Investigation into harmonic compliance with respect to the harmonic impedance envelope in the South African Grid Code (SAGC) for Renewable Power Plants (RPPs)

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Declaration

I declare that this dissertation is my own unaided work. It is being submitted for the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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(Signature of Candidate)

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Abstract

The South African Grid Code (SAGC) for Renewable Power Plants (RPPs) uses a specific method for the approximation of harmonic impedance at the Point of Common Coupling (PCC). This method assumes that the harmonic impedance as seen at the PCC is composed of a purely inductive impedance. The assumption is due to the lack of availability of accurate and complete network information. Another assumption is then made that the harmonic impedance is three times the base harmonic impedance.

The purpose of this research was to prove that the SAGC (for RPPs) method of approximating the harmonic impedance is too pessimistic. This was accomplished by comparing the SAGC harmonic impedance estimation to the estimation of what will be referred to as the load aggregation method and the current injection method.

The finding from this research is that a new middle ground, between the impedances calculated by the SAGC method and the actual harmonic impedance, can be determined for instances where the location of capacitors adjacent to the PCC is known.

It is recommended that the SAGC (for RPPs) approximation method be revised to make provision for instances where information regarding the location of capacitances in the network is available.

Dedication and Acknowledgements

This thesis is dedicated to Ben Mabizela, William Shata, and my cousins, who taught me that it is always important to assist others when it is possible. It is however primarily dedicated to my mother who engraved in me that my most important weapon towards success is education.

Prof. John van Coller has been the most patient thesis supervisor. His great advice and insightful criticism (when I was losing the primary aim of the research) aided the writing of this thesis in innumerable ways. I would like to acknowledge his efforts, in collaboration with "Powerfactory," in assisting me to obtain the power system simulation software "DigSilent" (student version).

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Glossary of Acronyms

AC	Alternating Current
MAPE	Mean Absolute Percentage Error
MV	Medium Voltage
NSP	Network Service Provider
PCC	Point of Common Coupling
PFC	Power Factor Correction
POS	Point of Supply
RMS	Root Mean Square
RPP	Renewable Power Plant
SAGC**	South African Grid Code
VA	Volt Ampere

*** in this research SAGC refers to the Grid Connection Code for RPPs*

Chapter 1 – Introduction

1.1 Motivational reasons and aims of the research

Renewable Power Plant (RPP) penetration into the conventional electrical power grid has grown significantly over the last few decades. This penetration has the potential of adversely affecting the power quality of the electrical grid. At the same time, RPPs should be immune to small disturbances from the power grid. Harmonics are common power quality issues associated with large RPPs. These harmonics are because of the switching frequency of the power converters and nonlinear behaviour of electrical components such as reactors, transformers and generators [1].

A deeper understanding of the impacts of RPPs on power quality is needed due to their ever-increasing growth in size and integration. This has led to the development of new grid codes, such as the SAGC for RPPs, which aim toward setting up the guidelines for RPP integration into the grid. One of the most important aspects of these codes is the maintenance of the quality of power generated by the RPPs.

The energy supplied by RPPs must be of good quality (i.e. low harmonic current emission, minimum voltage disturbances, constant voltage and frequency) to ensure stability and customer satisfaction [1]. Since the introduction of RPPs into the grid, harmonic distortion has been a major concern [2]. Harmonic distortion from RPPs can interact with pre-existing harmonic distortion in the network and cause issues if the harmonic frequencies excite resonances [3].

Harmonic resonance is caused by the interaction of capacitive and inductive elements in the power network. Within an RPP, electrical elements (such as capacitor banks, transformers, power cables) can potentially resonate with each other. Resonance occurs when the capacitive reactance is equal to the inductive reactance [4]. Resonant conditions can occur in two forms namely parallel resonance (associated with high voltage harmonics) and series resonance (associated with high current harmonics).

The alternating current (AC) waveforms are theoretically expected to be purely sinusoidal and of constant magnitudes to meet the customer expectations. A periodic deviation from this ideal expected behaviour, with a minimum period of one cycle of fundamental frequency, can be classified as harmonic distortion. Harmonics can cause power quality issues such as extra copper losses in transformers and torque pulsations in motors.

There are two aspects that require consideration when addressing problems related to resonance. The aspects are harmonic sources and resonant circuits.

The harmonic currents at a PCC must comply with the requirements of the Network Service Provider (NSP). Knowledge of resonant conditions is required.

The combination of power cabling, transformers, reactive power compensation, and LC filters can result in resonance at the PCC. Modelling of networks where resonant circuits are present is not always a straightforward exercise. To obtain an accurate model, elements such as power factor correction devices (or capacitors), generators, power cables and transformers must be included.

The main objective of this research is to prove that it is not the best approach to assume that the harmonic impedance can be determined based on the bus voltage, the fault level, and the harmonic order at the PCC. This approach, found in the SAGC for RPPs, leads to understanding that the harmonic impedance can be approximated as three times the base harmonic impedance, i.e. equation 1 – 1.

$$Z(h) = 3h\frac{V_{ll}^2}{S} \qquad (1-1)$$

Where,

V_{ll} is the line-to-line voltage in Volts.

S is the fault level in Volt Ampere (VA).

h is the harmonic order.

The aim of this research is to prove that this approach is too pessimistic when it comes to approximating the harmonic impedance. This pessimism will be proven by using two methods namely the load aggregation method and the current injection method for harmonic impedance approximation.

The importance of utilizing the load aggregation method is that it considers both adjacent load types and it is thus able to predict resonancies. Of further importance is this method's ease of application. It does however require critical adjacent network knowledge for the simulations to be conducted.

Theoretically, the current injection method can be performed with minimal adjacent network knowledge since it is an inherently dynamic method, i.e. its results are based on Ohm's Law. It does however require detailed electrical harmonic measurements.

1.2 Problem statement and research questions

The biggest difficulty with the SAGC method of approximating harmonic impedance is not only that it assumes a purely inductive supply impedance, but that it also does not take into consideration the resonant frequencies that may occur at the PCC.

The purpose of this research is to determine a more realistic harmonic impedance envelope (the middle ground between the SAGC for RPP and the RPP owner). It is however important to consider that accurate power network information might not be available. The primary plan is to obtain the basic information required to determine the harmonic impedance envelope at the PCC.

The assumption made by the SAGC for RPPs, about the approximation of the harmonic impedance, is too pessimistic in comparison to the actual harmonic impedance. The actual harmonic impedance can only exceed the harmonic impedance assumed by the SAGC when there is a large parallel resonance at the PCC.

Equation 1 – 2 requires that only the PCC voltage and the fault level are known so that the harmonic impedance envelope can be determined. When capacitance is known to be present at the PCC, it is possible to determine the resonant harmonic order using equation 1 – 2, shown below.

$$h_{res} = \sqrt{\frac{MVA_{fault\ level}}{MVAR_{capacitance}}} \quad (1-2)$$

Equation 1 – 2 may be less accurate when the capacitance is distant from the PCC.

The research question is whether a middle ground can be found between the actual harmonic impedance of a network (where all the required power network information is available) and the approximation of three times the base harmonic impedance (where no power network information is available).

Appendix 13.4.2.1 of the SAGC states that the NSP shall supply the RPP with impedance plots, but it is not clear whether the impedance plot is based on three times the base harmonic impedance or the actual harmonic impedance plot.

1.3 Difficulties of harmonic impedance approximation

There have been difficulties regarding approximating harmonic impedance at the PCC. The most significant part of these difficulties is the lack of accurate and complete power network information. Expansion of the power network simulation model (from the point of view of the PCC), until the harmonic impedance does not change significantly, is the best approach of dealing with this difficulty. The most important electrical components to be modelled for harmonic impedance study are overhead lines and underground cables, transformers, capacitors, resistive loads and large rotating machines.

In South Africa, there have been debates between RPP owners and power utilities such as Eskom and NSPs around the approximation of harmonic impedance. The interim solution for the approximation of harmonic impedance, according to the SAGC for RPPs, ended up being three times the base harmonic impedance. The detailed historical background around this issue is discussed in Chapter 2 [5]-[11].

There are methods that have been implemented in the past to determine the harmonic impedance [12]-[17]. This research only focuses on two methods on the load aggregation method and the current injection method. The basic theory of these two methods is outlined in Chapter 3, [12]-[39].

The approximation of harmonic impedance using the SAGC method is pessimistic from the point of view of the effect of network capacitance. Chapter 4 outlines the two methods used for harmonic impedance approximation, i.e. the load aggregation method and the current injection method.

The assumption behind this research is that the location of adjacent capacitance is known from the point of view of the PCC of interest. A simple radial network to prove the load aggregation method as well as the current injection method was used and simulated in Chapter 5 to evaluate the usefulness of this knowledge.

Chapter 6 discusses and conclude the research, it is concluded that the proposed load aggregation method can be used to strike a middle ground between the actual harmonic impedance and the harmonic impedance of the SAGC method. The current injection method can work better, but it may require further research in terms of practical application.

Chapter 2 – Background

2.1 Technical requirements according to the SAGC for RPPs

The NSP shall be accountable for any voltage harmonic limit exceedance which is as a result of the network harmonic impedance being more than three times the base harmonic impedance [5]. The harmonic impedance applied by the SAGC is calculated as shown in equation 1 – 1.

This implies that any RPP that connects to an existing electrical network is responsible for any excessive harmonic pollution when the actual harmonic impedance is less than that calculated using equation 1 – 1. The primary parameter that is used for harmonic compliance assessment is the measured current harmonic at the PCC [5]. The measured current harmonics can be converted to voltage harmonics through the network harmonic impedance calculated by using equation 1 – 1, by applying Ohm's Law [5].

It is the responsibility of the NSP to provide harmonic apportionment limits [5]. The NSP may provide either voltage or current harmonic limits. The RPP may be required to convert to either based on the network harmonic impedance calculated using equation 1 – 1 [5].

2.2 Power quality requirement issues

The Republic of South Africa has seen major growth in RPPs connecting to the conventional electrical power grid since 2011 [6]. Even though the introduction of RPPs has been considered a success, power quality issues have arisen [7]. These issues are analysed in this chapter from both an NSP and an RPP perspective.

The first SAGC for RPPs was published in 2012, but only dealt with conventional load customers and most requirements were based on past Eskom practices [6]. It remains the responsibility of the NSP to maintain power quality within certain limits [8]-[10].

One of the most critical parameters of the harmonic emission is the network harmonic impedance as seen by the power network participant (the RPP owner in this research) [6]. This is because the harmonic impedance directly affects the voltage harmonic levels produced by the current harmonics which are injected by RPPs. The SAGC approach of approximating the harmonic impedance as three times the base harmonic impedance is a problem for all RPPs [6]. The power quality requirements detailed in the SAGC for RPPs are as follows [5] and [6]:

- The power quality parameters that require regulation.
- The power quality compliance assessment that shall be performed at the PCC.

- The NSP shall determine the (voltage or current) harmonic emission limits and state the network conditions under which such limits must be met with a focus on the following parameters:
    - Expected background power quality parameter levels.
    - Fault levels.
    - Three times the base harmonic impedance.
- The RPP owner shall ensure that the RPP is appropriately designed and operated.

The above requirements had already been provided for in the Eskom standards, and the approach was that the RPPs must be treated the same way as the traditional customers [6].

The concerns that the NSPs had are summarized as follows [6]:

- To minimize the adverse impact of any customer on the power quality.
- To co-ordinate the customers at the PCC.
- To monitor the power quality at the PCC.
- To communicate relevant information to all customers.

The RPPs were concerned about the following [6]:

- The SAGC power quality requirements were unclear. The code only explicitly showed selected voltage harmonic limits and an explanation of how to obtain other voltage harmonic limits was absent.
- The requirements were different from other country standards as other countries do not consider the apportioning method stated in IEC 61000-3-6.
- The harmonic assessment method is based on measuring root mean square (RMS) values with no regard to the current direction and it might be possible that the RPP is absorbing current harmonics and the outcome of the assessment might be categorised as non-compliant.
- The SAGC (for RPP) approximation of harmonic impedance is pessimistic (this is the focus of this research).

