Cape Peninsula University of Technology

DEVELOPMENT OF TECHNIQUES FOR ASSESSING CUSTOMER ACCOUNTABILITY FOR HARMONIC DISTORTION ACROSS A RING MAIN NETWORK

BY

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DECLARATION

I, Rosalia Sinvula, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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ABSTRACT

Modern power systems consist of non-linear loads and high integration of renewable energy sources (RES). The conventional power system is not designed to accommodate new smart grid technologies. This causes challenges for power quality, which can no longer be ignored by both utilities and customers. There are several power quality issues that the utilities have to monitor and manage in real-time. One of the most important is the level of harmonic distortion. A certain percent of harmonic distortion at the Point of Common Coupling (PCC) as prescribed by national and international standards is allowed by power utilities. However, the challenge experienced is that the harmonic distortion from the distinctive individual points to the PCC sometimes exceeds the standard harmonic limits. This harmonic distortion can originate either from upstream through the background harmonics (utility side responsibility) or downstream through the non-linear loads and renewable energy sources (customer's responsibility). There are multiple customers connected at the PCC, thus it is challenging to identify the harmonic source between customers and utility. Hence this research work proposes a practical and commercial method to quantify the harmonic contribution between the power utility and different customers. This method will enable the engineers to assess the accountability of the harmonic distortion measured at the PCC. This research is based on the modified direction of active power flow. This is because this method is generally used by the industrial power quality measurement instruments which the power utility uses for power quality analysis. Harmonic active power is considered when the harmonic source detection methodology is set. A new technique is developed to detect the source of harmonic distortion. Most methods in literature only highlight harmonic detection between the utility and the customer. The research undertaken below highlights the direction of active power at the fundamental and harmonic frequency. A proposed new formula is presented for total active power at a combined frequency (fundamental and harmonic frequencies). The known Norton and Thevenin equivalent circuits are adapted by deriving a mathematical model that accommodates the multiple customers connected at the PCC. To monitor and manage the harmonic distortion during the initial stage of the electricity supply agreement, a harmonic monitoring management system is proposed. Different case studies were modelled in the DIgSILENT software package to validate the proposed methods. The industrial simulation case study is validated by the measurement taken from the NamPower network for six months. It was concluded that the new adapted equivalent circuits be used for power system analysis but not recommended for harmonic source detection. If the proposed harmonic monitoring management system is implemented by the utility, the challenge of harmonic source detection will be minimised. The direction of the active power flow method is proved to be a practical and commercially viable method of harmonic source detection.

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DEDICATION

To my husband, Charles

I would like to thank you for your encouragement and granting me this opportunity to further my study full time, for nurturing our two daughters in my absence, for your prayers – you are my hero. Milcah and Joanna my two princesses, I owe you a lot of appreciation. Glory to God, who sustained and guided you emotionally while I was away. Thank you for the support and company during the late nights of typing.

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GLOSSARY

Definition/Explanation

The following terms used in this research are taken from the IEEE dictionary (IEEE, 2000)

1. Variable speed drive (VSD): a system consisting of one or several electric motors and electric control/equipment designed to govern the performance of these motors (speed and torque characteristics).
2. Frequency: the rate at which alternating current makes a complete cycle of reversals, is expressed in cycle per second or Hertz (Hz).
3. Harmonic: a sinusoidal component of a periodic wave or quantity having a frequency that is an integer multiple of the fundamental frequency.
4. Harmonic order: a number indicating the harmonic frequency; the 1st harmonic is the fundamental frequency, 3rd is three times and the 5th is five times, etc.
5. Linear load: a load that draws a sinusoidal current wave when supplied by a sinusoidal voltage source.
6. Non-linear load: a load that draws a non-sinusoidal current wave when supplied by a sinusoidal voltage source.
7. Harmonic distortion: distortion of an electrical waveform (voltage or current) when decomposed into frequency components which have sinusoidal waveforms at the fundamental frequency and harmonics. The resulting waveform is non-sinusoidal.
8. Total harmonic distortion (THD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50^{th} order and specifically excluding inter-harmonics, expressed as a percentage of the fundamental. Harmonic components of order greater than 50 may be included when necessary.
9. Point of common coupling (PCC): Point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation.
10. Pulse number: The total number of successive non-simultaneous commutations occurring within the converter circuits during each cycle when operating without phase control. It is also equal to the order of the principal harmonic in the direct voltage, that is, the number of pulses present in the dc output in one cycle of the supply voltage.

ABBREVIATIONS AND SYMBOLS

RMS	Root Mean Square
PCC	Point of Common Coupling
PoC	Point of Connection
Hz	Hertz
AC	Alternating Current
DC	Direct Current
MW	Megawatt
PF	Power Factor
PFC	Power Factor Correction
kV	kiloVolt
QoS	Quality of Supply
MVA	Mega Volt-Ampere
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
HD	Harmonic Distortion
THD	Total Harmonic Distortion
ITHD	Total Current Harmonic Distortion
VTHD	Total Voltage Harmonic Distortion
PoC	Point of Connection
ASDs	Adjustable Speed Drives
Wye	Star winding connection
Δ	Delta winding connection
SCADA	Supervisory Control and Data Acquisition
ESA	Electricity Supply Agreement
IEC	International Electrotechnical Commission
CDPES	Centre for Distributed Power and Energy Systems
IPPs	Independent Power Producers
PQ	Power Quality
PV	Photovoltaic
TR	Transformer
DIgSILENT	DIgital SImuLation and Electrical NeTwork Calculation Program
IEEE	Institute of Electrical and Electronics Engineers
V	Voltage
I	Current
Z	Impedance
Y	Admittance
c	Related to the customer side
$c\text{-}pcc$	Related to the contribution of the customer side
u	Related to the utility side
$u\text{-}pcc$	Related to the contribution of the utility side
pcc	Related to the point of common coupling
cA	Related to the customer A side
cB	Related to the customer B side
cC	Related to the customer C side
cN	Related to the customer Nth side

CHAPTER 1: INTRODUCTION

1.1. Motivation

Power systems are designed to operate at the fundamental frequency. With the introduction of non-linear load in the 1900s, it was observed this led to an increase in the challenges of power quality (Tanaka & Hirofumi, 1995; Swart et al., 1996). One of the significant power quality challenges is harmonic distortion (Ruiz-Cortés et al., 2015; Micallef, 2019; Faifer et al., 2019), which causes the current and voltage waveforms to be distorted. Harmonic frequency begins to be part of the power system and this cannot be ignored by power system designers, planners, and operators. The design of the equipment of the power system needs to be adapted to accommodate power quality challenges. It is an expensive exercise for the equipment suppliers to change equipment design. The routine, type and special tests have to be revised and carried out by suppliers to confirm the compatibility of their equipment. These tests are guided by the international and national standards (NRS 048-2:2007, 2007; IEEE Std 1459™-2010, 2010; IEC Std 61000-3-6, 2013; EEE Std 519-2014, 2014), thus these standards have to be reviewed and revised to accommodate the challenge.

In the early 2000s, global electricity demands increased significantly while the cost of fossil fuels rapidly increased (Lin et al., 2014; Osuri et al., 2015). The national governments within the Southern African region launched an initiative for the implementation of renewable energy sources as an alternative to conventional electricity production (Adenle, 2020). Renewable energy sources offer electrical power that is pollution-free and leads to a sustainable environment. This initiative of integration of renewable energy sources with the national grids has faced challenges of harmonic distortion in the use of non-linear loads. Most of the power systems are currently called ‘smart grids’ because they consist of automated electronic devices (Sinvula et al., 2019b). Smart grids are easy to operate and are reliable, but exhibit the power quality challenges. Engineers can operate smart grids from a convenience of their homes, as they are automated.

Harmonic distortion is the main challenge that most power systems face. The total harmonic distortion at the Point of Common Coupling (PCC)/Point of Connection (PoC) exceeds the harmonic distortion limit specified in national and international standards. It is a challenge to determine the contributors to harmonic content at the PCC between the utilities and industrial/commercial customers. Traditionally, the harmonic content was assumed to be contributed by the customer only, as the source was assumed to be ideal (Sinvula et al., 2019a; Xu & Liu, 2000). Modern networks experience harmonics from either upstream or downstream of the connection point. The upstream harmonics are caused by the utility because of the background harmonics whereas the downstream harmonics are caused by customers who have non-linear loads (rectifiers, variable speed drives, arc furnaces, etc., and renewable energy sources (solar PV and wind farms) (Farhoodnea et al., 2011; Nicholson et al., 2007). The background harmonics from the utility can no longer be neglected as they have a major negative effect on the power system.

Once the harmonic distortion exceeds the harmonic limits, it affects the equipment and operation of the power system. The efficiency and power factor of the power system with harmonics are reduced due to high power losses. The insulation of the equipment deteriorates, and its life expectancy is reduced. Hence, the harmonic distortion at the PCC should be monitored and managed to remain within the prescribed limits to minimise its negative effects. The contributor of harmonic content at the PCC needs to be identified and quantified. Thus, it is beneficial to the contributor to be assisted with the design of a harmonic filter to mitigate these effects. Research has been ongoing to develop a method for harmonic source detection (Sinvula et al., 2019a; Cataliotti & Cosentino, 2010a; Rens & Swart, 2001; Stevanović & Petković, 2011; Tanaka & Hirofumi, 1995; Chupeng et al., 2016; Ujile & Ding, 2016; Xu et al., 2018; Cataliotti & Cosentino, 2010b; Pfajfar & Papič, 2011). Most of the currently used harmonic detection methods depend on assumptions and theoretical calculations, and they are difficult to implement in the practical power system.

Power utilities allow the customers to inject harmonic current in the power system. The harmonic limits each customer is allowed to inject into the network are specified and documented in the Electricity Supply Agreement (ESA). This harmonic limit should be within the specified limits prescribed by the national and international standards and based on the approved apportioning guidelines of the country. Utilities should have a harmonic monitoring management system in place that assists the power quality engineers to identify the source of harmonic distortion. Harmonic distortion has major effects on the components of the power system, hence it should be considered in detail at the planning phase of the electricity supply application from the customers. Customers should provide the utilities with relevant information needed to determine their harmonic limit at the PCC. Utilities should inform the customers during the application period to adhere to national and international standards.

Therefore, there is a need to develop a method to assess customer accountability for harmonic distortion. As mentioned, there are multiple customers connected to the PCC. The use of Thevenin and Norton equivalent circuits needs to be modified as customers cannot be represented as one customer, because of different load and operating conditions. Measurement of harmonic distortion is currently conducted at the PCC using different power quality analysers. Nevertheless, these measurement techniques do not give a true overview of each customer's contribution. Thus, the power utilities need to invest in power quality instruments to enable each customer to have a power quality analyser connected at the incoming point of their load to measure the individual and total harmonic distortion of the current. It gives a better understanding by quantifying the harmonic content contributed by each customer to the total harmonic distortion as measured at the PCC. Harmonic distortion measurement and its continuous monitoring assist to detect the origin of harmonic source problems.

1.2. Research objectives

The overall objective of this thesis is to develop a method for assessing customer accountability for harmonic distortion.

The specific study objectives are to:

i. develop a practical and economically viable method for harmonic source detection that can quantify the harmonic source contributors as well as determine the dominant harmonic order;
ii. propose a harmonic monitoring management technique to be used during the planning phase of the application for the Electricity Supply Agreement (ESA), to reduce harmonic source detection challenges; and
iii. investigate Thevenin and Norton equivalent circuits that can represent the practical power system with multiple customers connected at the PCC.

1.3. Research questions

Due to the increase in the use of non-linear loads and renewable energy sources as part of today's power systems, it is vital to identify and quantify the source of harmonic distortion from multiple customers and/or utility connected at the PCC. This research investigates the solution to the questions that follow:

i. How can a practical and commercially viable method for harmonic source detection be identified?
ii. How the harmonic contribution of each customer and/or utility connected at the PCC be quantified?
iii. How can the sign of active power at the harmonic frequency be interpreted?
iv. How can the total active power be determined when harmonic frequency exists in the network?
v. How can the Thevenin and Norton equivalent circuits be modified to represent the number of customers connected at the PCC?
vi. What can be done to monitor and manage the harmonic content?

