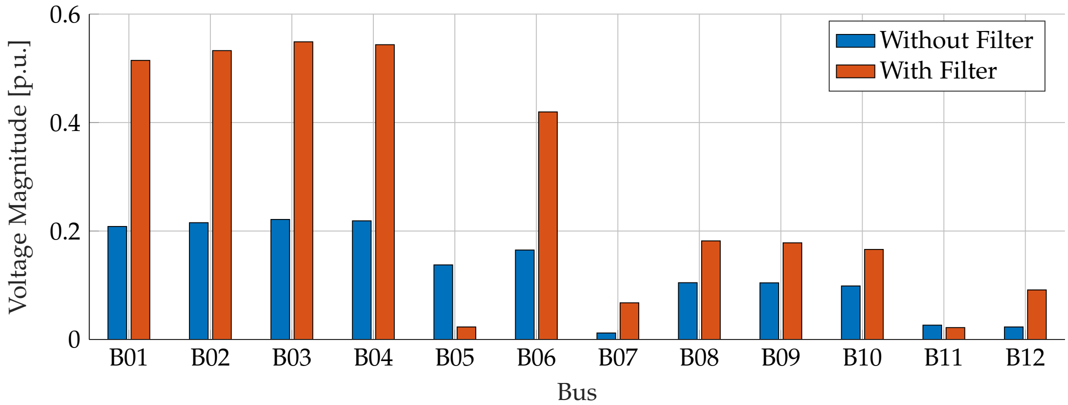


Figure D.5: 7th harmonic voltage level in all busses before and after the filter implementation in Bus 5, when the location of the harmonic emission source is in Bus 1.

It can be seen in the figure that the 7th order harmonic voltage has increased in Bus 1. The propagation gains G12, G23, G34 has not changed significantly, and consequently, the 7th harmonic voltage in Bus 2, Bus 3 and Bus 4, increase with almost the same gain as Bus 1. A reduction in the 7th harmonic voltage can be seen in Bus 5, as the filter is implemented in that bus. Bus 5 is connected to Bus 7, and that propagation gain, namely G57, has changed significantly as a result of the implementation of the filter, causing an increased harmonic voltage in Bus 7. The same significant change in propagation gain can be seen to occur to G1112.

In general it can be seen that the target frequency is amplified of a system-wide level, even though it is reduced in the bus at which the filter is implemented. That is because the amplification that occurs in the bus at which the harmonic emission source is located, in addition to the change in the propagation gains. This is a general phenomena that can be seen for all the frequency, resulting in significant harmonic amplification on a system-wide level.

D.3 Anti-Resonance Phenomena at Filter Location

The change in the harmonic voltage at the bus at which the filter is implemented in a system are constant and do not depend on the location of the harmonic emission source. So if the filter is located in Bus 1, the voltage gains in that bus does not depend on the location of the harmonic emission source, as explained in Section 6.1.

The amplification that occur in the bus at which the filter is implemented as, can be explained by the change in impedance seen from that bus, as explained in Section 6.2. It should though be mentioned that the amplification of the harmonic levels in the rest of the busses in the system are not constant, as explained in Section D.1 and D.2. The voltage gains in Bus 1, when a filter is implemented in Bus 1, while the location of the harmonic emission source is varied, can be seen in Figure D.6.

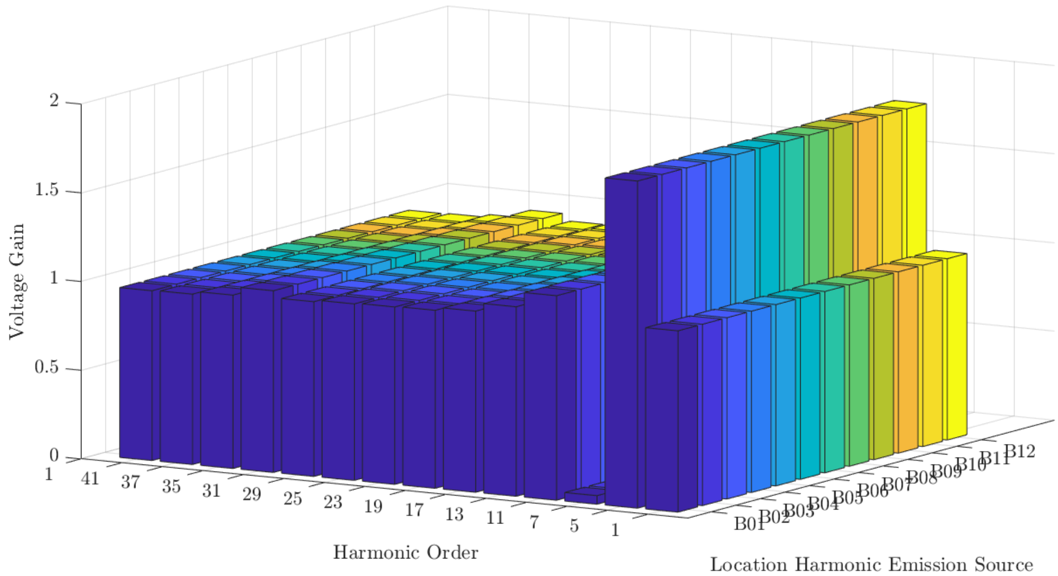


Figure D.6: Harmonic voltage gain factor in Bus 1 for each harmonic order when the filter is implemented in Bus 1, and the location of the harmonic emission sources is varied.

It can be seen in the figure that the amplification at the location of the filter is not dependent on the location of the harmonic emission source. Furthermore, it can be seen that the amplification are different for each harmonic order. The change in the impedance is dependent on the impedance seen from the bus at which the filter is to be implemented in, before the implementation of the filter, and the impedance of the filter.