Even though Eskom had extensive experience in dealing with conventional customers, it did not have enough experience in dealing with RPPs [6]. It is also important to note that municipalities in South Africa sometimes lack the network information required to do detailed network studies [6]. This means that grid connection processes and harmonic studies must consider the possible lack of network information. These processes must also be easy to implement.

2.3 Basis of assumptions for the SAGC calculated harmonic impedance

The conversion between the voltage and the current harmonic limits is based on the simulated harmonic impedance [8]. Simplified approximations of harmonic impedance are acceptable only for Medium Voltage (MV) systems, as shown in IEC 61000-3-6 [8]. The approximation approach for MV networks is as shown in Figure 2-1 and Table 2 –1. Figure 2-1 also shows the SAGC method of harmonic impedance approximation ($3Z_{base}$). The approximations shown in Figure 2-1 may not be accurate at voltages higher than 33 kV [8].

Figure 2-1 Proposed harmonic impedance envelope [8]

Eskom in South Africa has implemented the above approach since the late 1990s to deal with large industrial customers [6]. Due to limited skills, resources and network information, the SAGC adopted this harmonic impedance approximation method at all potential PCCs, Points of Supply (POS) and eventually for RPPs [6]. This adopted approach was based on the essence of consistency across all existing potential PCCs in the country [6]. The other intention was to cover probable future network changes and ensuring consideration of potential resonances [6].

Table 2-1 k values according to supply voltage and harmonic order [8]

Supply voltage at the PCC	k value according to the harmonic order				
	h ≤ 7	h ≤ 8	h > 7	h > 8	h < 16
11 kV		2		1	
33 kV					1.25

Table 2-1 above is related to equation 2 – 1 below:

$$Z(h) = kh\frac{V_{ll}^2}{S} \qquad (2-1)$$

The RPPs were not in agreement with the SAGC method of harmonic impedance approximation [6]. The probable need for unnecessary filters was the main reason for the disagreement. These unnecessary filters would ensure that the NSP would not be accountable for harmonic limit exceedance during the first 20-year operational period of the RPP.

From all the above discussion an amendment of the RRP requirements was necessary. Recommendations such as reducing harmonic impedance by the NSP and increasing harmonic limits for the RPP were contradictory [6].

The power quality researchers conducted a harmonic impedance study on the Eskom power network to determine a realistic harmonic impedance envelope [6]. The resultant harmonic impedance is normalized to the impedance at 50 Hz for comparison with the SAGC harmonic impedance estimation [6]. Based on this simulated study, aggregation of the normalized harmonic impedance (50th harmonic order) was conducted and compared with the SAGC harmonic impedance [6]. Figure 2-2 shows the results of this exercise.

The simulation shown in Figure 2-2 disregarded any contingencies that may affect the harmonic impedance at the respective PCC [6]. The SAGC harmonic impedance is an interim solution which creates a risk for both the RPP and the NSP [6]. Further research needs to take place to develop a harmonic impedance envelope that can satisfy both an NSP and an RPP [6].

There is currently no simplified model provided by either the NSP or SAGC for RPPs to determine the network harmonic impedance at the PCC.

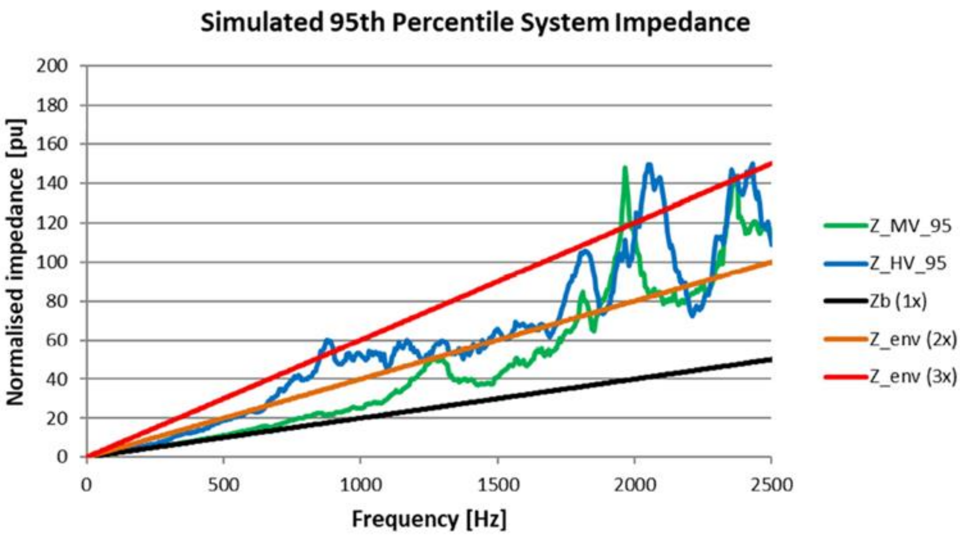

Figure 2-2 Harmonic impedance plots for the MV systems for system normal operation [6]

Accurate harmonic impedance determination is important for the following reasons:

- Resonance analysis.
- Harmonic filter design.
- Harmonic compliance assessment using the slope method [11].

2.4 Determination of the harmonic impedance envelope

For this study, a comparison between the SAGC method of harmonic impedance approximation and the international standard, particularly IEC 61000-3-6 [8], is necessary. According to IEC 61000-3-6, the harmonic impedance envelope can be determined by equation 2 – 1, where k can be determined from Table 2-1 [8] with typical fault levels in Table 2-2 [11].

Table 2-2 Typical fault levels according to voltages [11]

Nominal system voltage	Fault level, S
0.4 kV	10 MVA
6.6 kV	60 MVA
11 kV	100 MVA
22 kV	200 MVA

Both the IEC 61000-3-6 and SAGC method of harmonic impedance approximation cannot determine the resonant frequencies. As a result, the next chapter aims at investigating harmonic impedance approximation methods that can aid in approximating the location of resonant frequencies.

Chapter 3 – Literature Review

The difficulty with determining the network harmonic impedance is the lack of precise modelling information of the power network. Network modelling without comprehensive knowledge of electrical components that might affect the network harmonic impedance can lead to inaccurate harmonic impedance estimations. The electrical information that is analysed takes into consideration the various load configurations, the length of cables and the load aggregation that may not be accurately known at the PCC of interest [12]. In the past, this approach has proven that this electrical information is significant in ensuring a high degree of accuracy [12]. The load aggregation approach can be used to determine the harmonic impedance.

The aim of this study is to determine the harmonic impedance of the power network. The exact network composition is usually unavailable. Even when available, it changes over time. Any harmonic impedance calculation determines harmonic impedance characteristics for that moment. It is therefore good practice to calculate polar diagrams of the harmonic impedance [12].

Transmission systems harmonic impedance calculation methods are found in [13]-[17]. The detailed electrical models used for the calculations are outlined in [18]. More models can be found in [18]-[22]. Distribution system harmonic impedance and modelling sensitivity is detailed in [23]-[26] and [27]-[29], respectively. The analysis of parallel resonance can be used as a guideline to determine which electrical parameters have a considerable influence on the harmonic impedance.

3.1 Element modelling

It has been revealed that the presence of capacitance in a power network, particularly adjacent to the PCC, has the effect of shifting the first parallel resonance to a low frequency range [30]. Power cables are modelled by their PI equivalent circuits. The power transformers are modelled as a combination of series RL circuits. For power transformers, the capacitance can be ignored if the highest harmonic frequency of interest is not greater than 3 kHz.

Consideration of electrical losses is critical when modelling components such as cables, overhead lines, transformers and reactors. Electrical loads can be accurately modelled as series RL circuits. In other cases, composite loads can be purely resistive, especially when the loads do not include motors. Harmonic impedance modelling of induction motors is usually the locked rotor inductance [22] and [24].

3.2 Harmonic impedance analysis

The analysis of harmonic impedance can depend on various parameters, but this research only focuses on the following:

- Load aggregation.
- Load models.
- MV networks, overhead lines and cables.

3.2.1 Load aggregation

Usually power networks are too large to model each load separately and in detail. This leads to load aggregation when performing harmonic impedance studies. This aggregation process may lead to inaccuracies when approximating harmonic impedance.

To show the effect of load aggregation, Figure 3-1 shows a simplified power network. In this figure L is a representation of the supply inductance. The supply inductance is connected to earth at the source end if the supply voltage does not have a voltage component at the respective harmonic frequency (superposition theorem). L_1 and L_2 are a representation of the feeder system inductances. C_1 and C_2 are a representation of the load capacitances.

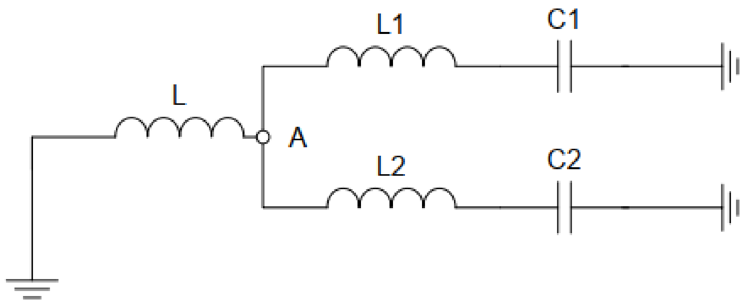

Figure 3-1 Explanation of the effect of load aggregation

If L_1 and L_2 are omitted, equation 3 – 1 ($\omega = 2\pi fh$) can determine the harmonic impedance (at PCC A) as follows:

$$Z_{PCC,A} = \frac{j\omega L}{1 - \omega^2 L(C_1 + C_2)} \qquad (3-1)$$

If the L_1 and L_2 are included, the impedance is calculated as follows:

$$Z_{PCC,A} = \frac{j\omega L(1 - \omega^2 L_1 C_1)(1 - \omega^2 L_2 C_2)}{1 + \omega^4 L_1 C_1 L_2 C_2 - \omega^2 (L(C_1 + C_2) + L_1 C_1 + L_2 C_2)} \qquad (3-2)$$

If the supply inductance L is much larger than L_1 and L_2, and there is a low frequency parallel resonance, equation 3 – 1 and equation 3 – 2 will result in approximately the same first parallel resonant frequency. The resonances of the above two equations may be different but L_1 and L_2 will always produce two series resonances and an added resonance at higher frequencies [12]-[23]. That added resonance is inversely proportional to L_1 and L_2. This implies that the shorter the length of the power cables, the higher the frequency of the second parallel resonance. This resonance may not need to be considered for frequencies below 2500 Hz.

The literature suggests that the accuracy of load aggregation is dependent on the ratio of upstream and downstream inductance [24]-[30]. In essence, this means that with smaller downstream inductance (shorter cables), the aggregation method will not lead to significant errors when approximating harmonic impedance. In contrast, the longer the length of the feeder cables, the larger this error may be, but the cable impedance can be more significant at the PCC of interest.

Networks are more detailed than the one shown in Figure 3-1. Research has shown that load aggregation leads to an increase in resonant frequency but the error margins are quite acceptable when the power cables are short [12]. The disadvantage is that it does not reveal all the resonances within the frequency spectrum.

The aggregation of feeders (including cables) may easily lead to accurate lower resonant frequencies. The load aggregation also reveals more resonances and increased uncertainty at frequencies higher than 2500 Hz [12].

3.2.2 Load modelling

Accurate modelling of loads is difficult but important. This is because the loads are the primary source of damping in a power network. They are also able to produce resonances at higher frequencies [24]. Fundamental assumptions are made to address the issue of load demand variations [24]:

- The capacitance of power lines must be included.
- RL equivalents for transformers are good enough for low frequencies.
- Active power is not proportional to damping for rotating machines.
- Accurate capacitance modelling is critical.
- The configuration, the composition of line inductors and filters must always be analysed with accuracy.
- Real power for power electronic modules should not be modelled as resistance values. It is preferable to consider the input capacitance of the power electronic modules.

The measured reactive power is not a direct representation of the inductive or capacitive levels, as it inherently carries distortion power [24].

Capacitance can change the resonant frequency directly. The direct effect of changing capacitor C by ΔC can change the resonant frequency by $1 \; / \; \sqrt{\Delta C}$.