1.4. Methodology

This research was carried out at the Centre for Distributed Power and Energy Systems (CDPES) at the Cape Peninsula University of Technology.

To answer the research questions, a specific methodology was put in place for the best theoretical foundations, simulation models, and commercial software to:

i. conduct a systematic literature review to understand the different techniques of identifying harmonic distortion source and their shortcomings;
ii. develop a modified method addressing a network with multiple customers connected at the PCC;
iii. model the network in DIgSILENT software with different customers and conduct the harmonic load flow;
iv. explain the sign of active power at the harmonic frequency based on the simulation case study;
v. develop the formulae of total active power at a combined frequency (fundamental and harmonic frequency);
vi. develop new adapted Thevenin and Norton equivalent circuits to represent the number of customers connected at the PCC;
vii. develop a harmonic monitoring management system; and
viii. identify unanswered or new questions and make recommendations for future research.

The method based on the direction of active power flow was identified to be practical and widely used by most power quality analysers, thus it was identified for modification to include multiple customers connected at the PCC. When referring to the total active power of the network, harmonic power is taken into consideration. The sign of harmonic power within the power system is studied and understood to modify the method accurately.

1.5. Outline of the thesis

The thesis is divided into seven chapters:

Chapter 2 – Power Quality

This chapter entails a comprehensive literature review carried by the researcher on the topic. It gives an overview of the topic as set out in the objectives and combines relevant inputs from published journals, books, conference proceedings, and other references. The significance, validity, and applicability of this research to be conducted in the field is determined.

Chapter 3 – Literature review of harmonic source detection methods

This chapter investigates the existing methods, categorises, and discusses them in detail. It further identifies the shortcomings of the existing methods and explains the developed method as a contribution of this research that differs from the existing methods.

Chapter 4 – Contribution to the field of harmonic distortion

New adapted Thevenin and Norton equivalent circuits are developed to cater to the practical power system. This includes the deriving of the mathematical model as a contribution to the field of harmonic distortion. The harmonic monitoring management system would be developed in terms of a flow chart.

Chapter 5 – Modelling of power system equipment in DIgSILENT

This chapter is dedicated to software modelling of the relevant power system components using DIgSILENT PowerFactory software. The details of each case study and its purpose are explained. The main purpose of case studies is to prove the mathematical model and theories presented in the earlier chapters.

Chapter 6 – Results and Discussion

The results obtained from various case studies conducted are analysed in detail.

Chapter 7 – Conclusions and recommendations

The main contributions of the research are enumerated, explaining the impact of the results and their importance to the industry. Further recommendations for future research are made.

Appendices

These provide for completeness the specialised details that the case studies modelled, and the equipment data.

1.6. Summary

The chapter began with an introduction of non-linear loads and renewable energy sources into a power system as they cause challenges of harmonic distortion. A practical power system where multiple industrial and commercial customers are connected needs to be analysed to determine the main contributor of harmonic source and to quantify their contribution. Shortcomings in the literature were pointed out leading to the formulation of the objectives of this research. The layout and organisation of the thesis are also included in this chapter.

1.7. List of Publications (see Appendix A)

i. **Sinvula, R**., Abo-Al-Ez, K.M. & Kahn, M.T. 2019, March. Total Harmonic Distortion (THD) with PV System Integration in Smart Grids: Case study. In *2019 International Conference on the Domestic Use of Energy (DUE)* (pp. 102-108). IEEE. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8734285

ii. **Sinvula, R**., Abo-Al-Ez, K.M. & Kahn, M.T. 2019. Harmonic Source Detection Methods: A Systematic Literature Review. *IEEE Access*, *7*, pp.74283-74299. https://ieeexplore.ieee.org/abstract/document/8731953

iii. **Sinvula, R**., Abo-Al-Ez, K.M. and Kahn, M.T., 2019, November. Efficiency in Distribution Network with Harmonic Distortion. *In AIUE Proceedings of the 17th Industrial and Commercial Use of Energy conference*. https://ssrn.com/abstract=3638104

iv. **Sinvula, R**., Abo-Al-Ez, K.M. and Kahn, M.T., 2020, August. Design of Utility Harmonic Mitigation Filters for Power Transformers. In *2020 IEEE PES/IAS PowerAfrica* (pp. 1-5). IEEE. https://ieeexplore.ieee.org/abstract/document/9219866

v. **Sinvula, R**., Abo-Al-Ez, K.M. and Kahn, M.T., 2020. A Proposed Harmonic Monitoring System for Large Power Users Considering Harmonic Limits. *Energies*, *13*(17), p.4507. https://www.mdpi.com/1996-1073/13/17/4507

vi. **Sinvula, R**., Abo-Al-Ez, K.M. and Kahn, M.T., 2020. Harmonic Source Detection for a Typical Industrial Network with Hybrid Wind and Solar Energy Systems. Book Chapter Accepted for the book titled: "Modelling and Control of Wind Energy Grid Integration".

vii. **Sinvula, R**., Abo-Al-Ez, K.M. and Kahn, M.T., 2020. Harmonic Power Flow Direction Method for Smart Grids. *Accepted for AIUE Proceedings of the 18th Industrial and Commercial Use of Energy conference*.

viii. **Sinvula, R**., Abo-Al-Ez, K.M. and Kahn, M.T., 2020. New Adapted Norton and Thevenin Equivalent Circuits. Under Review for the *IEEE Transactions on Power Delivery*.

CHAPTER 2: POWER QUALITY

2.1. Introduction

The main concern of power utilities worldwide is to ensure the quality of power supply to their customers. If the quality of power supplied is poor, it harms the customers' equipment. Power quality (PQ) is vital because of the high energy demand within countries. Modern industrial and mining plants have implemented automated power electronic devices that are extremely sensitive to the degradation of power quality service. Once the quality of power is compromised it results in financial losses due to poor reliability, lower productivity, and loss of equipment because of damage (Dugan et al., 2003).

Power outages are frequent in modern power systems and are a major cause of concern for the power supply utilities and customers (Alhelou et al., 2019). Many customers might consider a power system to be reliable and easy to operate, but this does not guarantee the quality of supply being delivered to the customers. It is well known that the power flowing through the network should be at the constant (fundamental) frequency (50Hz) and with the purely sinusoidal voltage at all times with no interruption. Currently, no power system can operate purely without disturbance; harmonic distortion and its impact is a major challenge which must be continuously monitored and managed once identified.

2.2. Challenges of power quality

In traditional power systems, the challenges faced regarding power quality were unknown. Since then, due to technological innovation, power systems have become intelligent, automated, and smarter; they are thus identified as smart grids and are designed with intelligent electronic devices. Although the introduction of smart technologies has changed the paradigm of the technical environment, it comes with challenges (Johnson & Hassan, 2016; Miller, 2018). These challenges need to be addressed during the process of planning, manufacturing, and operating the system. The existing traditional power system cannot cope with the excess integration of renewable energy in transmission and distribution networks (Alshahrani et al., 2019; Sajadi et al., 2019). The automation of existing power systems has led to networks developing many challenges due to the fact they were not designed to be automated (Sinvula et al., 2019b). Power utilities manage their grids with varying challenges to achieve the required reliability and stability (Alshahrani et al., 2019; Sajadi et al., 2019). Three categories of customers that are sensitive to poor power quality (Kulkarni & Shingare, 2016) are digital customers, uninterrupted process industries, and essential services. Digital customers include research facilities, data processing, banks, online traders, and communication facilities (television, telephone, cellular stations, and satellites). These customers demand electricity for their computers, computer cooling equipment, data storage facilities, and broadcasting equipment for their operation to be efficient and effective. The smooth operation of uninterrupted process industries, for example, manufacturing and mining industries, requires uninterrupted electrical power of good quality to avoid loss of revenue. Essential services, for example, wastewater treatment and medical care facilities, basically demand uninterrupted quality power supply for the safety of their personnel and to prevent the malfunctioning of essential equipment.

The supply of renewable energy is unreliable as unpredictable unless energy storage devices are installed and tested to work efficiently (Kulkarni & Shingare, 2016). It is noted that PQ challenges are caused by the introduction of electronic devices and the integration of renewable energy sources into national grids (Johnson & Hassan, 2016; Traca de Almeida et al., 2003). It has been established that the increased integration of renewable energy sources (RES) with the distribution network elevates power quality challenges (Kulkarni & Shingare, 2016). These challenges are enumerated in Figure 2.1 and explained in detail. In this thesis, the main focus is on harmonic distortion as one of the most significant power quality challenges, as highlighted in green in Figure 2.1. It should be noted that the stability of power systems and power quality is affected by the high penetration of renewable energy while the disturbances affect transmission line loading. The power quality challenges are analysed by investigating voltage, frequency and power interruption. Poor power quality leads to economic losses incurred by individual consumers and industries, thus finally negatively impacting or compromising the national economy.

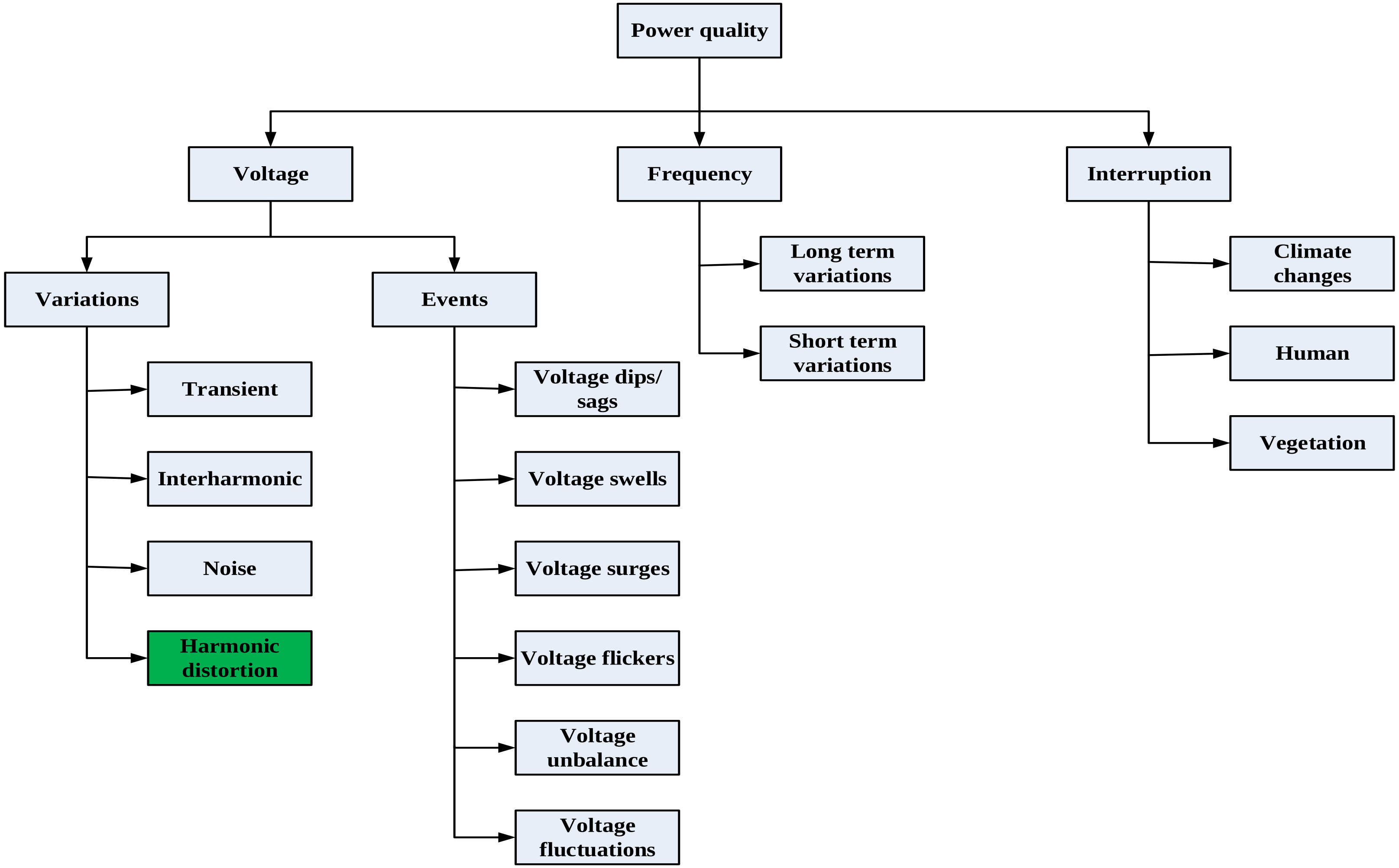


Figure 2.1: Power quality challenges with RES

2.2.1. Voltage

The supply voltage should be monitored continuously, the occurrence of voltage variations and voltage events as identified in Figure 2.1 can lead to a poor PQ (Johnson & Hassan, 2016; Kulkarni & Shingare, 2016; Zobaa et al., 2018).

2.2.1.1. Voltage events

i. **Voltage dips/sags** are defined as when one or more phases has lower than the normal rated voltage for a short period. This occurs when the supply voltage varies between 10 % and 90 % of the rated nominal voltage at the standard frequency. It takes a duration of 0.5 cycles to 1 minute. Starting large electric motors, starting wind turbines, or switching any other heavy loads, insulator flashover, switching, and ground faults can cause this event. The effects are failures of computer systems, shortened lifetime of electrical motors, tripping of electromagnetic relays, and flickering of lights.
ii. **Voltage Swells** are observed when one or more phase has a higher voltage than the normal voltage at the standard frequency. Voltage swells are opposite phenomena to voltage sags/dips. Voltage swells can occur in the range of 110 % to 180 % of the normal voltage for a period of 0.5 cycles to several seconds. There are numerous reasons attributed to the occurrence of voltage swells, for example, an ungrounded neutral connection, insulation deterioration, loss of generation, starting/stopping of heavy loads, a transformer connected in the system without the on-load tap changer (OLTC) for voltage regulation, and electrical faults at one phase causing the voltage to rise in the other phase. The effect of swells is the degradation of electrical contacts and flickering of lights and screens. However, these effects are not as critical as those observed due to voltage dips/sags.
iii. **Voltage surges**: a voltage surge is similar to a voltage swell; however, it represents an extremely high voltage spike for a short duration of time which damages the electrical equipment. A voltage surge can occur when there is overvoltage between the phases or between phase and ground; it can be caused by lightning strikes or arcing during the operation of circuit breakers.
iv. **Voltage flicker** is caused by repetitive and random events in voltage that varies between 90 % and 110 % of the normal supply voltage. This event is caused by switching on and off large cyclic loads such as arc furnaces, electric motor, and welding equipment. Brightening and dimming of screens and luminosity of light bulbs indicate a visible change. It affects humans more as we are sensitive to flickering lighting.
v. **Voltage unbalance** is observed in a three-phase system, due to an unbalanced system in which the three phases do not exhibit identical voltage magnitude and the phase

angle difference between the three phases is not equal to 120°. This affects the unbalanced load/loads between phases as observed in induction machines.

vi. **Voltage fluctuation** is a deviation of supply voltage from the accepted nominal value which is caused by speed fluctuation in the wind, in turn causing wind turbines to generate a continuously varying electric output power. This fluctuating electric power is injected into the grid which finally results in variation in the voltage in the wind farm terminal due to system impedance.

2.2.1.2. Voltage variations

Examples of voltage variations are transients, inter-harmonics, noise, and harmonic distortion, which are explained below.

i. **Transients:** Variation which is observed in the form of voltage spikes or impulses which are characterised by notches and voltage disturbances with high amplitude with a very short duration in microseconds. Since this variation with less energy exists for microseconds, it is a challenge to trace it. Transients can be caused by several factors, for example, power factor correction capacitors, switching inductive loads and electronic equipment, and lightning. Transient variation has a detrimental effect on equipment and leads to damage to the insulation of motors, cables, and transformers. Transient variations can cause permanent damage and data loss in microprocessor-based equipment.

ii. **Inter-harmonics** are due to the current or voltages at a random frequency that is not integer multiples of the fundamental frequency at which the supply system operates, usually 50 or 60 Hz. Inter-harmonics are found in all network voltage classes. Waveform distortion caused by inter-harmonics originates from sources such as static frequency converters, induction furnaces, arcing devices, cyclo converters, and power line carrier signals. The effects of inter-harmonics are frequency conversion, severe resonance, and visual flicker effect in fluorescents.

iii. **Noise** is an unwanted distortion caused by frequency lower than 200 kHz upon the power system current or voltage found on neutral conductor, phase conductors, or signal lines. The power electronic devices, control circuits, electromagnetic interference, arcing equipment, switching power supplies, and loads with solid-state rectifiers are the main causes of noise in the power system. If the power system is not perfectly grounded, the system fails to filter the noise from the power system. Electronic devices such as programmable controllers and microcomputers are disturbed by noise variations causing data processing errors. Noise voltage and its effects can be eliminated/minimised from the power system by implementing line conditioners, isolation transformers, and filters in the power systems to mitigate the noise effects.

iv. **Harmonic distortion** is the deviation of current or voltage waveform from a pure sinusoidal wave. This is attributed to harmonic frequency components present in the signal with a fundamental frequency of either 50 Hz or 60 Hz. The supply system operates at the fundamental frequency, usually 50 or 60 Hz. The harmonic distortion in waveforms can be caused by the combined frequency which consists of fundamental and harmonic frequencies. The causes of harmonic distortion are non-linear loads and renewable energy sources. Non-linear loads that can cause harmonic distortion are static power converters, adjustable speed drives, solid-state switches, arc furnaces, welding equipment, saturated transformers, and battery chargers. Renewable energy sources such as solar photovoltaic, wind, etc., can cause harmonic distortion. Its effects are serious damage to capacitors and transformers, degradation of motor insulation, control equipment malfunctions, and decreases in performance and efficiency of the power system.

2.2.2. Frequency

This is a deviation of power system frequency from the accepted standard nominal value, usually 50 Hz or 60 Hz. Under normal conditions, power system generation should be equal to the power demand. Once power demand exceeds generation, the frequency tends to drop; whereas if demand is less than a generation, the frequency becomes higher. The power system is more complicated and complex because of the interconnections of different loads that vary as well as power generation operating at a different frequency (Kulkarni & Shingare, 2016). The allowed fundamental (standard) frequency variations are given in Table 2.1 and Table 2.2, although currently, the network fundamental frequency can vary from the allowed values, and it consists of harmonic frequencies. The most critical parameter that utilities have to control is the supply frequency which is becoming an issue due to the generation of different kinds. Supply frequency deviation is caused by many factors.

Table 2.1: Deviation from the standard frequency
Adapted from NRS 048-2:2007 (2007)

Network type	Compatibility level
Grid	± 2 % (± 1 Hz)
Island	$\pm 2{,}5$ % ($\pm 1{,}25$ Hz)

Table 2.2: Maximum deviation from the standard frequency
Adapted from NRS 048-2:2007 (2007)

Network type	Limit
Grid	$\pm 2{,}5\ \%\ (\pm 1{,}25\ \mathrm{Hz})$
Island	$\pm 5\ \%\ (\pm 2{,}5\ \mathrm{Hz})$

The fault occurs on transmission lines due to the disconnection of large loads or large generators, which leads to frequency variations. The frequency variations outside the maximum limit mentioned in Table 2.2 are very critical to a power system as any variation can cause it to collapse.

2.2.3. Interruption

Interruption of power is observed when the supply voltage reduces to less than 10% of the nominal for a duration of no longer than 60 seconds. When the period of power supply interruption is greater than 1 minute it is called sustained interruption. Interruptions are mainly caused by insulation failure, lightning, insulator flashover, and faulty grounding. Protection devices have to come into operation immediately to isolate faulty zones in the system. Apart from the interruption caused by technical aspects, interruption in renewable energy sources is caused by weather changes, human intervention, and vegetation (Panteli & Mancarella, 2015).

Apart from the rest of the power quality challenges, this research is focused on a detailed investigation of harmonic distortion introduced by voltage variations, which is a major factor contributing to poor power quality.

2.3. Harmonic distortion

As technologically advanced smarter power systems are being manufactured, investigation of the harmonic challenges in a power system needs to be analysed on a priority basis. Hence the sources of harmonic distortion and its penetration into the power system must be researched. The mitigation techniques possibilities to minimise the individual and total harmonic distortion is part of this study. Figure 2.2 illustrates the current waveforms of the individual harmonic frequency and the combined frequency (fundamental and harmonic frequencies). The linear load (non-distorted load) does not cause harmonic distortion although equipment can be affected by the harmonics injected by the distorted load (non-linear load) connected at the same PCC or anywhere along with the network (Bezuidenhout, 2003).

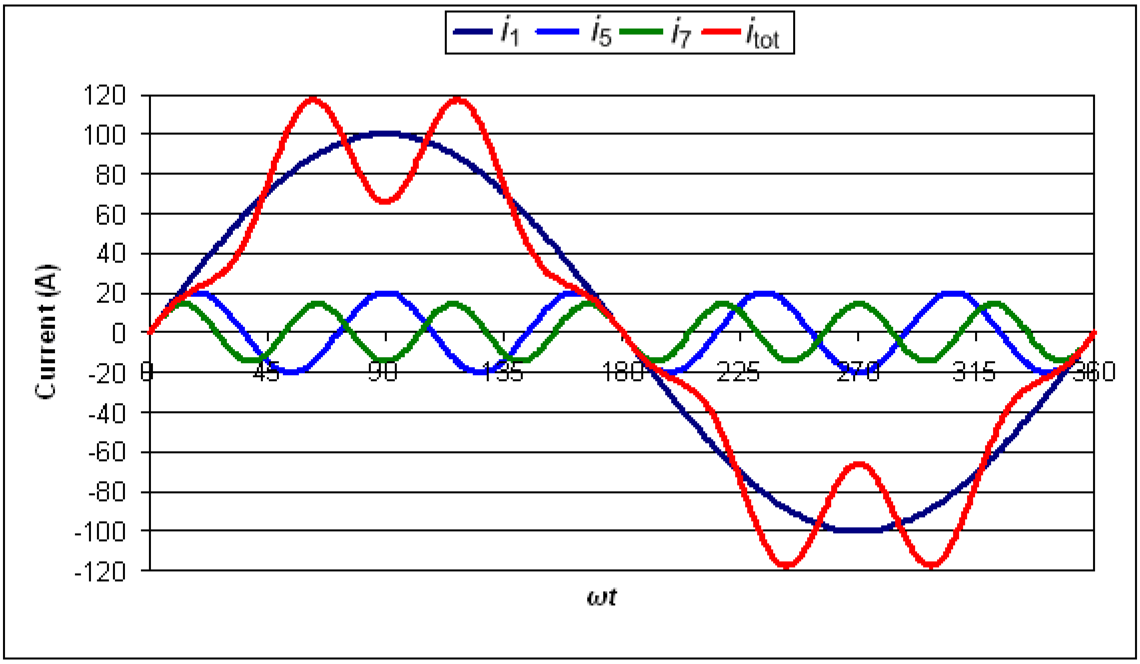


Figure 2.2: Current waveform of the combined frequency
Adapted from Negumbo (2009)

A voltage drop for each harmonic is caused by the harmonic current passing through an impedance which results in voltage harmonics occurring at the PCC bus. This voltage distortion is controlled by the system impedance and the current through the load equipment. The load has no control of the voltage distortion that is caused by the load current harmonics. Fourier analysis is used to analyse the harmonic components of the distorted current and voltage waveforms under steady-state conditions (Dugan et al., 2003). The distorted waveforms of positive and negative half-cycles are identical. Only odd harmonics are used in Fourier analysis, which is called characteristic harmonics (hch). Most of the harmonic distribution sources only generate odd harmonics; if even harmonics are noticed, it indicates the error with the system if the supply voltage is symmetrical. In a modern power system, it is unlikely to find the ideal supply voltage consisting of some percent of background harmonics from the rest of the network. The magnitude of the harmonic current component (I_h) is inversely proportional to and given expression by:

$$I_h = \frac{I_1}{h} \tag{2.1}$$

where: I_1 is the current magnitude at the fundamental frequency (f_1); h is the harmonic number and is equivalent to hch $(h = hch)$; however, when only characteristic harmonics are present, f_1 represents a first harmonics then $f_1 = h_1$. It makes the explanation easier to use h_1 instead of f_1.