Resistive loads do not influence the resonant frequency, but they only influence the peak value of the impedance. Resistive loads or resistive electrical components are important to consider when studying harmonic impedance.

3.2.3 MV networks, overhead lines and cables

The application of the aggregation method can produce significant errors when cable or line inductance is comparable to supply inductance (equation 3 – 2). The supply inductance needs to be much larger for the aggregation method to produce reliable results.

In most cases, the MV network is normally modelled as a short-circuit harmonic impedance (based on fault level). Components such as capacitors and generators, require detailed modelling.

3.3 Current injection

Presence of prominent harmonic voltages makes it difficult to measure harmonic impedance [31]. The technique of harmonic current injection must be performed with different (from pre-existing voltage harmonics) phase angles [31]. There is currently a rapid growth of distributed generation, such RPPs, which means that power quality problems can arise. When there is no voltage control in the system, both power quality problems and voltage regulation problems may be experienced [32].

The voltage harmonics can increase to more than the allowed voltage harmonic limits. Countries, such as Germany and Denmark amongst others, have set standards for these limits [33]. Current harmonics could be injected into the system by inverters. This concept is called active filtering [34]-[36]. It would be valuable if these inverters could also measure the resultant voltages and calculate the harmonic impedance.

The foundation and basics of current injection are based on the following:

- Measurement system.
- Methods of dealing with pre-existing voltage harmonics.

3.3.1 Measurement system

There are methods that have been used to measure harmonic impedance [37]-[39]. One of these methods used in the past is the injection of variable frequency sinusoidal current, using a voltage source converter.

When injecting a current at a specific frequency, a voltage drop will be experienced at that frequency. Figure 3-2 explains this concept. The measurement system may be getting power from the fundamental component of the grid voltage.

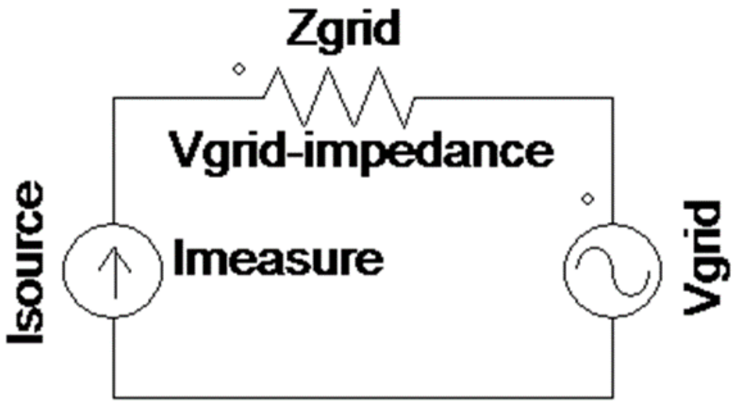

Figure 3-2 Measuring system

V_{grid} is assumed to be zero for all frequencies other than the fundamental component. This implies that the harmonic impedance can be measured by applying Ohm's law which is shown in equation 3 – 3.

$$Z_{grid} = \frac{V_{grid-impedance}}{I_{measure}} \qquad (3-3)$$

The method can also be used to calculate the grid impedance at inter-harmonic and at super-harmonics.

3.3.2 Methods of dealing with pre-existing voltage harmonics

The assumption that the V_{grid} is zero at frequencies above fundamental is not always accurate. The voltage harmonics may not be zero due to the non-linear loads that are normally connected to the power network. The pre-existing voltage harmonics must be measured and subtracted from the measured voltage harmonics (after injection) [32].

The other method of dealing with pre-existing voltage harmonics is to inject current at a harmonic frequency with two opposite phase angles. This implies that the difference in these phase angles is 180°. The $V_{pre\text{-}voltages}$ voltages are the voltages before injection. The $V_{post\text{-}voltage}$ are voltages after the current injection.

The harmonic impedance can be calculated as follows (phasor values):

$$Z_{harmonic} = \frac{V_{post-voltages} - V_{pre-voltage}}{I_{measure}} \qquad (3-4)$$

It is important to note that network impedance or voltage harmonics are not constant over time.

Chapter 4 – Methodology

To estimate the network harmonic impedance, the load aggregation method and the current injection method were used in this study.

4.1 The load aggregation method

This method intensively utilizes three capabilities of PowerFactory DigSilent which are load flow studies; short circuit calculation and frequency scanning (for harmonic impedance approximation).

When all the network information is available, the determination of the harmonic impedance can be executed using one of two methods. The methods are based on inverting the nodal admittance matrix (manual calculation) or simulation. The latter method is what is referred to as frequency scanning.

The aim of this study is to prove that the application of equation 1 – 1 can result in significant errors when compared to actual harmonic impedance. For comparison purpose, equation 2 – 1 is written with k = 1 in equation 4 – 1 below.

$$Z(h) = \frac{V_{ll}^2}{S} h \qquad (4-1)$$

The harmonic impedance comparison (between equation 1 – 1, equation 4 – 1, and the load aggregation method) will be conducted by calculating the Mean Absolute Percentage Error (MAPE) using equation 4 – 2.

$$MAPE = \frac{1}{n} \sum_{h=0.2}^{n} \frac{|C_h - A_h|}{A_h} 100 \qquad (4-2)$$

Where,

C_h is the calculated harmonic impedance at h.

A_h is the actual (simulated) value of harmonic impedance at h.

h is the harmonic order from 0.2 to 50 (up to 2500 Hz), incrementing with steps of 0.02, which implies that n is 25000.

One of the most critical pieces of information required for harmonic impedance determination is the location of capacitors adjacent to the PCC of interest. This is for the purpose of ensuring that resonances can be determined.

The most significant disadvantage of equation 1 – 1 is that it assumes that the harmonic impedance is always directly proportional to the harmonic order. This assumption is only applicable to inductive reactance and not to capacitive reactance. Thorough electrical modelling shows how the harmonic order h should be mathematically dealt with when calculating or simulating harmonic impedance. To clarify this point, more detailed mathematical modelling is discussed below.

4.1.1 Mathematical modelling of electrical equipment

Transformer modelling

Figure 4-1 shows transformer harmonic impedance modelling as follows [40]:

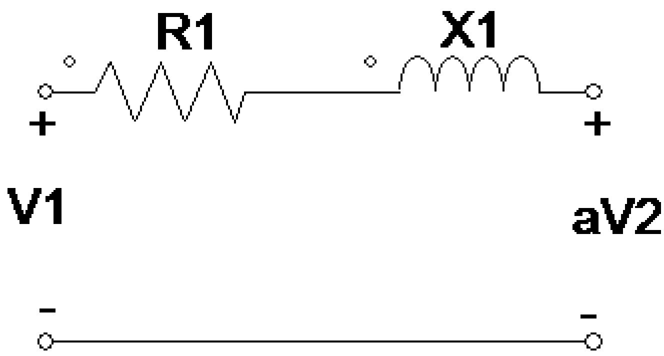

Figure 4-1 Transformer modelling with magnetizing current neglected

The transformer harmonic impedance is calculated as follows:

$$Z(h)_{TX} = R_1 + jhX_1$$

Where,

$R_1 = r_1 + a^2 r_2 \; and \; X_1 = x_1 + a^2 x_2$

r_1 is the primary winding resistance.

r_2 is the secondary winding resistance.

x_1 is the primary winding reactance at 50 Hz.

x_2 is the secondary winding reactance at 50 Hz.

$a = \frac{N_1}{N_2}$, the ratio of the transformer turns.

Capacitance modelling

Capacitance harmonic impedance modelling can be shown as follows [40]:

$$X_C = \frac{V_{pcc}^2}{Q_C} \; which \; means \; Z(h)_C = -j\frac{X_C}{h}$$

Where,

X_C is the capacitive reactance at 50 Hz.

Q_C is the reactive power rating (VAr).

V_{pcc} is the voltage at the PCC.

Load modelling

Load harmonic impedance modelling can be shown as follows [40]:

$$Z_L = \frac{V_{pcc}^2}{S_L} \ \ which\ means\ Z(h)_L = Z_L \cos\theta \pm jhZ_L \sin\theta$$

Where,

S_L is the load VA rating.

θ is the power factor angle.

Transmission line modelling

Modelling of transmission lines is dependent on their lengths. Transmission lines can be categorized into three groups. There are short lines (up to 80 km long), medium lines (80-240 km) and long lines (longer than 240 km) [40].

For short lines, shunt capacitance can be omitted. This implies that the line can be modelled as series resistance R and series inductance L [40]. This can be done without any loss of accuracy in harmonic impedance approximation [40]. The total R is calculated by multiplying resistance r (normally given by the manufacturer in Ω/km) by the total length of the cable. The same analogy holds for inductance [40].

The lumped R and L can accurately represent medium length lines. For these lines, it is important to take note of the capacitance, C, of which half can be lumped on both ends of the transmission line, as shown in Figure 4-2. This same model can be used up to a length of 320 km [40].

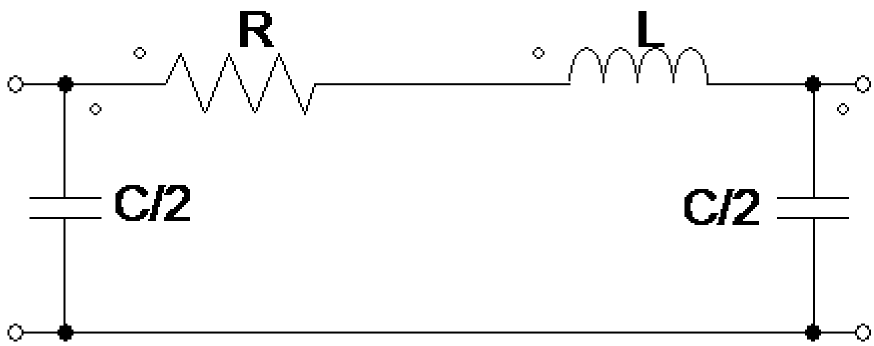

Figure 4-2 Medium length overhead line model

The long lines require calculation of distributed constants. The model provided in Figure 4-2 can be used with the following changes [40]:

The series RL component becomes $Z_C \sinh \gamma l$ and the C/2 component becomes:

$$\frac{1}{Z_C} \tanh \frac{\gamma l}{2}$$

Where,

Z_C is the characteristic impedance.

γ is the propagation constant.

l is the length of the transmission line.

The method is generically and systematically elaborated as follows:

STEP 1: Identification of the PCC of interest.

STEP 2: Identify all components that are directly connected to the PCC of interest. STEP 2 is meant to build up a reduced power network model, based on what is directly connected to the PCC. Importantly, the branch feeding the downstream power network needs to be identified. The reason for identifying this branch is because there is a need to build a reduced power network model based on the loading information on that feeder branch. This step may include identifying all capacitors that may be adjacent to the PCC of interest, as this will improve the accuracy of the model. The fault level at the PCC is determined, it may aid in calculating the base harmonic impedance (where h = 1).

STEP 3: Perform load flow analysis. This is critical for branches feeding other networks that are not fully known. In practice, this may also be performed using power quality meters. For the purpose of this research, load flow studies were utilized, as the point of the research was to prove the principle. If load flow information may not be attained, it may be necessary to build the reduced model based on transmission or distribution system loading ratings.

STEP 4: From the reduced model, harmonic impedance simulation can be performed using frequency scanning. In this step it is necessary to investigate the closest downstream and upstream network configuration to determine if there are any Power Factor Correction (PFCs) that need to be considered in the reduced model.

Replace all downstream components with an equivalent load that is determined from load flow studies.

4.2 The current injection method

4.2.1 Considerations before applying the current injection method

There are two considerations that are important when applying this method. It is the type of applied current source (two-pulse single-phase rectifier or six-pulse three-phase rectifier and so forth) and the pre-existing harmonics. The short description of the inaccuracies of this method are found in section 6.4

The method is generically and systematically elaborated as follows:

STEP 1: Identification of the PCC.

STEP 2: Current harmonic injection.

Before the current harmonic injection is applied, the pre-existing voltage harmonics must be known. The importance of this information will be realized in STEP 4. Apply harmonic current injection at this PCC.