The characteristic harmonic current of a three-phase power system is calculated using the expressions respectively as per Red-White-Blue (R-W-B):

$$\mathrm{i}_R = I_{1m}\cos(\omega t) - I_{5m}\cos(5\omega t) + I_{7m}\cos(7\omega t) - I_{11m}\cos(11\omega t) + I_{13m}\cos(13\omega t) - I_{17m}\cos(17\omega t) + I_{19m}\cos(19\omega t) \ldots\ldots \quad (2.2)$$

$$\mathrm{i}_W = I_{1m}\cos(\omega t - 120°) - I_{5m}\cos(5\omega t - 240°) + I_{7m}\cos(7\omega t - 120°) - I_{11m}\cos(11\omega t - 240°) + I_{13m}\cos(13\omega t - 120°) - I_{17m}\cos(17\omega t - 240°) + I_{19m}\cos(19\omega t - 120°) \ldots\ldots \quad (2.3)$$

$$\mathrm{i}_B = I_{1m}\cos(\omega t + 120°) - I_{5m}\cos(5\omega t + 240°) + I_{7m}\cos(7\omega t + 120°) - I_{11m}\cos(11\omega t + 240°) + I_{13m}\cos(13\omega t + 120°) - I_{17m}\cos(17\omega t + 240°) + I_{19m}\cos(19\omega t + 120°) \ldots\ldots \quad (2.4)$$

Equations (2.2), (2.3), and (2.4) are used to determine the waveform of the complex current for three-phase systems. The complex current waveform illustrated in Figure 2.2 is similar to the distorted current waveform for the three-phase six-pulse rectifier/inverters that contain the 5^{th} and 7^{th} harmonics as dominant.

The harmonic indices need to be scrutinised when it comes to harmonic analysis, as this gives enhanced, well-focused information regarding the components involved in the calculation for total harmonic distortion. The total harmonic distortion calculated and analysed can be either for current or voltage.

$$\%THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} F_h^2}}{F_1} \times 100\% \quad (2.5)$$

Where: F_h is harmonic component rms value, F can be voltage or current and F_1 is the voltage or current magnitude at $h = 1$. Individual harmonic component of current or voltage magnitude is expressed as:

$$\%HD = \frac{F_h}{F_1} \times 100\% \quad (2.6)$$

Equation (2.5) and (2.6) can be expressed in terms of current and voltage;

$$\%I_{THD} = \frac{\sqrt{\sum_{h=2} I_h^2}}{I_1} \times 100\% \quad (2.7)$$

$$\%V_{THD} = \frac{\sqrt{\sum_{h=2} V_h^2}}{V_1} \times 100\% \tag{2.8}$$

$$\%HD = \frac{I_h}{I_1} \times 100\% \tag{2.9}$$

$$\%HD = \frac{V_h}{V_1} \times 100\% \tag{2.10}$$

These equations are used in most power system software packages to calculate the individual harmonics and total harmonic distortion of current or voltage, based on the fundamental frequency current or voltage magnitude.

2.3.1. Harmonic source

The sources of harmonic distortions are renewable energy sources and non-linear loads. Examples of renewable energy sources are solar PV and wind turbines, while the non-linear loads are adjustable speed drives (ASDs), fluorescent lighting, and electronic devices. Figure 2.3 indicates the typical parts of an adjustable speed drive.

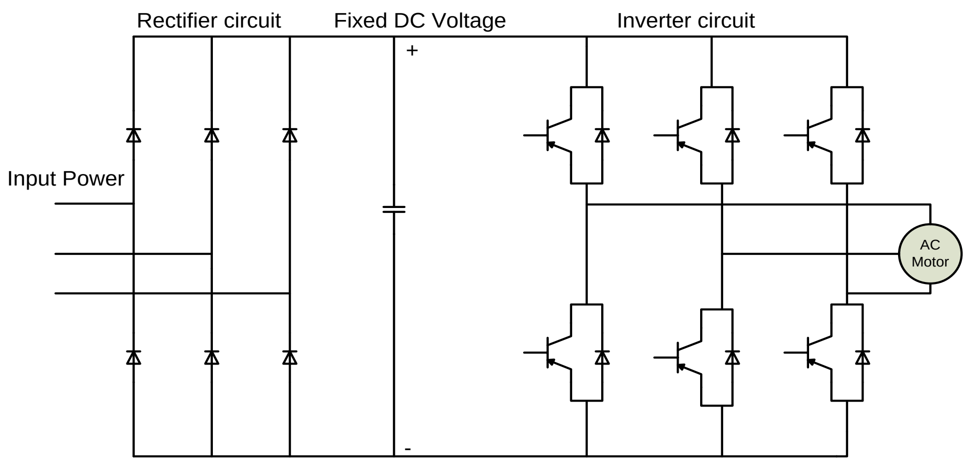


Figure 2.3: Parts of ASD
Adapted from Negumbo (2009)

The harmonic sources are categorised into three categories such as rectifiers, inverters, and others (Zobaa et al., 2018). The rectifiers and inverters are differentiated based on the typical power rating. Table 2.3 tabulates the harmonic source types.

Table 2.3: Types of harmonic sources
Adapted from Bezuidenhout (2003)

Type	Application	Typical Power rating	Dominant harmonic order
Rectifiers			
Single-phase half wave, 1- pulse and Single-phase full-wave, 2 - pulse	• Computers • Receivers for communication and Television • Battery charges • Electronic devices	0 – 30 kW	Half-wave rectifiers: 2, 3, 4, 5, 6, 7, …. Full-wave rectifiers: 3, 5, 7, 9, ….
Three-phase, six-pulse	• Battery charges • Commercial DC source • Electroplating • Ultrasonic heaters • DC motors • Mainframes computers • Radio transmitters	20 – 1000 kW	5, 7, 11, 13, 17, 19, ….
Three-phase, twelve-pulse	• DC motors • Industrial DC sources • Transportation systems • DC arc furnaces • Smelters • Electrolysis cells • SVCs • HVDC transmission	Above 1 MW	11, 13, 23, 25, 35, 37, ….
High phase order	• Smelters • DC Arc furnaces • Electrolysis cells	Above 50 MW	
Inverters			
Three-phase, six-pulse	• Small solar PV panels • UPSs	Up to 1 MW	5, 7, 11, 13, 17, 19, ….
Three-phase, twelve-pulse	• solar PV panels • UPSs • HVDC systems	Above 1 MW	11, 13, 23, 25, 35, 37, ….
Others			
• Rotating AC machines • Fluorescent lighting • Glow discharge lighting • Overexcited transformers • Adjustable speed drives • Light dimmers • Electric heating controllers			

2.3.2. Characteristics of harmonic orders of power system

The symmetrical component is used by engineers to describe three-phase network behaviours. The power system harmonic order is divided into three sequence component categories, namely positive, negative, and zero sequences (Dugan et al., 2003). Table 2.4 describes the components harmonic sequence, the harmonic order, and its frequency.

Table 2.4: Harmonic order and its behaviour

Harmonic order	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}	7^{th}	8^{th}	9^{th}
Frequency	50	100	150	200	250	300	350	400	450
Sign of sequence	+	-	0	+	-	0	+	-	0
Sequence	↺	↻	↑	↺	↻	↑	↺	↻	↑

i. Positive sequence

The positive sequence components consist of three displacement angles, equally spaced at an angle of 120° from each other. It is normally termed as A-B-C or R-W-B with phase rotation starting from 0°, 120°, and -120°. The harmonic frequencies which exhibit the positive sequences are 1^{st}, 4^{th}, 7^{th}, 10^{th}, and 13^{th}. In other words, these harmonic currents rotate in the same direction as the fundamental frequency current. These harmonic currents cause overheating to the power system equipment such as transformers and conductors due to the addition of the current to the fundamental frequency current. The current becomes relatively higher than the rated current.

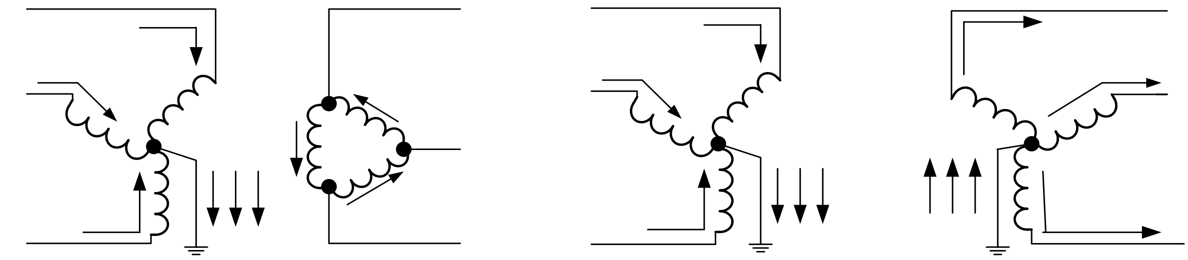
ii. Negative sequence

The sinusoid displacement of the negative sequence is 120° but with the reverse phase rotation i.e. A-C-B or R-B-W, the phase rotation starts from 0°, -120°, and 120°. The negative harmonic order is 2^{nd}, 5^{th}, 8^{th}, 11^{th}, and 14^{th}. In other words, these harmonic currents rotate in the opposite direction of the fundamental frequency current. Rotating machines such as motors are affected by these harmonic currents as it causes the machines to rotate in the opposite direction to the design. The rotating magnetic field in the opposite direction affects the torque and performance.

iii. Zero sequence

The zero sequences are in phase with each other. Thus, the angle of A-B-C or R-W-B is 0°, 0°, and 0°. The zero-sequence harmonics flow into the neutral of the transformer. The third or triplen harmonics are part of the zero-sequence components of the balanced power system. When the system experiences imbalances, the triplen harmonics can exhibit positive or negative sequence components. The vector group of the transformers plays a vital role in cancelling/blocking the zero-sequence current caused by the arc furnaces.

Thus, understanding the type of loads the transformer is supplying has an impact on the transformer vector group design. In delta winding connection the triplen or zero sequence harmonics is blocked. In the distribution network, transformers with star-delta winding connected to the transmission feed are the most used. The triplen harmonic current enters the star (wye) winding connection and it adds in the neutral because it is in phase. Therefore, in the delta winding the triplen harmonic current remains within the delta and cannot escape to the line current; in other words, delta winding provides balance, as shown in Figure 2.4. Only the odd harmonic phase sequence is considered in this research because these are the only harmonics that form part of the power system distorted waveform.



a) Vector group: Wye – Delta b) Vector group: Wye – Wye

Figure 2.4: Flow of third-harmonic current in three-phase transformers
Adapted from Dugan et al. (2003)

2.4. Harmonic limits

The individual harmonics and total harmonic distortion of current or voltage have limits set by international and national standards (NRS 048-4:2009, 2009; IEC Std. 61000-3-6, 2013; IEEE Std 519-2014, 2014). Harmonic distortion exists if it exceeds the limit as set by IEEE Std. 519 – 2014 (USA), IEC 61000 – 3 – 6 (Europe) and NRS - 048 (South Africa). The individual and total harmonic distortion of current and voltage are limited according to these standards. Through measurement analysis, the harmonic limits are measured and compared with the standard limit. Harmonic distortion must be managed by both parties (customers and utilities). Some level of harmonics in the networks is allowed by the utilities as long as they are within the harmonic limits set by the standards. According to NRS 048-4 standard, three different stages of the harmonic emission evaluation procedures are illustrated as per Figure 2.5.