STEP 3: Investigate the effect on the voltage harmonics at this bus as a result of the current injection. In this case study, the voltage harmonics before the current injection are zero. The only voltage harmonics to be investigated are voltage harmonics after the current injection is applied.

STEP 4: The harmonic impedance can now be calculated, based on Ohm’s Law, except for the impedance at fundamental frequency, which will be determined by equation 4 – 1. This implies that the fault level and voltage level at the PCC of interest must be known to calculate the fundamental harmonic impedance at the PCC of interest.

The rest of the harmonic impedance is determined using the below equation:

$$Z(h) = \frac{\Delta V_h}{\Delta I_h} = \frac{\left|V_{h,before\ injection} - V_{h,after\ injection}\right|}{\sqrt{3} I_{injection}} \qquad (4-3)$$

As a result, the calculated harmonic impedance can be plotted and compared to the actual impedance.

Chapter 5 – Evaluation of the method

The power network shown in Figure 5-1 was used to evaluate the methods that are outlined in Chapter 4. The harmonic impedance study is performed at three different substations:

- Power generation substation.
- Transmission substation.
- Mine intake substation.

The load flow study of the actual complete power network has already been performed, as shown in Figure 5-1.

5.1 Evaluation of the load aggregation method on the power generation substation

STEP 1: Identification of PCC, i.e. power generation substation.

STEP 2: The components that are directly connected to this PCC are a 350 MVA, 400/132 kV YY transformer and supply impedance of the utility that is supplying power through this transformer. The power transformer is supplying power to the downstream load. The fault level at this bus is 18154 MVA.

STEP 3: A load flow study is performed on the actual power network. It is important to note that this information can be obtained from power quality analysing instruments. According to the load flow study information (simulation), the load supplied from the power generation substation is 162.38 MW and 45.56 MVAr. This information is utilized in STEP 4.

STEP 4: The reduced model for the harmonic impedance study can be built. It consists of the transformer, the utility supply and the aggregated equivalent load determined from STEP3.

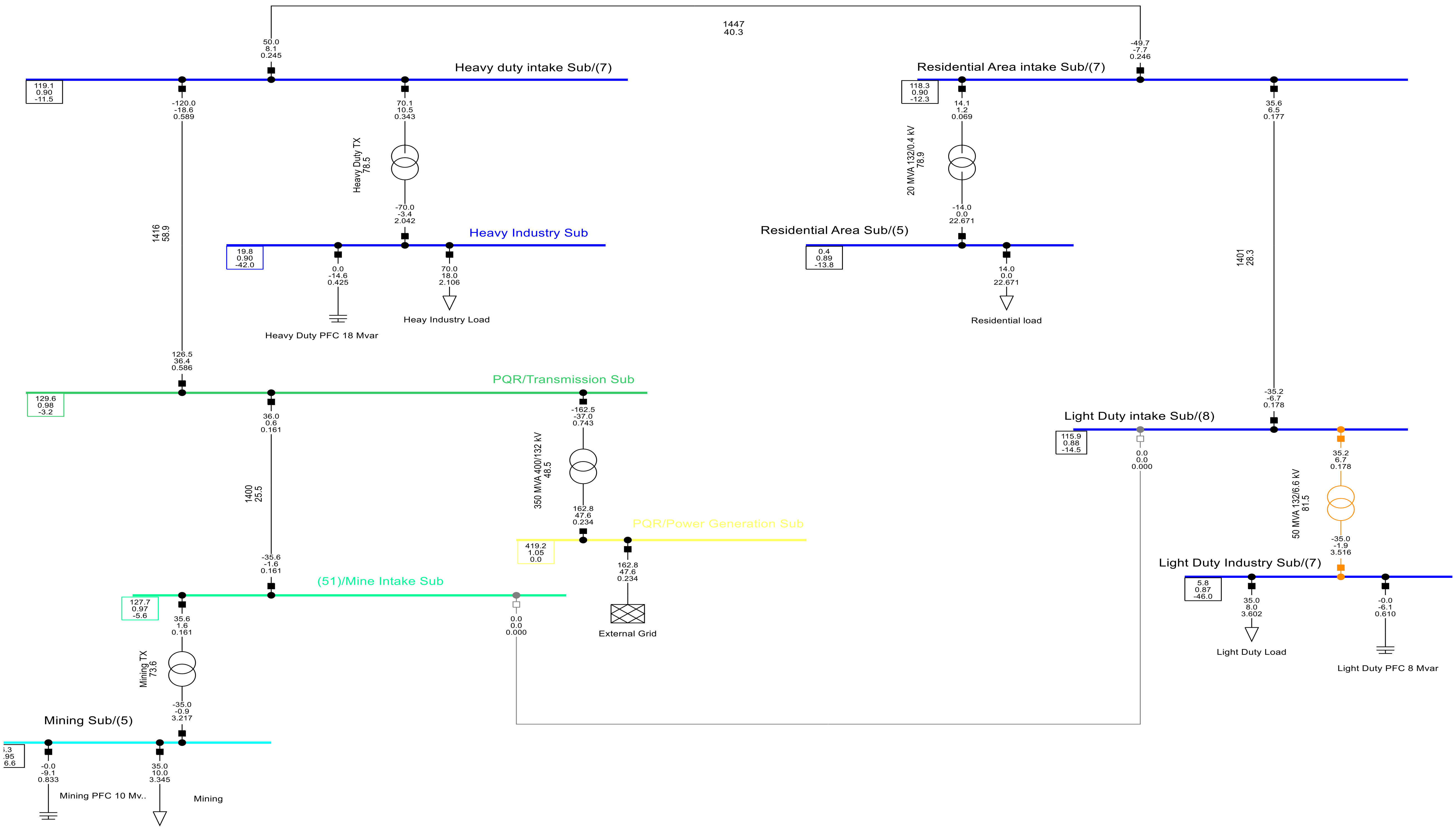

Figure 5-1 Power network used for testing the method

Figure 5-2 shows the reduced model of Figure 5-1. The harmonic impedance of the reduced model is plotted and compared to the actual harmonic impedance as shown in Figure 5-3. It should be noted that all the calculated harmonic impedances, including the approximation of equation 1 – 1 (SAGC for RPP) and equation 4 – 1, do not resonate above the 40^{th} harmonic. It is because the impedances calculated by equation 1 - 1 and equation 4 - 1 do not take the capacitance in the system into consideration.

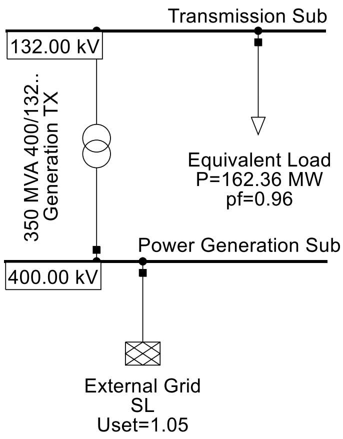

Figure 5-2 Reduced model of the power network, as seen from the power generation substation.

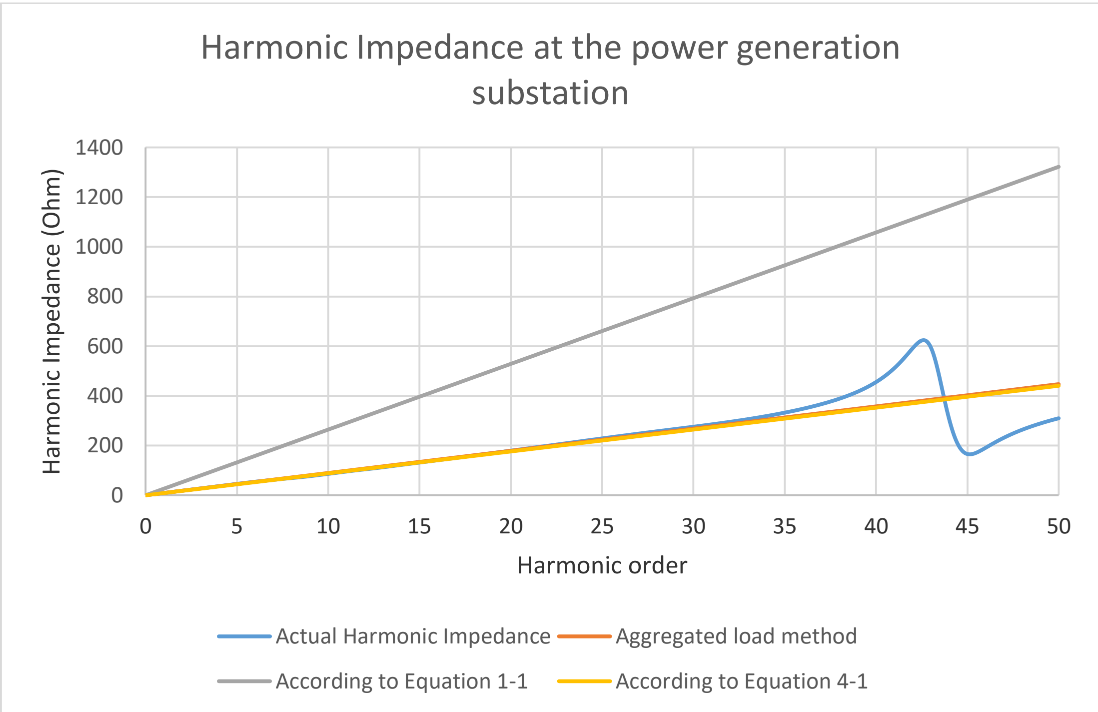

Figure 5-3 Harmonic impedance at the power generation substation

The error calculated using equation 4 - 2 is 14% when using the load aggregation method, 231% when using equation 1 – 1 and 15,5% when using equation 4 - 1. The errors that result from applying the load aggregation method and equation 4 – 1 are attributed to the resonances that are realized after the 40^{th} harmonic order. The error is a result of not taking into consideration the capacitance that is in the vicinity of the PCC of interest. The next step is aimed at taking into consideration the closest capacitance to the PCC.

When referring to Figure 5-1, there are two transmission lines that are connected to the transmission substation. The lines are OBJ1-HBG1 and Al/St 230/30. The electrical properties of these lines are respectively 0.1245 Ω/km resistance, 0.3878 Ω/km reactance, 0.0094 µF/km capacitance; and 0.1249 Ω/km resistance, 0.386 Ω/km reactance, 0.0095 µF/km capacitance. They are both 50 km long.

Practically, the power generation substation and the transmission substation are only separated by the power transformer (Figure 5-1). A more accurate reduced model for these two sub-stations is shown in Figure 5-4.

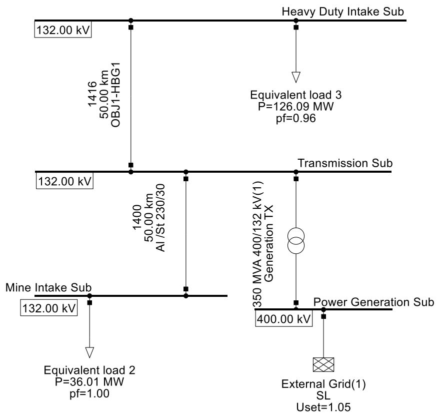

Figure 5-4 Reduced model of the power network as seen from the power generation substation and the transmission substation.

The equivalent loads 2 and equivalent load 3 are determined from load flow studies, as shown in Figure 5-1. The loads are, respectively 36.01 MW and 0.22 MVAr & 126.01 MW and 35.09 MVAr. For evaluation purposes, the harmonic impedance study can be repeated (STEP 4). Figure 5-5 shows the results. The load aggregation harmonic impedance also resonates in the same pattern as the actual harmonic impedance after the 40^{th} harmonic order. The error calculated according to equation 4 - 2 is 15%, when using the load aggregation method; but the pattern is more comparable to the actual harmonic impedance.

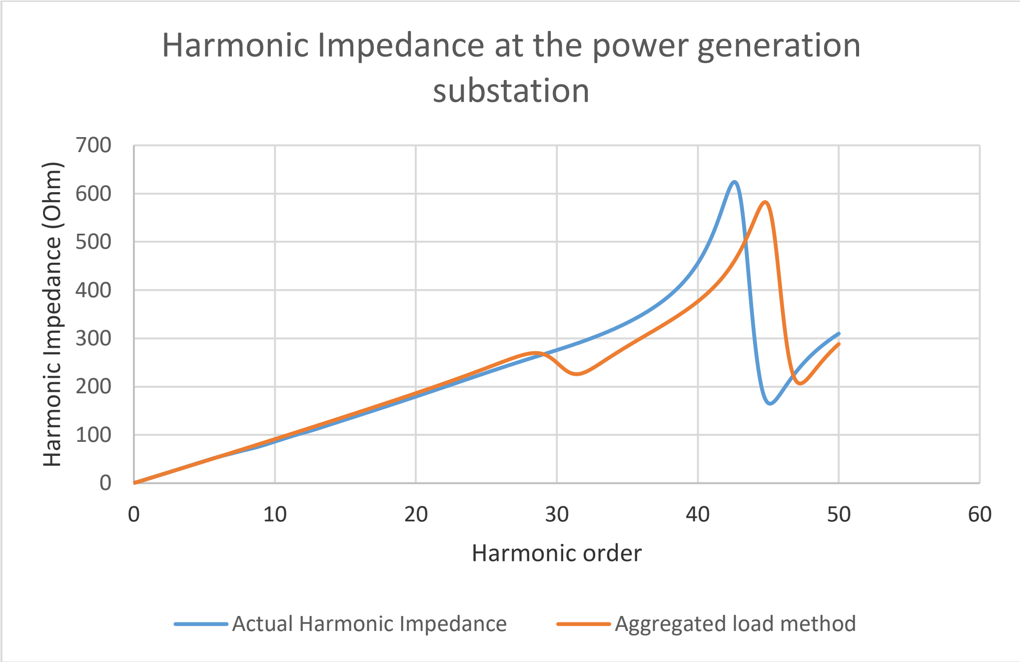

Figure 5-5 Harmonic impedance at the power generation substation with the transmission lines included

In Figure 5-5 the load aggregation harmonic impedance characteristic is shifted at higher frequencies. This is because the rest of the exact load has been excluded in the reduced model shown in Figure 5-4. It is also important to note that the length of the overhead line is a crucial factor in this approximation method, since it determines the total inductance and capacitance of the line.

The next step is to do a comprehensive analysis of the part of the network that significantly influences the harmonic impedance at the power generation substation. As a result of this analysis, it became important to investigate the amount of capacitance that is connected at the end of the transmission line OBJ1-HBG1. It was found that there is about 18 MVAr plus 8 MVAr (totalling 26 MVAr) of capacitance that is connected.

From this point, a more comprehensive reduced model can be built as shown in Figure 5-6. From this reduced model, the harmonic impedance is plotted in Figure 5-7 and the error is reduced from 15% to 4%.

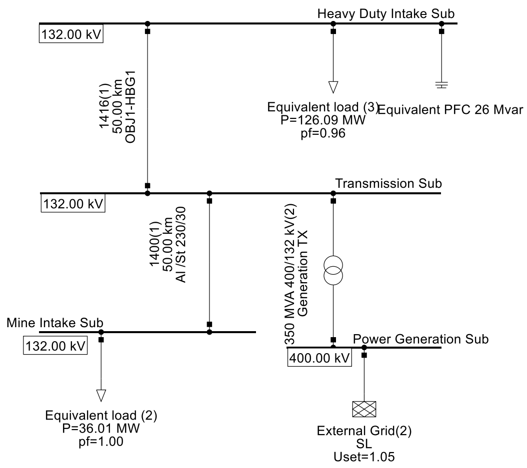

Figure 5-6 Reduced model of the power network as seen from the power generation substation and the transmission substation

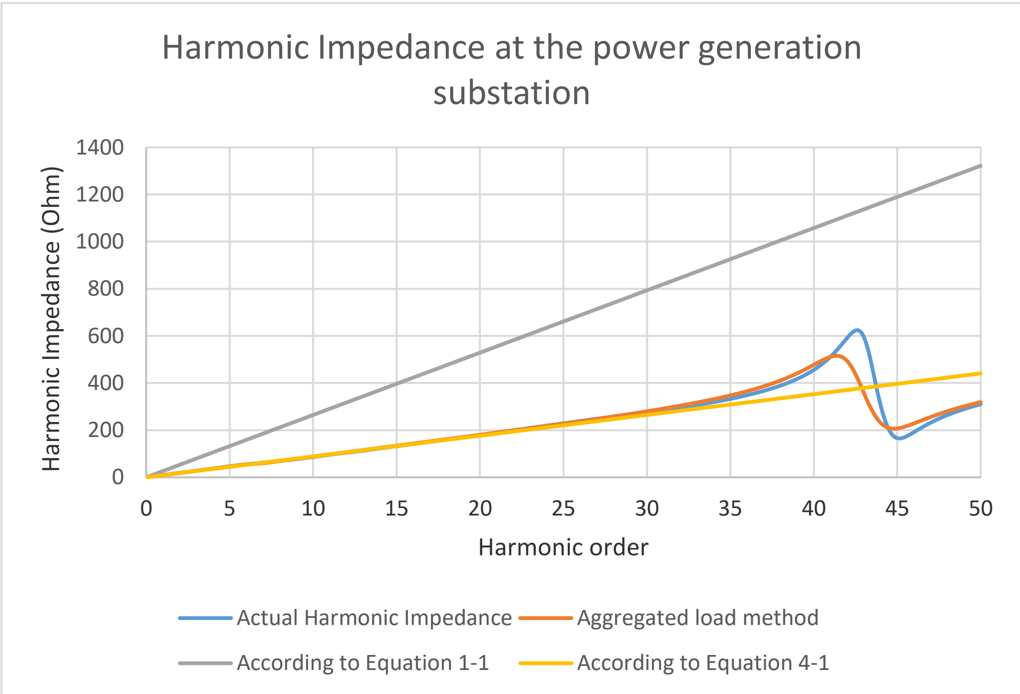

Figure 5-7 Harmonic impedance at the power generation substation

5.2 Evaluation of the load aggregation method on the transmission substation

STEP 1: Identification of PCC, i.e. transmission substation.

STEP 2: The components that are directly connected to this PCC are 350 MVA 400/132 kV YY transformer and the two transmission lines that supply power downstream. These are lines OBJ1-HBG1 and Al/St 230/30. The line electrical properties have been outlined in section 5.1. The fault level at this bus is 2555 MVA.

STEP 3: From the load flow study information, the loads being supplied from transmission substation are respectively 36 MW and 0.22 MVAr by line Al/St 230/30, 126.09 MW and 35.09 MVAr by line OBJ1-HBG1. This information will be utilized in STEP 4.

STEP 4: The reduced model for the harmonic study, which consists of the transformer, utility impedance and the load aggregation equivalent loads determined from STEP 3, can be built. The reduced model is shown in Figure 5-4. The harmonic impedance of the reduced model was plotted and compared to the actual harmonic impedance, as shown in Figure 5-8. The error calculated according to equation 4 - 2 is 50% when applying the load aggregation method, 192% when applying equation 1 – 1 and 35% when applying equation 4 - 1. The load aggregation harmonic impedance does not resonate at exactly the same harmonic order (40th harmonic) since the effect of the rest of the capacitance in the system is not taken into consideration in the reduced model. It is also noted that the harmonic impedance produces a resonance in the 29th harmonic order, but the actual impedance does not resonate at that harmonic order

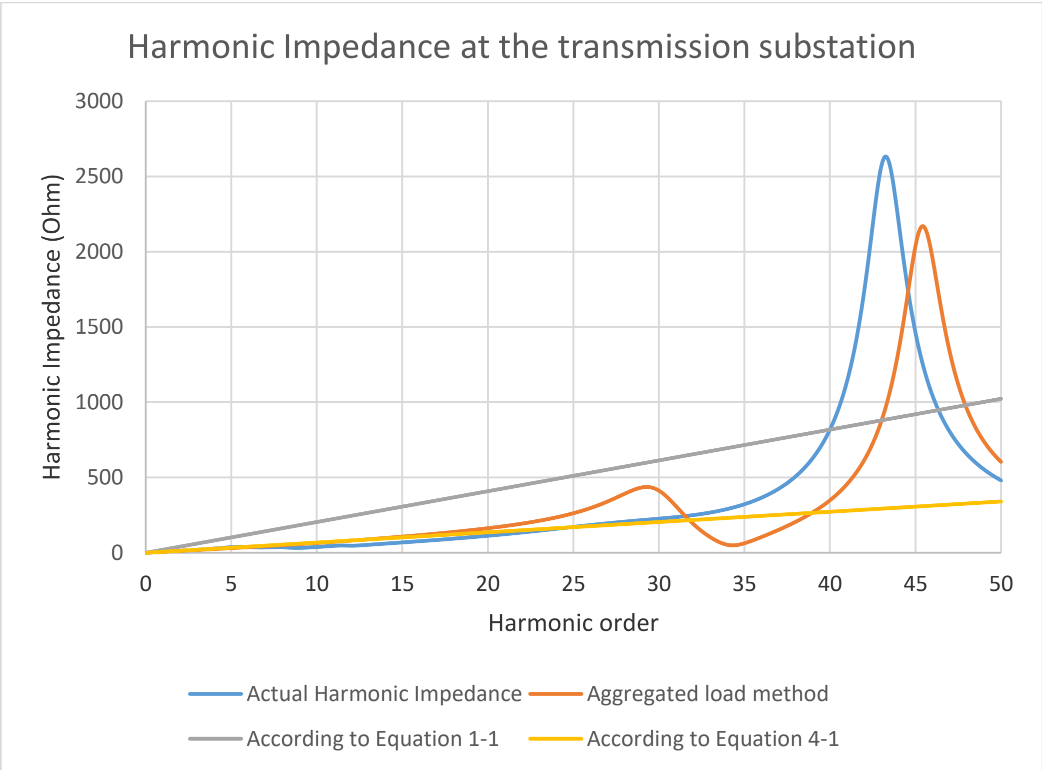

Figure 5-8 Harmonic impedance at the transmission substation

The next step is to do a comprehensive analysis of the part of the network that significantly influences the harmonic impedance at the transmission substation. The reduced model shown in Figure 5-6 is utilized, as this sub-station is connected to the power generation substation directly by a transformer. The harmonic impedances are shown in Figure 5-9. The error is now reduced from 50% to about 13%. It is noted that the harmonic impedance is still not 100% accurate since not all elements are included in the reduced model.

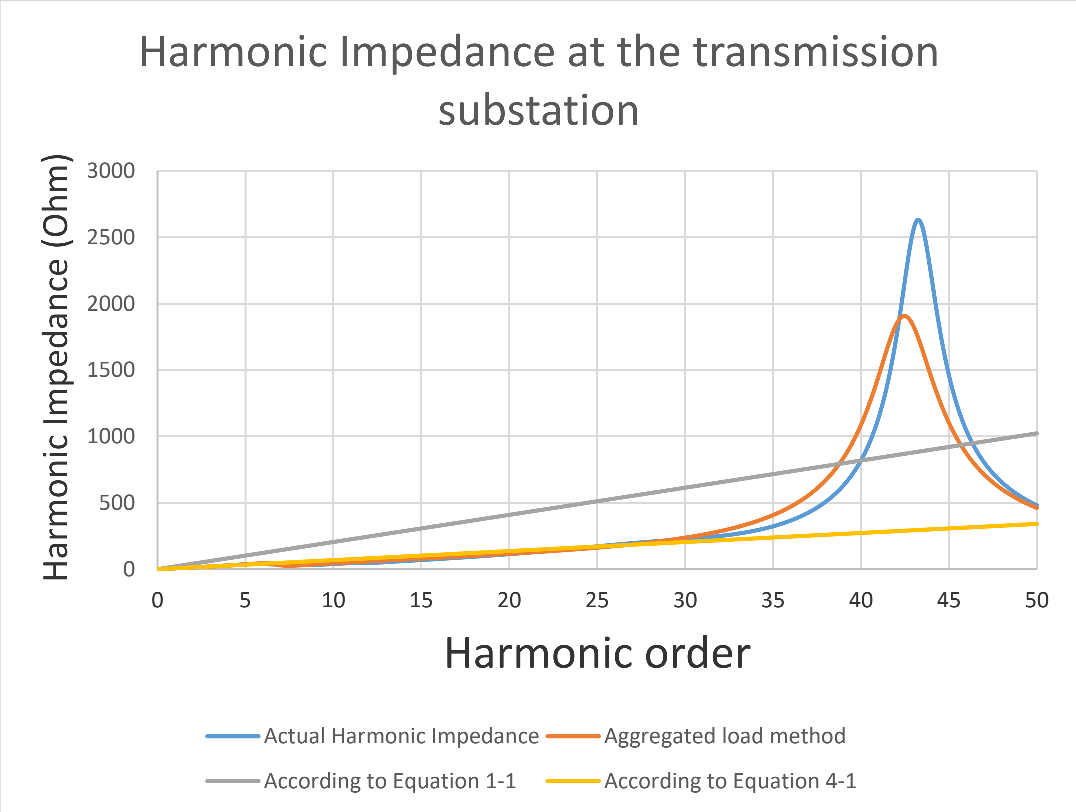

Figure 5-9 Harmonic impedance at the transmission substation

5.3 Evaluation of the load aggregation method on the mine intake substation

STEP 1: Identification of PCC, i.e. mine intake substation.