Stage 1 states that the load is too small concerning the network short-circuit, unable to inject the harmonics once it is connected. This raises a concern regarding the feasibility of the contractual agreement required to be revised to accommodate these customers in case their operating conditions change. It is possible in the future to install the distributed generators as part of this load, although the maximum load will remain identical, which can change the harmonic content the load introduces at the PCC. Certain criteria need to be in place in the ESA regarding the change of the operation while that was not part of the initial contractual agreement and introductory procedures. This is feasible when only one customer is connected at the PCC; however, it is a challenge in a modern power system where multiple customers are connected at the PCC. This load in stage 1 can be exposed to harmonic emission from other loads connected at the same PCC, as well as background harmonics, which can affect the load's equipment. The customer must be notified of the maximum harmonic emission allowed at the PCC for optimal design and safety of the equipment. It is the customer's responsibility to discuss with the utility the possible future operation of the load. Thus, in this research, stage 1 load is investigated and Figure 2.5 is modified.

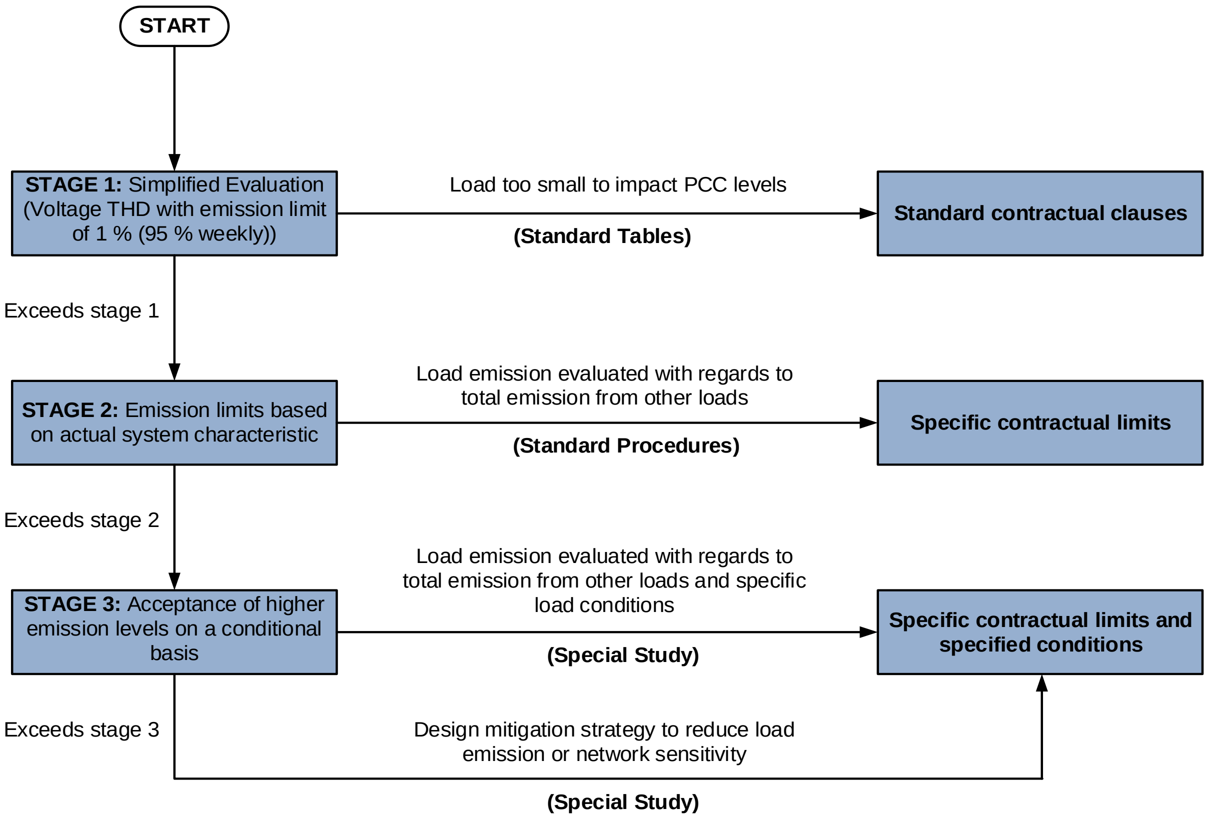


Figure 2.5: Illustration of the emission evaluation procedure, and how emission limits are addressed in contracts
Adapted from NRS 048-4:2009 (2009)

2.4.1. Current distortion

The limitation of the individual and total harmonic distortion of current is specified in Table 2.5. The voltage variations at the PCC of this investigation are within the range of voltage 120 V to 69 kV.

Table 2.5: Current distortion limits for systems rated 120 V through 69 kV
Adapted from IEEE Std 519-2014 (2014)

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a,b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
$< 20^c$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limit above.
[b]Current distortions that results in a dc offset, e.g., half wave converters, are not allowed.
[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.
Where;
I_{sc} = maximum short-circuit current at the PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions.

The power transformers are crucial assets of the power system; thus it is crucial to monitor the harmonic distortion. According to the IEEE standard (IEEE Std C57.12.00™-2015, 2015) a limit is imposed on transformers operating in a harmonic environment where the current total harmonic distortion should not exceed 5 %.

2.4.2. Voltage distortion

The individual and total harmonic distortion of the voltage is tabulated in Table 2.6, where the PCC bus voltage is within 1 kV and 69 kV.

Table 2.6: Voltage distortion limits
Adapted from IEEE Std 519-2014 (2014)

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

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

2.5. Effects of harmonics

The integration of renewable energy sources and non-linear loads cause harmonic distortion and is identified as a major challenge of the modern power system. Voltage distortion is present at the PCC; although only linear loads might be connected at the PCC, the harmonic penetration can be a result of background harmonics. The conductors exhibit a skin effect that creates heat because of the harmonic current which is part of the outer edge. Circuit breakers start tripping, phase conductors and the neutral conductor heat up, while the induction motors and transformers fail prematurely because of the heating effects. On the other hand, the customers who do not generate harmonics can suffer a financial impact. Customers who have loads generating harmonics required to determine the capital investment to decide on the harmonic mitigation method to reduce the power system harmonic content. The harmonics have detrimental effects on the equipment that forms part of the power system and its effects are summarised below (Arrillaga et al., 2013; Davudi et al., 2011; Wakileh, 2001; Zobaa et al., 2018):

i. Rotating machines

The rotating machines generally used in the power system are motors. Overheating, noise and pulsating torque occur as the distorted voltage is supplied to the electric machines. The electric machine rotors are overheated, with higher power losses. The inverter produces high harmonic frequencies that twist the rotor and cause significantly higher core and stray losses in induction machines. The life expectancy of motor operation is reduced by the high operating temperature as the temperature is not uniform within the motor, which causes a hot spot around the conductor and affects the iron core. It can cause vibration on the motor axis, minimised torque, and worn bearings. Single-phase motors are mainly affected by temperature.

ii. Transformers

The heat generated by the losses due to the harmonic content of the load current mainly affects the transformers (Dao & Phung, 2018; Pejovski et al., 2017). Transformers are designed to operate at the rated temperature, thus excessive temperature drastically reduces their life expectancy. Harmonic distortion causes resonance between the system capacitance and transformer inductance. High temperature can affect the core vibration, insulation of the winding, and deterioration of the lamination. The harmonic currents are noticed flowing through the windings. This also leads to increasing transformer losses such as winding eddy-current, stray, and I^2R losses. The skin effect and conductor heating contribute to the I^2R losses, as the load current and frequency, increase the winding eddy-current losses. The stray losses depend on the increase of frequency and usually, the lowest losses are compared to the eddy-current and I^2R losses.

iii. Electronic and electromechanical protective relays

The performance of protective electromechanical and electronic relay is affected by harmonic distortion (Wannous & Toman, 2018; Dalci et al., 2005). This implies that relays will malfunction or not operate as specified. The relays are part of the power system intending to protect the major assets like transformers, transmission lines, etc. Thus, a malfunctioning relay will cause high risks to the major assets. A utility can be faced with a financial loss due to damaged equipment if the protection fails to operate at a specific programmed time. The fault current of the power system is affected by the waveform distortion of the load current. Protective relays react differently depending on the design parameters. Protective relays may fail to trip under fault conditions or may react tripping by without faults in the systems because of distortion.

iv. Capacitors

To improve the power factor of the power system it is required to install shunt capacitors which significantly increase the harmonic content. Thus, it is advisable to design a shunt harmonic filter that can improve the power factor of the power system and at the same time mitigate the harmonic content. Capacitors cause parallel resonance and increase harmonic content at the PCC. Resonance occurs generally near the harmonic frequency that is dominant in the load current present in the network or background harmonics, and which is tuned by the capacitors. During resonance harmonic frequency, a large current or voltage is produced. Harmonic distortion can cause heating and dielectric stress on the capacitors. The fuses can blow and capacitor units can fail. The position of the shunt capacitor in the power system is critical as it has effects on the overcurrent because of resonance. Heating leads to premature aging of capacitors.

v. Circuit breakers and fuses

The current capability of the circuit breaker (CB) is interrupted by the harmonic distortion. The CB interruption is challenging due to the higher current at zero crossing than for a sinusoidal waveform. Fuses have specified inherent root mean square value for overcurrent devices and are thermally triggered. The fuses are subject to skin effect heating by harmonic currents.

vi. Conductors

Harmonic current is greater than the normal root mean square (rms) value of the current due to the heating effect of the conductors. This leads to an increase in conductor resistance and thermal losses. There is current redistribution within the conductor which introduces the skin effect and the proximity effect. The frequency and conductor diameter is directly proportional to the skin effect increases. Abnormally high current can be noticed in the neutral conductor of the three-phase four-wire distribution system which supplies the single-phase loads. A significant third harmonic current will be noticed at the neutral conductors. Hence, the third harmonic current in a three-phase circuit sums up instead of cancelling the neutral current. Thus, the neutral current can increase to 1.7 times that of the phase current of the rectifiers/inverters. The design of the neutral conductor is similar to a phase conductor with an identical current-carrying capacity. This results in neutral conductors being overloaded. This challenge occurs in a commercial building when the three-phase distribution system supplies a large single-phase load. Hence, it is important to design the neutral conductor's carrying capacity of current at least twice as great as the phase conductor capacity to mitigate this challenge (IEEE Std C57.110TM-2008, 2008). The cable will heat up, which could lead to the tripping of the protection devices as the temperature rises above the programmed protection relay setting.

vii. Electronic devices

Electronic devices are affected by harmonic distortion in numerous ways. The voltage zero crossings of the fundamental power frequency are used as a reference by the electronic devices for control purposes. The operation of electronic devices is disrupted because of the harmonic distortion caused by the frequent voltage zero crossings. Devices that coordinate with the reference zero crossing are exposed to harmonic distortion effects.

viii. Lighting

Voltage operating levels are important for the lamps to operate efficiently. Incandescent lamps can stop working if they get a supply from the distorted voltage. It should be noted that if the supply voltage is higher than the rated nominal voltage supplied to the lamps because of harmonic distortion, this high temperature can minimise the operation period of lamps. Audible noise is noticed on discharge lighting. Low-pressure sodium, high-pressure halide, and fluorescent lights are discharge lights that require a series of current-limiting elements of an inductive ballast. Capacitors are generally used to improve the power factor. A dual fluorescent lamp ballast can be lit by using a lamp current phase shift to improve the power factor without capacitors. However, harmonic resonance in lighting can occur between the resonant frequency of 75 Hz – 80 Hz caused by the combination of capacitors, ballast conductors, and lamps, thus, the interaction of the resonant frequency with the power supply should be avoided.

ix. Telephone interference

The supervisory control and data acquisition (SCADA) system is a critical part of intelligent power systems, especially in the modern world where technology is changing to smart grid technology. With the introduction of advanced cellular phones, and optical fiber communication trunking to transmit communication signals, the effects of telephone interference due to harmonic distortion have decreased considerably. Although in some areas where fiber optic cable has not yet been implemented, it is necessary to include fiber optic as part of power systems on which harmonic distortion affects. On utility poles, it is necessary to position the telephone and power lines well to form good interference between the power frequency and telephone. The peak of sensitivity for human hearing and telephone response occurs near 1 kHz, thus harmonic frequencies create greater challenges than the fundamental frequency. Power lines are coupled to the telephone lines using four mechanisms:

i. Loop induction where the power line magnetic field induces a voltage in the loop formed by two telephone conductors.
ii. Loop induction where the power line magnetic field induces a voltage in the loop formed by the telephone conductor and the earth. The path through the ground is created by the ground connections at opposite ends of the circuit. This is a common type of interference mechanism that is used as it creates a larger area for the induction loop.
iii. The power conductor and the phone conductor are capacitively coupled. It is essential to have a proper shielding on the telephone conductors to eliminate capacitive coupling effectively.
iv. Conductive coupling is observed whereby a local ground potential increases because of the neutral applied to the telephone conductor. A potential is created between raised ground level and a distant ground point of the telephone circuit. An abnormal local ground potential increase could happen when there is a poor power neutral connection.

x. Control and measuring equipment

Errors will be registered in equipment due to variation in the zero wave reference giving rise to inaccurate magnitude values of voltage and currents. Thus, the control processes register errors, and the measuring equipment measures invalid results.

xi. Power generators

Power generators encounter challenges of automatic synchronisation and operation because of the distorted voltage and a soft system with a greater impedance than the normal impedance of the power system.

The effects of harmonic distortion become economic challenges which are problematic to evaluate, such as technical and economic costs. The technical costs occur when power system equipment loses performance due to this disturbance. Most of the technical costs turn into economic costs. The technical costs include but are not limited to loss of capacity on an energy distribution line, overloaded conductors and transformers, the power system with higher voltage drop leading to excessive heating equipment, transformers derating and deteriorating, and losses of high-power equipment such as power lines and electrical machines.

The economic costs can be quantified, although it is challenging to do so. These costs can be categorised as hidden or visible. The hidden costs can be distribution losses, power, and energy loss, expansion of the power systems, and the end of the productive process. The visible costs are increases in the cost of electricity consumption as the price of the time of use tariff increases especially during peak hours, and reactive energy payment. These costs can vary as it depends on the loads connected as well as the power system installation or functionality.

Thus, the effects of voltage and current harmonics can result in series and parallel resonance, inefficient generation, minimizing the energy due to degradation of power system insulation components, or certain components and malfunction of power systems.

2.6. Harmonic monitoring system

A harmonic monitoring management system must be in place to minimize harmonic effects. There are international standards that guide the limit of individual and total harmonic distortion of current and voltage (Rendroyoko & Rusli, 2014). These limits need to form part of signed electricity supply agreements. During the planning phase, harmonic studies must be conducted intensively to determine the maximum number of customers to be connected at the PCC. The vital aspect in today’s network is to conduct harmonic monitoring management and this can only be achieved when both customers and utility involved are working as a team. Most utilities have installed monitoring equipment to measure three-phase harmonic current and voltage distortion to assist in detecting and mitigating the harmonics (Asheibi et al., 2006). Harmonics can be from the upstream (utility side) through background harmonics or downstream (customer side) through the installation of equipment that injects current harmonics. Kagan et al. (2002) developed a methodology for monitoring harmonic distortion in electric power distribution systems by assessing the power quality indices, the measurement protocol, and testing procedures. Additionally, traditional distribution systems must be upgraded to meet the growing electricity demand, with improved energy efficiency and supply quality. This is when smart grids need monitoring, control and measurement of power quality disturbances (Muzi & Barbati, 2011).

A smart grid offers many benefits, but it brings with it power quality challenges. Some of the measuring equipment can no longer be used as it needs to be compatible with the power system equipment used. Smart grids are known to increase the performance of power systems. It is the responsibility of the utilities to maintain the quality of power at identical standards during different operating and load conditions (Muzi & Barbati, 2011). Unruh, (2008) and Bingham, (2008) referred to the power quality monitor in an electrical power system according to the IEEE 1159 and gave an explanation of Clause 7 of these standards in detail. Data can be gathered using this method through measurement, although, it is a long process once harmonic limits are not part of the ESA. Clause 7 of IEEE 1159 highlights the safety of personnel and equipment during measurement; the monitoring location depends on the utility schedules, and the equipment connection should be known by measuring engineers. If not, this can cause an error in the data measured. The measured data should be monitored continuously with measuring equipment to minimize data loss due to the limited space. It was indicated clearly that the setting of contracts between the utility and customers will change once there is competition in the electricity market (Hamoud & El-Nahas, 2003). Rewards and penalties are set on power quality and reliability and need to be honoured by both parties (Hamoud & El-Nahas, 2003). The harmonic emission level affects the cost of customers in the purchase of electricity. Thus, it can cause an increase in the network tariffs to mitigate these disturbances if not monitored well. An online monitoring system was developed in the South Hebei power network in China to meet the needs of a smart grid. This system is based on the IEC 61970 standard. Monitoring and management of the harmonics are required to minimize the power loss, maintain the effective stability of the network, and improve the power quality of the distribution network (Duan et al., 2012).

Liang Cai & Hongkun (2004) developed a power quality monitoring system based on the principle of the fuzzy cluster. A neural-network method was proposed by Nascimento et al. (2013) for harmonic distortion monitoring. Many studies have developed methods of monitoring harmonic distortion (Vlahinić et al., 2009; Kulkarni & Bharadwaj, 2015; Farhat, 1998; Olechiw et al., 2014; Chandler, 2008; Stanescu et al., 2007), thus there is a system analysis gap to monitor and manage the harmonics as early as planning phase and include the harmonic limits in the contract agreement. McGranaghan et al. (1998) highlighted the requirements for different contracts within the electricity sectors and the means of monitoring performance to evaluate compliance. The IEEE 519-2014 standard gives an overview of the voltage distortion to be managed by the utility. In Romania, a power quality monitoring system was developed to verify the contract requirement and report the network performance (Stanescu et al., 2008).

For the good management of a distribution network, harmonic distortion needs an effective monitoring system to be in place (Asheibi et al., 2006). A harmonic monitoring system is an important tool to use to limit the harmonic distortion at the PCC. The monitoring system requires accurate harmonic measurements using the correct measuring equipment for it to be effective. A discussion of the harmonic measurement results between the parties is minimally done. An appropriate technical solution is used once the harmonic monitoring is conducted, but it takes a long time to be agreed upon. This solution involves harmonic mitigations; a well-known technique is using harmonic filters. A proposed monitoring system should encourage a technical as well as a financial solution through the payment of penalties. Once the payment of penalties is effected, this will assist in minimizing the time needed to design and install the technical solution, after a three-month consecutive notification that harmonics are exceeding the harmonic limits set on the ESA.

2.6.1. Harmonic measurement

The harmonic current and voltage have to be determined through measurement using three-phase power quality harmonic analysers. Measurement only gives a good indication if the limits are well set in the ESA and understood by all parties involved. Parties involved should be aware of the complications if they have not adhered to the technical compliance limits set in the agreement. All involved parties must agree on the equipment to be used for measurement. In case of disputes, agreed-upon instruments should always be used for measurements for easy interpretation. Power quality measurement methodology should be included in contracts. Most of the known power quality analysers used in Southern Africa are Vectograph, Impedograph, and Unipower (Adolfsson et al., 2009; Waraphok & Saengsuwan, 2007). These instruments use the current, voltage, and active power flow direction to detect the harmonic source. If there is the uncertainty of occurrence in the measurement of total harmonic distortion, this needs to be clarified in the contracts as followed:

i. Determination of the total harmonic distortion measured if it’s a phase–phase or line–neutral.
ii. Measuring instruments for all contractual/dispute situations must be calibrated, and IEC 61000-4-30 Class A compliance must be applied (Rens et al., 2014). In case there is no compliance, the parties need to agree upon the compliance standard that will be used to resolve the dispute.
iii. Determination of the type of power factor used (either three-phase power factor/power factor per phase or true power factor/displacement power factor) depends on the standard used.
iv. Events and load conditions can cause an error in the measurement results. Therefore the events and load condition needs to be agreed upon.
v. The accuracy percentage of transducers should be agreed upon.

Currently, there are power quality analysers connected at different points in the distribution network that provides vital information. The harmonic measurement needs to be conducted with the basis in place as part of the ESA. All the measuring equipment used should comply with the IEC 61000 – 4 – 30 and IEC 61000 – 4 – 7 for the correctness of measurement results. A power quality analyser such as Unipower measures the individual and total harmonic distortion of the current and voltage and additional harmonic parameters. These results need to be analysed in detail by investigating the trends of the waveforms at different periods in time and considering events that could occur within the specific period. Harmonic measurement trends to be used for monitoring of harmonics during the planning phase must be determined if a new customer applies for connection at the same point of connection. Harmonic phase angle measurements are implemented by using PQ analysers; the phase angle between individual harmonics of the current and voltage is determined. Modern power quality analysers indicate the sign of harmonic active power, which gives a clear indication of whether it is absorbing or generating the harmonic power. It is imperative to measure the harmonic distortion to verify the contractual limit stated in the ESA. These results will be used to implement mitigation devices/techniques. As most utilities have online condition monitoring of equipment, as part of the maintenance it is crucial to have online harmonic monitoring. This will monitor the state of harmonic mitigation equipment like harmonic filters connected at the grid. At any instant that an individual harmonic exceeds the limit, the system will give a notification to the user for them to start an investigation of the grid.

2.6.2. Harmonic mitigation

Due to practical impediments, it is impossible to have a network without harmonics, because of the smart grids. Generally, power system components are sources of harmonic distortion. Mitigation of harmonics has various methods such as phase shifting, harmonic injection, etc. (Davudi et al., 2011; Zobaa et al., 2018).

i. Phase-shifting

The electrical supply is separated into two or more outputs and the output of each phase is shifted with an applicable angle for a certain harmonic that needs to be reduced. The harmonic mitigation of a three-phase power system can be achieved using sequence components. Thus, the current of the positive sequence operates in contradiction of the negative sequence's currents, while the zero-sequence currents counter each other in their performance. The phase shift to eliminate the harmonic sequence is determined using Equation (2.11):

$$Phase\ shift = \frac{180°}{h} \tag{2.11}$$

where: h is the harmonic order that needs to be eliminated by the phase shift and 180° is the phase displacement. Once the phase shift is calculated for the positive harmonic sequence, a rated phase shifts higher than the calculated value to be selected. However, with a negative harmonic sequence, a rated phase shifts lower than the calculated value to be selected.

Thus, the phase shifts to be used to mitigate or cancel the harmonic sequence are summarised as:

i. A phase shift of 30° is used to cancel the 5th and 7th harmonic currents of a three-phase output.

ii. A phase shift of 15° is used to cancel the 11th and 13th harmonic currents of a three-phase output.

iii. A phase shift of 60° is used to cancel the triplen harmonic currents of a three-phase output.