STEP 2: The components that are directly connected to this PCC are a 20 MVA 132 kV/6,6 kV ΔYg transformer (that connects this sub-station directly to the mine substation adjacent to it) and the one transmission line "Al/St 230/30" that supplies power to the mine intake substation.

STEP 3: The load flow study indicates that the load supplied from the mine intake substation through the step-down transformer is 35.53 MW and 1.3 MVAr. The fault level at the upstream supply point is 2555 MVA which is how the utility supply will be modelled at that point.

STEP 4: The reduced model for the harmonic study is built, consisting of the utility supply impedance, the transmission line Al/ST 230/30, 20 MVA mining transformer, mining

PFC and the mining load. The reduced model is shown in Figure 5-10. The harmonic impedance of the reduced model is plotted and compared to the actual harmonic impedance, as shown in Figure 5-11. The error calculated according to equation 4 – 2 is 38% when applying the load aggregation method, 568% when applying equation 1 – 1 and 131% when applying equation 4 – 1. In this evaluation scenario, the load aggregation method harmonic impedance loses accuracy after the 29^{th} harmonic. The load aggregation method in this evaluation scenario does resemble the actual harmonic impedance at low frequencies (equation 1 – 2) as the PCC of interest is close to the significant PFC of the mine.

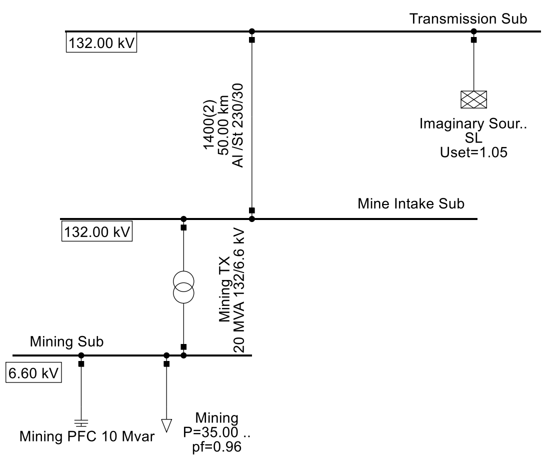

Figure 5-10 Reduced model of the power network as seen from the mine intake substation and the mine substation

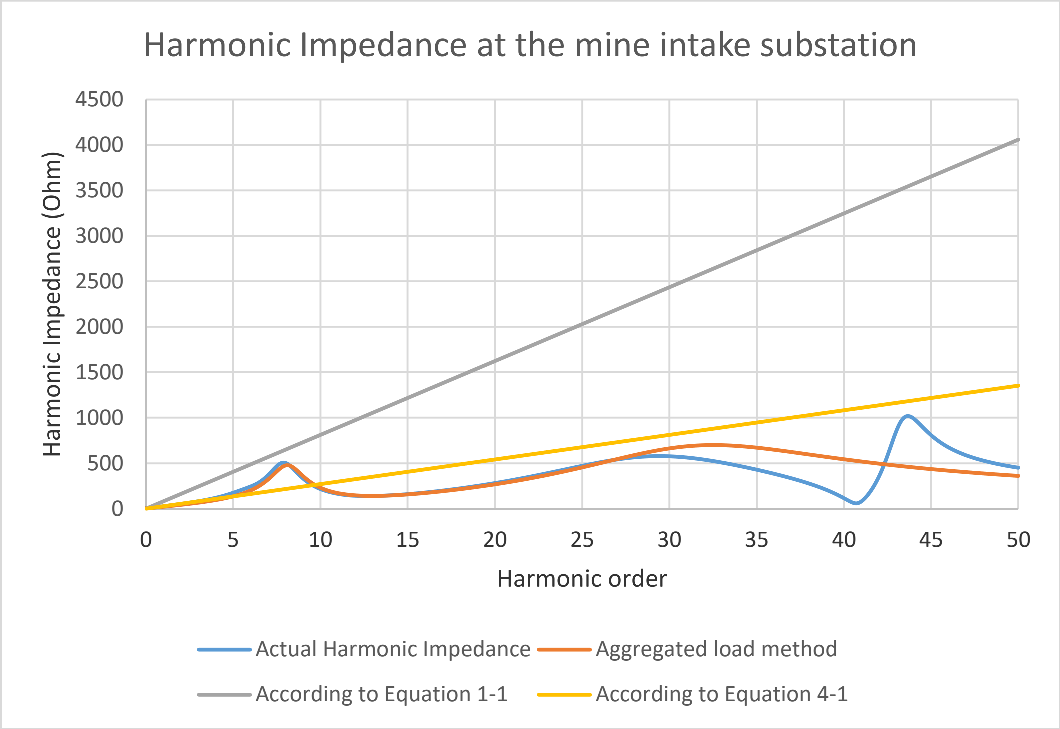

Figure 5-11 Harmonic impedance at the mine intake substation

The next step is to do an analysis of the part of the network that significantly influences the harmonic impedance at the mine intake substation. The same analogy that was followed for the power generation substation is followed here. There is however a difference, such as knowing where the supply comes from, for the mine intake substation. The upstream supply point of the mine intake substation is important since it must be known if there are capacitors that need to be modelled. The fault level at that supply point is also important, since it will be utilized for the modelled utility impedance. The upstream supply point of the mine intake substation has two transmission lines connected to it. The lines are OBJ1-HBG and Al/St 230/30. These were already analysed in section 5.1 (the power generation substation evaluation). The comprehensively reduced model is shown in Figure 5-12. Using this figure, harmonic impedance is as shown in Figure 5-13, with the error reduced from 38% to 10%.

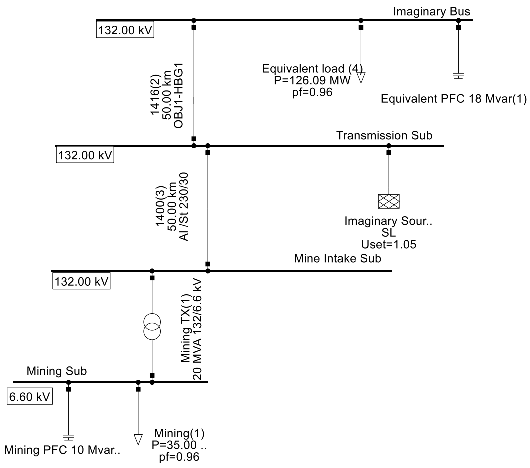

Figure 5-12 Reduced model of the power network as seen from the mine intake substation

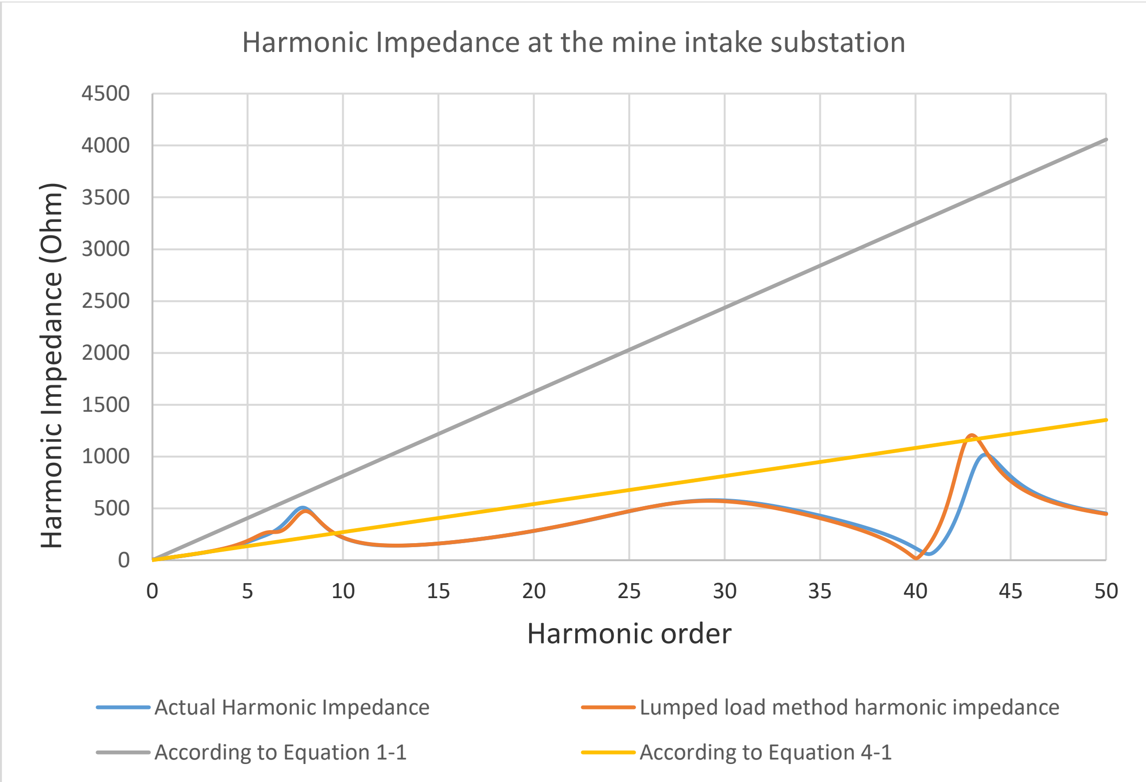

Figure 5-13 Harmonic impedance at the mine intake substation

5.4 Evaluation of the current injection method on the power generation substation

STEP 1: Identification of PCC, i.e. Power generation substation.

STEP 2: Apply harmonic current injection at the power generation substation. The harmonic current source that is applied is shown in Figure 5-14. The current source is used on all other substations for the study.

STEP 3: Investigate the effect on the voltage harmonics at this bus as a result of the current injection. In this step, the voltage harmonics before the current injection must be known. In this case study, the voltage harmonics before the current injection are zero. Figure 5-15 shows the voltage harmonics after the current injection.

STEP 4: The harmonic impedance can now be calculated using Ohm's Law. The exception is the impedance at fundamental frequency which is calculated using equation 4 - 1.