Table 2.7: Phase shift required for harmonic cancellation or mitigation
Adapted from Davudi et al. (2011)

Harmonic order	Sequence	Phase shift required		Solution mode
		Calculated	Rated	
3	Zero	60° or 180°	180°	Cancellation
5	Negative	36°	30°	Mitigation
7	Positive	26°	30°	Mitigation
9	Zero	60° or 180°	180°	Cancellation
11	Negative	16°	15°	Mitigation
13	Positive	14°	15°	Mitigation
15	Zero	60° or 180°	180°	Cancellation

With a three winding transformer exhibiting identical power rating at the secondary and tertiary windings, the vector group of Delta-Wye is implemented to mitigate the harmonic sequence distortion. The delta configuration is used to cancel the zero-sequence harmonics while the Wye configuration is to mitigate the positive and negative sequence harmonics caused by the 6-pulse converter, which is the 5th and 7th harmonic orders. This three winding transformer vector group can be represented as Yn0ynd11. The current flows into the primary winding through the secondary winding towards the loads. The tertiary winding leads the secondary winding by 30°, causing a phase difference of 150° between the tertiary and primary winding. Since using the three winding transformers is an expensive exercise, it is advisable to implement the N-1 configuration of the two-winding transformer with the phase shift to cancel the harmonics which is reported to be affordable and optimal. When one transformer is out for maintenance, the backup transformer in service can supply the load without load shedding.

ii. Harmonic injection

When harmonic current is added 180° out of phase to the waveform it can reduce the harmonic content. This method mitigates harmonic content as the design criteria are not included in the system impedance. However, it is a challenge for a harmonic source to remain synchronised with the power system. Harmonic generators are required to have a maximum of 10% of the DC power of the rectifier as a power dissipation which is part of the challenge of using harmonic injection as a harmonic mitigation method.

iii. Harmonic generation reduction

Harmonic generation from converters can be reduced by increasing the converters' AC reactance, and installation of s 12-pulse converter or higher, and improving the thyristor control symmetry.

iv. Magnetic flux compensation

Non-linear load harmonic content is identified by using the current transformers, which is supplied from the amplifier into the transformer tertiary winding for harmonic current cancellation. The tertiary winding of the transformers is coupled with the output of the amplifier to protect the amplifier from being damaged by the flow of the fundamental current. To minimise the amplifier output fundamental current, a filter and quaternary winding for auxiliary power are used. This method also mitigates the triplen harmonics or uncharacteristic harmonics. However, it is impossible to mitigate the lower harmonic order without needing an amplifier of high power feedback.

v. Harmonic filter

The function of the harmonic filter is to minimise the individual and total harmonic distortion of the current or voltage (IEEE Std 1531™-2003, 2003). The filters generally used are series shunt filters. A series harmonic filter consists of parallel inductors and capacitors exhibiting a large impedance above the relevant frequency to prevent unwanted frequencies from entering the power system. However, the series filter cannot be used for harmonic elimination. The shunt filter is mainly used for harmonic mitigation. The harmonic filters are expensive, and it requires technical expertise to design and install them. If not designed correctly, the filter will not mitigate the dominant harmonics effectively. It is always better to efficiently manage and control the harmonics, thus the harmonic filter should be the last option once all the mitigation factors have been tried without efficient results.

If the harmonic level is beyond the limits set by standards without being managed and monitored effectively, the harmonic source identification needs to be studied for purposes of understanding, which can lead to the proper design of the harmonic filter methods for mitigation purposes. Without identifying the exact source of harmonic distortion, the mitigation solution will not mitigate the harmonic content to the minimum level possible. Harmonic source detection is discussed in Chapter 3. It is beneficial to monitor harmonic distortion at the PCC when no load and full loads are connected. In the case that the harmonic distortion is similar with and without the load, this indicates that voltage distortion is from the external source. If there is a correlation between the voltage distortion increasing with the increase in load installation, this indicates that the loads have effects on the voltage distortion at the PCC. It is theoretically possible to simulate the network by switching off certain loads; however, it is not possible in a practical situation as switching loads to do this measurement need a long period of approval of different stakeholders and its outage time is limited, which might not be possible to conduct the analysis.

2.7. Summary

Harmonic distortion is a major PQ challenge of the power system. Poor power quality can occur due to voltage variations/events, frequency, and interruption. Thus, harmonic distortion is one of the voltage variations. The known harmonic distortion sources are renewable energy sources and non-linear loads. Modern network components are electronic devices that contribute to the non-linear loads. The conventional power system changed to the introduction of smart grids which are easy to operate with many power quality challenges. Various harmonic orders are part of the smart grids, categorised as positive, negative, and zero harmonic sequences. The harmonic sources are identified with varying dominant harmonic orders. The individual and total harmonic distortion of the current and voltage is limited according to the available standards. Power transformers are an example of power system equipment that has specified harmonic limits. If the harmonic distortion is not limited according to the established standards, the power system equipment is affected in different ways which in the long run will impact the life expectancy. Hence the harmonics must be well monitored and managed. Harmonic measurement is vital in international trends for the supervision of harmonics in the distribution networks. The most widely used harmonic mitigation method is using designing and installing the harmonic filters. It is important to find a method for harmonic source identification which can be used in practical power systems and can give a good indication of the customers that require harmonic mitigation design.

CHAPTER 3: LITERATURE REVIEW OF HARMONIC SOURCE DETECTION METHODS

3.1. Introduction

Ensuring the quality of power supply is the main target of power utility companies worldwide. Harmonic distortion is one of the power quality problems that can result either from upstream (utility side) through background harmonics, downstream (customer's side) through non-linear loads, or renewable energy generators. The detection of harmonic sources at the point of common coupling (PCC) is a major concern for both utilities and customers. Various methods have been proposed since the 1990s to be used for harmonic source detection. These methods have been classified into three categories based on the direction of active power flow, reactive power, and voltage-current ratio. A systematic literature review is done on the state of the art of current research on harmonic source detection methods, to select the method that gives better practical and commercial results to be used when multiple customers are connected at the PCC. This systematic literature review recognizes that most studies concentrate only on harmonic source detection between a customer and utility, but the practical power system has multiple customers connected to the PCC with different load conditions. Therefore, the results obtained from this literature review are useful for researchers and engineers working in the modern grids, who aim to develop practical and commercial methods to quantify the harmonic contribution for different customers and utility.

3.2. Background

The integration of renewable energy generators and the use of non-linear loads in the modern smart grid may cause power quality disturbances. Various types of disturbances can occur, and among them, one of the most important is harmonic distortion; voltage and current waveforms are distorted and consist of different harmonic orders. Power systems are affected by the disturbances, and monitoring needs to be in place to minimize the effects, which may include equipment failure resulting from overheating, shortened life expectancy of transformers due to the deterioration of insulation levels, and increases in equipment power losses (Vora & Bhatt, 2014). Disturbances can be caused by any customer connected within the grid and can influence the customers situated at the remote branches of the power grid.

The network configuration and resonance conditions must be monitored as this leads to high harmonic current multiplication that causes high voltage levels. Utilities do allow a certain level of harmonic emissions into the network as agreed in the electricity supply contract. However, it is responsible to manage the network in such a manner as to ensure that the voltage distortions remain within the contracted limits and adhere to the power quality standards prescribed by the national energy regulator of the specific country. This is achieved using power quality contract management. During the planning phase, harmonic studies must be conducted intensively to determine the number of customers connected at the point of common coupling (PCC). This exercise needs to be repeated at any time a new customer applies for the connection, to view the trend once a new installation is connected. Accuracy of simulation studies is achieved when adequate information is available, therefore it is recommended that customers provide the required information. Today, utilities are urged to be vigilant not to assume parameters during harmonic studies as this might cause a long-term challenge that could be mitigated in the planning phase.

There are standards (IEEE Std. 1459™-2010, 2010; IEEE Std 519-2014, 2014; IEC Std. 61000-3-6, 2013) with the set of limits used to monitor the individual and total harmonic distortion (THD) levels of current and voltage at the PCC. IEEE Std. 1459™-2010, (2010) gives the measurement of electric power quantities definitions under sinusoidal, non-sinusoidal, balanced, or unbalanced conditions. The amount of harmonic current a customer is allowed to inject into the power network at the PCC is limited as indicated in IEEE Std 519-2014 (2014). IEC Std. 61000-3-6 (2013) indicates the limits of the harmonic voltage distortions a customer can add to the network. These standards must be used during the planning phase for the application of a point of connection for electricity supply to customers by the utilities. To develop any method for harmonic distortion evaluation, it is vital to identify the disturbance sources that can be either upstream and/or downstream of the metering point; so, the responsibility of harmonic distortion can be from the supply and/or load (Barbaro et al., 2006; Cataliotti & Cosentino, 2010a; Cataliotti et al., 2008).

The vital aspect of a modern network is to conduct the harmonic management and this can only be achieved once the source of harmonic distortion is identified between the parties involved (Xu et al., 2018). Studies are conducted with the theoretical idea in mind that the harmonic distortion at the PCC is solely caused by customer loads, which is not true in a real-life situation. The amount of harmonic distortion present at the PCC is subjected to the installation of a customer and the background harmonics as part of the utility side (Papic et al., 2019). The background voltage distortion cannot be ignored or assumed to be minimal, as in some cases, it causes high harmonic currents at the PCC (Malekian, 2015). Currently, there are no guidelines that limit background harmonics. There is a need for the national regulator to develop a guideline to lead power quality engineers during the planning processes.

Whenever there are high levels of harmonic voltage distortions or current injections in the network, the source of harmonic distortion must be identified. This is essential to the utility and the customers concerned for a proper mitigation method and for identifying the responsible parties involved. Once the responsibility is apportioned, the affecting party is required to mitigate its contribution by providing a filter and bear the costs thereof. However, certain networks have proven to be difficult to manage harmonic levels because the source of harmonic distortion could not be accurately detected. This has necessitated the importance of finding an accurate method to identify harmonic-emitting sources.

Worldwide, harmonic source detection is an important challenge faced by utilities and customers. The location of harmonic source detection has been part of research since the 1990s (Swart et al., 1994) as the non-linear loads became part of the power system. Many methods and techniques have been developed and reported in the literature to detect harmonic source (Lin et al., 2005; Xu et al., 2018; Malekian, 2015; Cai et al., 2019; Chupeng et al., 2016; Gül & Gündoğdu, 2015; Jiang et al., 2016; Karimzadeh et al., 2016; Li et al., 2016; Papic et al., 2019; Karimzadeh et al., 2015; Peterson et al., 2017; Peterson et al., 2015; Spelko et al., 2017; Stevanović & Petković, 2011; Lin et al., 2018; Zhao & Yang, 2015; Zhao & Yang, 2016). These methods and techniques have been discussed and scrutinised about certain issues. Hence, researchers have reviewed and compared different methods and techniques (Cataliotti et al., 2008; Peterson et al., 2015; Durdhavale & Ahire, 2016; Safargholi et al., 2018a; Safargholi et al., 2018b; Supriya & Nambiar, 2012; Bazina & Tomiša, 2014).

Papic et al. (2019) proposed a benchmark test system representing the MV/LV network to be used to close the gap in evaluating the existing proposed methods of harmonic source detection. This is a comprehensive idea as many studies can be done using this benchmark test system, with different power system software packages to test and analyse different developed methods and techniques. Most industries can use software that is available to them to test the benchmark and use it for a real-life situation. Papic et al. (2019) concluded that different topologies of the grid should be studied, although renewable energy generators fed by power electronic inverters were not considered in the proposed benchmark. Therefore, further research was required for the improvement of the benchmark test system. In a steady-state normal condition, this benchmark will be a good tool to be used, although, in real-life, practical grids, the network responsibility and loading condition may change as the need arises, and harmonic generation from non-linear source can change anytime depending on the load conditions.

A practical method for detecting the harmonic source must be determined to assist the field engineers in apportioning the harmonics fairly to customers. This will be the best idea for current and future power system models where renewable energy generators are integrated and multiple customers are connected at the PCC. Presented methods by Safargholi et al. (2018a) and Safargholi et al. (2018b) concerned harmonic distortion is between a utility and a customer, although this does not give a true scenario of a power system. Today, power systems are represented in Figure 3.1 where multiple customers are connected at the PCC. These customers have different operating conditions that need to be known by power quality engineers during the planning phase.