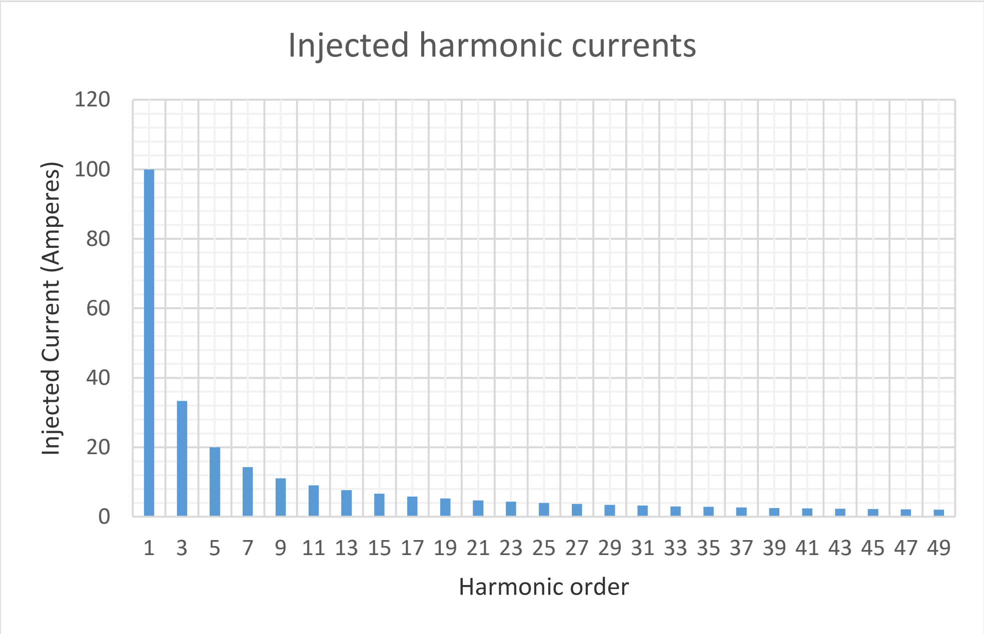

Figure 5-14 Injected harmonic currents at the power generation substation

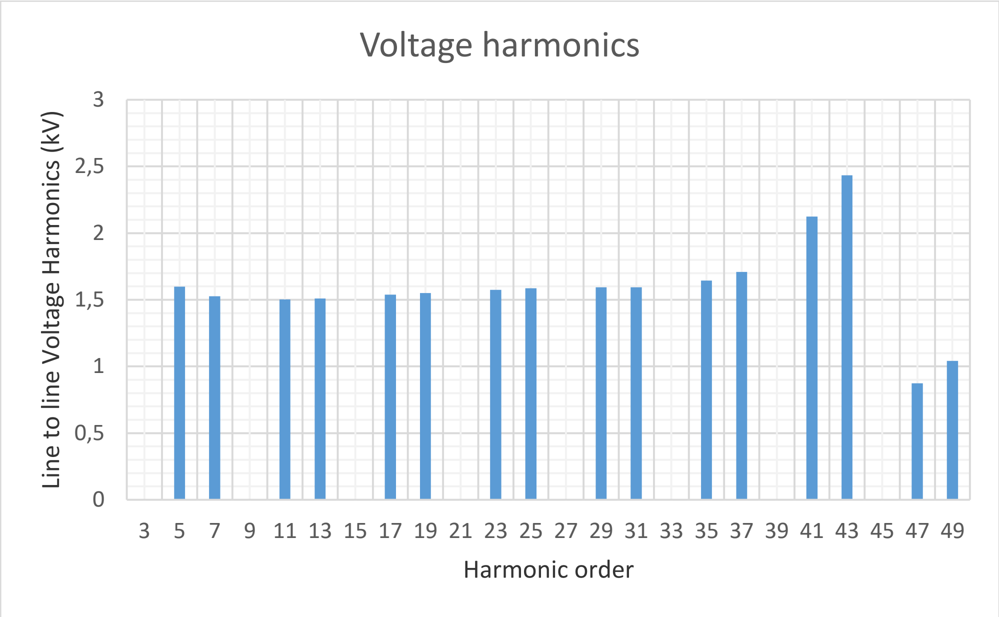

Figure 5-15 Voltage harmonics at the power generation substation after the current injection

The fault level at this bus is 18163 MVA and the voltage is 400 kV, which gives an impedance of 8.8 Ω at 50 Hz. The rest of the harmonic impedances are calculated using the following equation:

$$Z(h) = \frac{\Delta V_h}{\Delta I_h} = \frac{\left|V_{h,before\ injection} - V_{h,after\ injection}\right|}{\left(\sqrt{3}\right) * I_{injection}} \qquad (5-1)$$

The harmonic impedance is plotted and compared to the actual impedance, as shown in Figure 5-16.

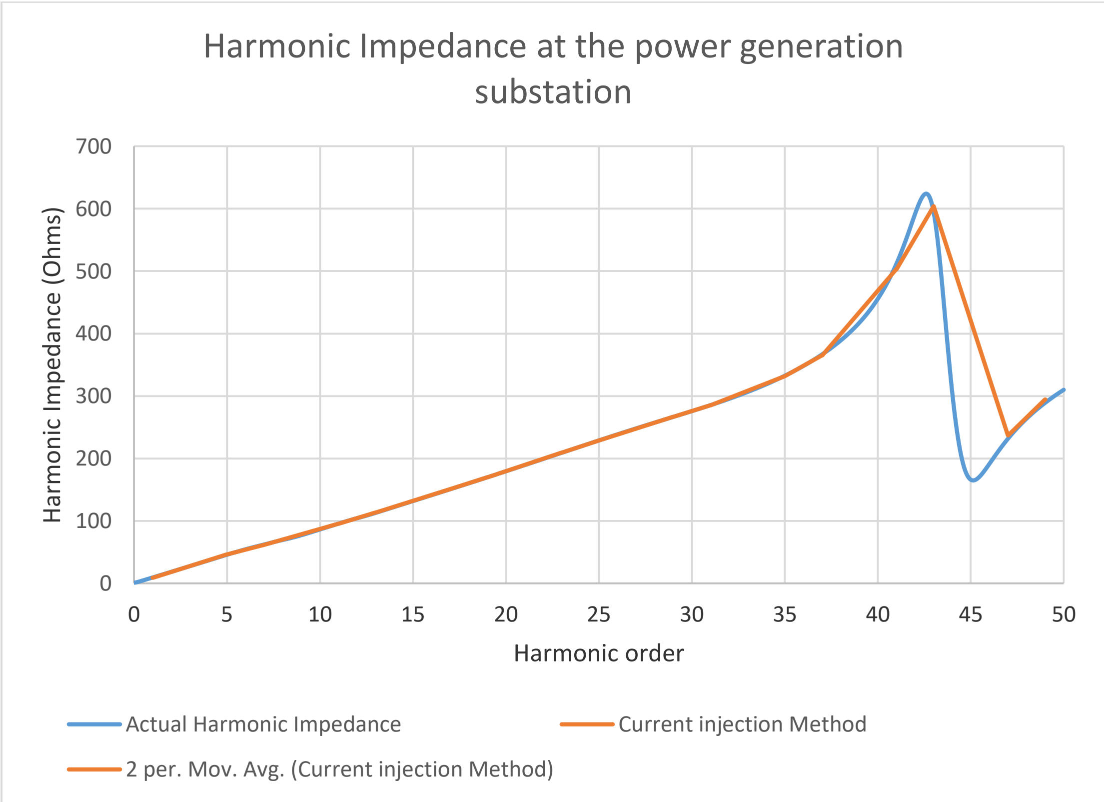

Figure 5-16 Harmonic impedance at the power generation substation using the current injection method

5.5 Evaluation of the current injection method on the transmission substation

STEP 1: Identification of PCC, i.e. the transmission substation.

STEP 2: Apply harmonic current injection at the transmission substation. As stated earlier, the harmonic current that is injected is shown in Figure 5-14.

STEP 3: Investigate the effect on the voltage harmonics at the transmission substation because of the current injection. The voltage harmonics after the current injection are shown in Figure 5-17.

STEP 4: The harmonic impedance can now be calculated using Ohm's Law. The harmonic impedance at fundamental frequency is calculated using equation 4 – 1. The fault level at this bus is 2533 MVA and the voltage is 132 kV, which gives an inductive reactance of 6.9 Ω at 50 Hz. The rest of the harmonic impedances are calculated using equation 5 – 1. The harmonic impedance is plotted and compared to the actual impedance, as shown in Figure 5-18.

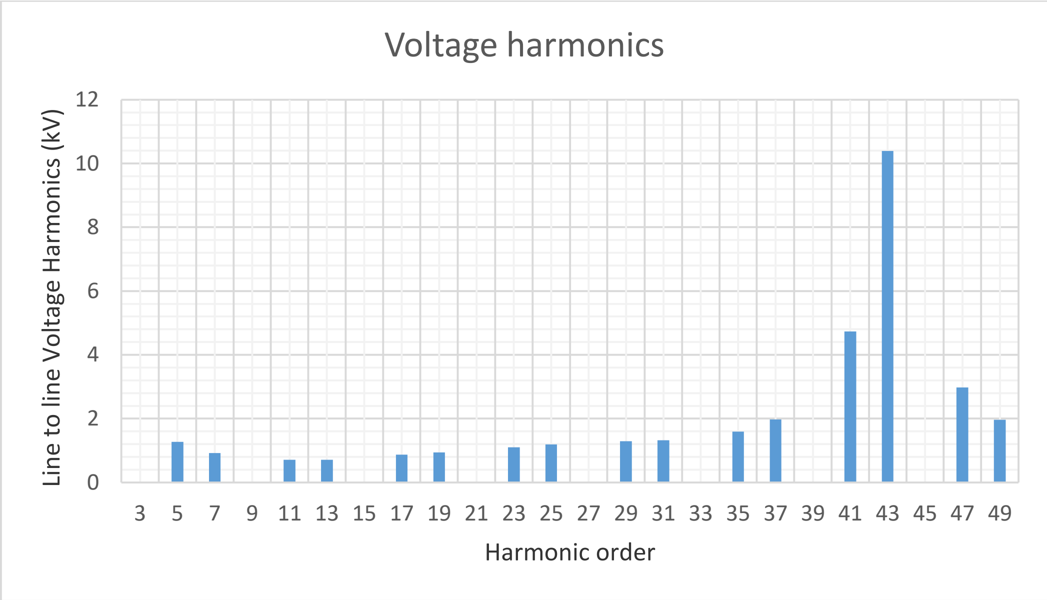

Figure 5-17 Voltage harmonics at the transmission substation after the current injection

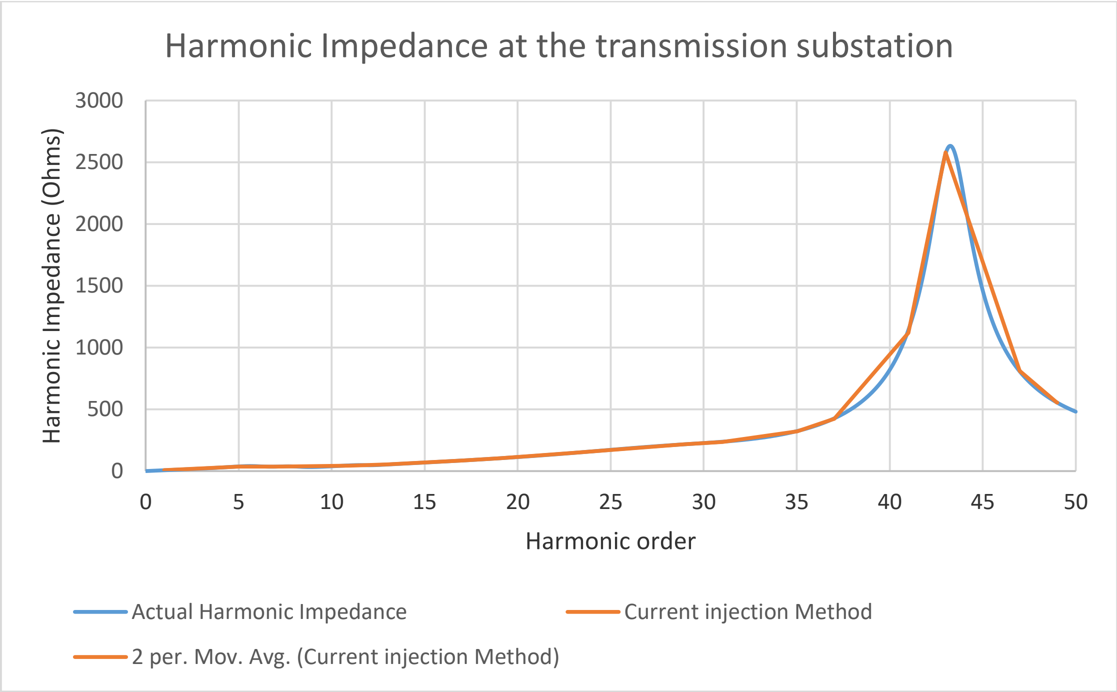

Figure 5-18 Harmonic impedance at the transmission substation using the current injection method

5.6 Evaluation of the current injection method on the mine intake substation

STEP 1: Identification of PCC, i.e. Mine intake substation.

STEP 2: Apply harmonic current injection at the mine intake substation. The harmonic current source that is injected is shown in Figure 5-14.

STEP 3: Investigate the effect on the voltage harmonics at this bus as a result of the current injection. The voltage harmonics after the current injection are shown in Figure 5-19.

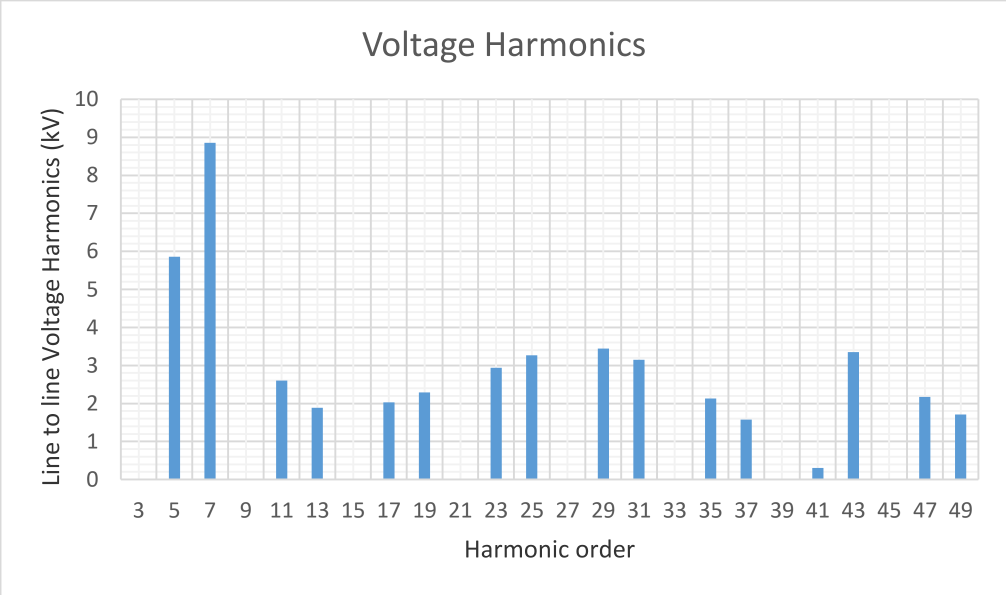

Figure 5-19 Voltage harmonics at the mine intake substation after the current injection

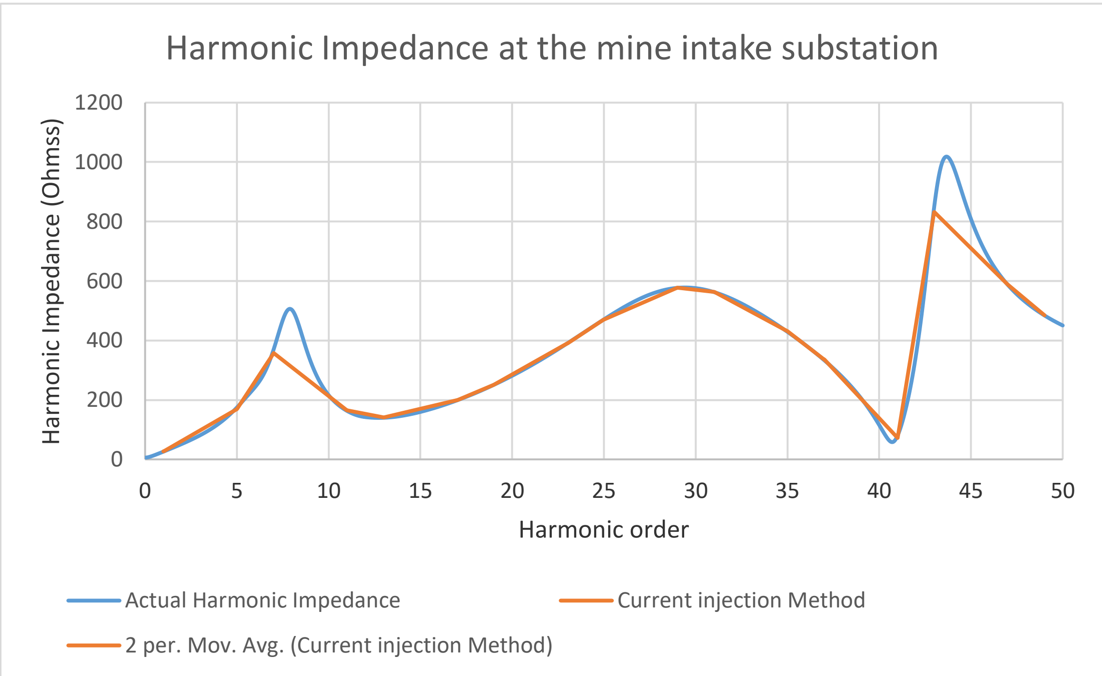

Figure 5-20 Harmonic impedance at the mine intake substation using the current injection method

STEP 4: The harmonic impedance can now be calculated using Ohm's Law. The fault level at this bus is 636 MVA and the voltage is 132 kV, which gives an impedance of 27.4 Ω at 50 Hz. The harmonic impedance is plotted and compared to the actual impedance, as shown in Figure 5-20.

Chapter 6 – Discussion and conclusions

The discussion of the results in Chapter 5 will be divided, according to the two methods that are evaluated. The two methods are as follows:

- The load aggregation method which was performed in the following substations:
    - Power generation substation.
    - Transmission substation.
    - Mine intake substation.
- The current injection method which was performed on the same substations.

6.1 Power generation substation harmonic impedance discussion

The harmonic impedance of the reduced model shown in Figure 5-2 is plotted in Figure 5-3. It is noted that the resonance occurring at the 44th harmonic order does not appear both for the load aggregation method and from the equation 1 – 1 approximation. The reason for this is that the line capacitance (PI model of power transmission lines), directly connected to the transmission substation is not included in this reduced model. The error produced by the load aggregation method is the lowest at 15% while the SAGC method of approximation produces the largest error of 231%.

By taking into consideration the transmission lines connected to the transmission substation, a more detailed reduced model is shown in Figure 5-4. The two harmonic impedances are shown in Figure 5-5. It is noted that the load aggregation method network impedance does not resonate at exactly the same frequency as the actual harmonic impedance.

The last step was to analyse in more detail the network that directly affects the harmonic impedance at the power generation substation. It therefore becomes important to investigate the capacitance that is connected downstream of the transmission substation. A more comprehensive reduced model is shown in Figure 5-6, with the respective harmonic plot shown in Figure 5-7. The error is now reduced from 15% to 4%. The knowledge of the location of the PFCs proved to be important in this simulation study.

6.2 Transmission substation harmonic impedance discussion

The harmonic impedance of the reduced model shown in Figure 5-4 is plotted in Figure 5-8. It is noted that the resonance occurring at the 44th harmonic order does appear when using the load aggregation method but not when using the equation 1 – 1 approximation. The resonance produced from the load aggregation method is because of the inclusion of the transmission lines connected to the transmission substation. The reason for this is that the capacitance downstream is not included in this reduced model. The other consideration of these results in Figure 5-8 is that an extra resonance is produced at the

29th harmonic. The error produced by the load aggregation method is the lowest at 50% while the SAGC method of approximation produces the largest error of 192%.

The last step was to comprehensively analyse the network that considerably affects the harmonic impedance at the transmission substation. This action is important because of the capacitance that is connected downstream of the transmission substation. A more comprehensive reduced model is shown in Figure 5-6, with the respective harmonic plot shown in Figure 5-9. The error, when comparing the actual impedance with the load aggregation impedance, is now reduced to 13%. This simulation again shows the importance of the including the adjacent PFCs in the model.

The other key factor to note is that the amplitude of resonance, produced by the load aggregation method, is slightly smaller than that of the actual harmonic impedance.

6.3 Mine intake substation harmonic impedance discussion

The harmonic impedance of the reduced model shown in Figure 5-10 is plotted in Figure 5-11. It is noted that the resonance occurring at the 44th harmonic order does not appear when using the load aggregation method. The first parallel resonance is realized at about the 7.5th harmonic order. This resonance is not only because of the power transmission line capacitance, but it is also due to the close PFCs of 10 MVAr. The error produced by the load aggregation method is the lowest at 38% while the SAGC method of approximation produces the largest error of 568%.

The last action was to comprehensively analyse the network that directly affects the harmonic impedance at the mine intake substation. From the comprehensive observation of the network, it realised that there are PFCs (18 MVAr) connected to this substation. These PFCs must therefore be included in the comprehensive model. A more comprehensive reduced model is shown in Figure 5-12 with the respective harmonic impedance plot shown in Figure 5-13. The error, when comparing the actual impedance with the load aggregation method, is now reduced to 10%. It is important to note, in this case, that there is another resonance above the 40th harmonic, which is a result of the harmonic impedance produced at the transmission substation. The other principal factor to note is that the amplitude of resonances, produced by the load aggregation method, is comparable with that of the actual harmonic impedance. The series resonance just above the 40th harmonic is also noted.

The comprehensive analysis of the network proved that the inclusion of PFCs is important when performing harmonic impedance studies.

6.4 Reason for inaccuracies of the harmonic impedances when using current injection method

The reason for the inaccuracies of the harmonic impedance when using the current injection method is because in this study only odd voltage harmonics have been produced.

This means that the harmonic impedance can only be accurately calculated at these harmonics. This implies that the rest of the harmonic impedances are determined by interpolation except for the impedance at the fundamental frequency.

From the above discussion, it means that the parallel resonant condition can be inaccurate. The phenomenon is a reality for the mine intake substation, Figure 5-20. Both parallel resonancies are not exactly approximated by the current injection method.

6.5 Conclusions

Two harmonic impedance approximation methods have been investigated in this research, namely, the load aggregation method and the current injection method.

Based on the application of both methods, it was proven that the SAGC method of harmonic impedance approximation is pessimistic. This may lead to inaccurate conversion of voltage or current harmonics. The other downfall of the SAGC method is that it cannot calculate or predict resonant frequencies.

The advantages of the load aggregation and the current injection methods is that they can immediately calculate where parallel resonance occurs, which serves as a good guideline in approximating harmonic impedance. By using these two methods, the middle ground between the NSP and the RPP owner can be reached when the location of the PFCs in the vicinity of the PCC of interest is known.

The basic information that is required to estimate harmonic impedance has been found to be the length of transmission lines, position of PFCs, load flow information and fault levels when using the load aggregation method. The length of the transmission lines is more critical for the load aggregation method since the upstream and downstream network configuration may need to be included in the reduced harmonic impedance model. This can be the most beneficial advantage of the current injection method as it has an inherent capability to determine the harmonic impedance from Ohm’s law.

The other advantage of the load aggregation method is that it requires minimal electrical measurements, i.e. power demand. It can be performed by using simulations only and produce reasonably accurate results. The critical part of this method is that it might be challenging to determine the extent (upstream and downstream) to which the comprehensive analysis of the power network must be executed. This can be overcome by using equation 1 – 2 or comparing the supply inductance to the feeder inductance (explanation deduced from equation 3 – 1 and 3 – 2). When the feeder inductance is low in comparison to the supply inductance, the aggregated load method becomes more accurate.

On the other hand, the current injection method may be quite complex and involved since it may have to be performed in conjunction with detailed site measurements of voltage and current harmonics. In addition to this difficulty, the current injection method is also invasive, and it may be difficult to determine the amount of current to be injected in order experience noticeable voltage harmonic changes.

It is therefore apparent that the accuracy of the load aggregation method is intensively dependant on the location of PFCs and the length of the transmission lines in the power network. The importance of this information can potentially strike a mutually beneficial middle ground between the NSP and the RPP owner.

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