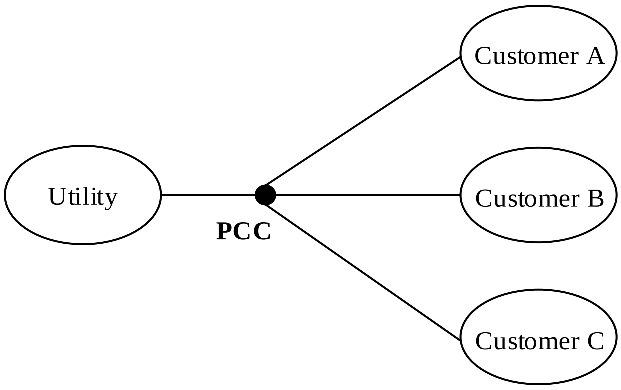


Figure 3.1: Implementation of harmonic source detection

Therefore, to evaluate the literature research adequately a systematic literature review (SLR) methodology as defined in Torreglosa et al. (2016) was used. This study addressed more precisely how to detect the harmonic source when multiple customers are connected at the PCC. More specific questions are as follows:

i. how to determine which customer is contributing more harmonics;
ii. how to quantify the customer's contributions;
iii. how to improve the harmonic monitoring management
iv. what happens when different customers with operating and load conditions are connected at the PCC; and
v. what are the most common simulation and experimental methodologies used to give proof of a selected method?

Although various researchers have proposed methods for harmonic source detection, they only focused on the cases of one customer and a utility. Therefore, there is a shortcoming to detect the harmonic source when multiple customers are connected at the PCC with different operating and load conditions. The objective of this study is to select and propose a practical and commercial method for harmonic source detection when multiple customers are connected at the PCC. The systematic literature review methodology is given in the next section.

3.3. The methodology used to conduct this literature review

A systematic literature review (SLR) is carried out based on a method used mostly in the medicine, social sciences, and as well as in other fields such as education, supply chain management, and economics. In Torreglosa et al. (2016), this methodology was considered in the engineering field and it gives s good evidence-based approach. The stages specified in Figure 3.2 describe how this study was conducted: stage 1 defines what the problem is and its delimitation; stage 2 determines relevant aspects to be included in the study; stage 3 specifies how the information is obtained; stage 4 organises and classifies obtained information in a simple form; stage 5 discusses the information obtained, and stage 6 compiles the report.

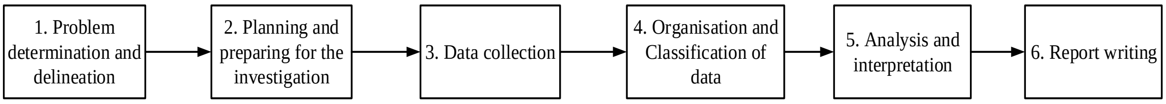


Figure 3.2: Systematic literature review stages

Stage 1: Total Harmonic distortion at the PCC is increasing with the use of non-linear loads and the integration of renewable energy generators in power systems. Harmonic source detection is one of the challenges that face power utilities and customers. It is a concern for both parties as no method can be used to indicate who is responsible for harmonics when multiple customers are connected at the point of common coupling. Most researchers only focus on a single customer connected at the PCC. Knowing whether the harmonic source is from utility or customer does not assist apportioning between the customers connected at the PCC. Once a harmonic source is identified to be from the customer side, how can one know which customer is contributing more? Solutions need to be provided for the industry-wide problems concerning the identification of harmonic sources and in dealing with customer complaints arising from harmonic problems on the network. This review was done to develop a practical solution for engineers to determine the source of harmonics at the PCC. This literature review concentrates on only three categories of harmonic source detection methods.

Stage 2: The first step of this literature review is to give an overview of the important factors when proposing harmonic source detection methods as indicated in Figure 3.3. The second step is how harmonic source detection is determined, as indicated in Figure 3.4.

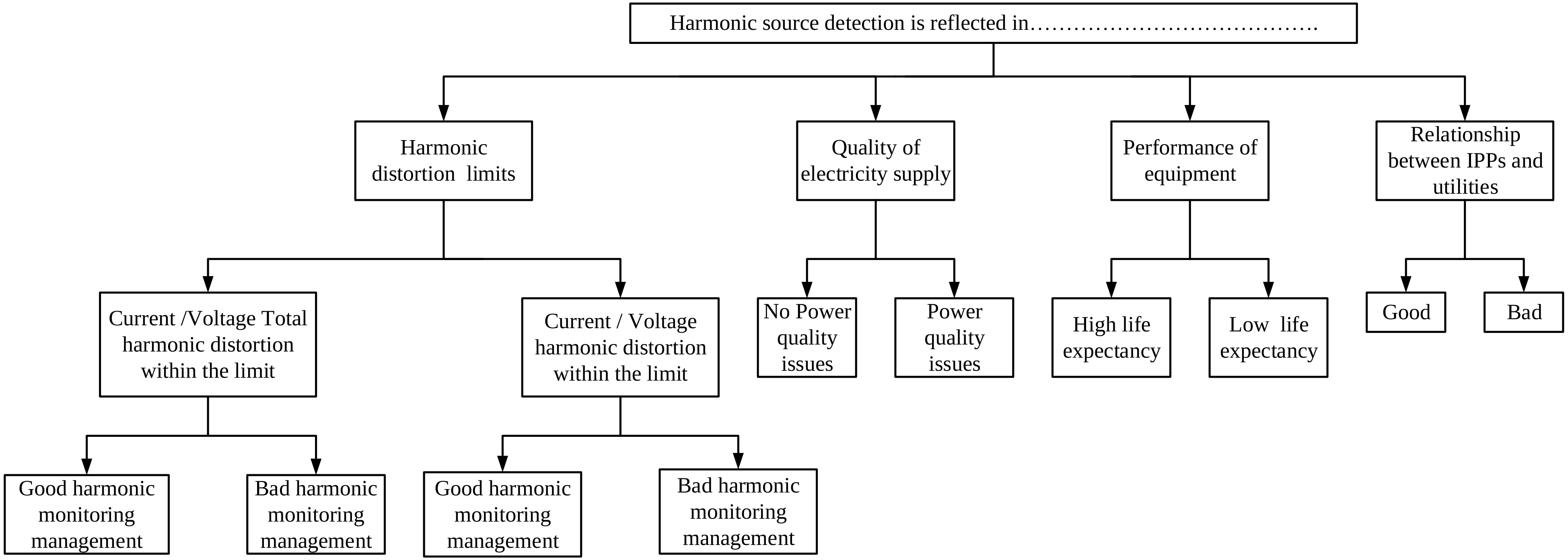


Figure 3.3: Dendrogram of inductive research design

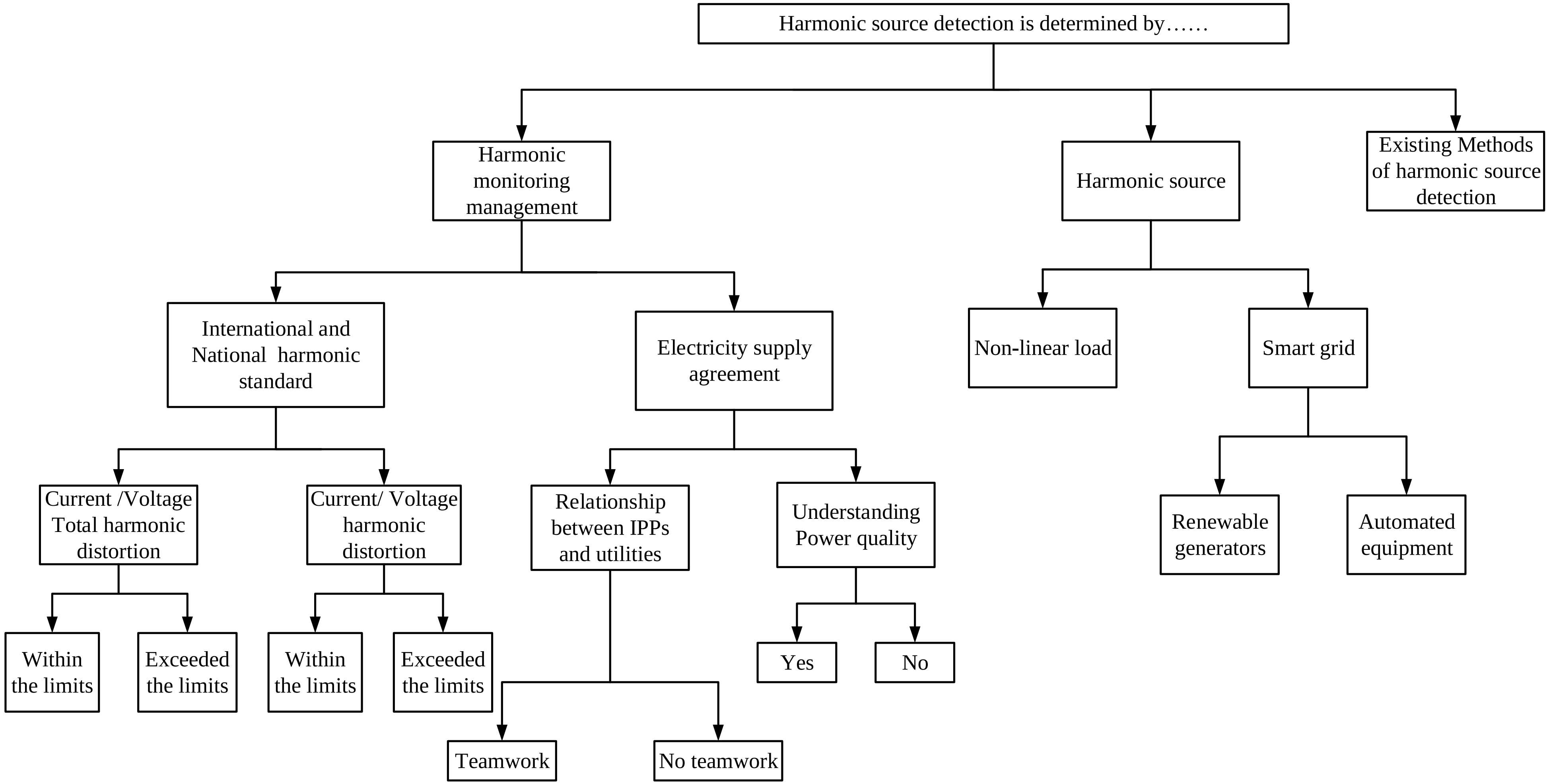


Figure 3.4: Dendrogram deductive research design

Stage 3: Data is collected by using databases as search engines using keywords. Databases of a web of science such as Science Direct, IEEE Xplore, and Scopus were considered. Google Scholar was used to searching certain journal papers and conduct citations straight from the web using EndNote X7 and the referencing database was exported to Mendeley. The topic of harmonic source detection is covered by many studies with different methodologies/techniques. The keywords used to search for information are indicated in Table 3.1.

Table 3.1: Keywords used for the search

Harmonic distortion	**Measurement**
Power quality, harmonic distortion, total harmonic distortion, harmonic source detection, harmonic allocation, sharing harmonic responsibility, the direction of active power flow, harmonic monitoring, harmonic management, harmonic limit, independent power producers, smart grid, point of common coupling, harmonic apportioning, harmonic limit	Single point measurement, distributed and synchronous measurement

Stage 4: The collected papers on the topic of interest were arranged according to the existing methods of harmonic source detection. The papers were arranged according to the Prisma 2009 flow diagram (Moher et al., 2009) as follow:

100 papers were collected through database searching such as IEEE Xplore, Science Direct, and Scopus using the keywords in Table 3.1. 50 additional papers were identified through the Google Scholar search engine. The analysis was done to check duplication of the saved papers and only 120 studies remained and were taken for screening. 38 papers were excluded as they discussed topics on harmonic distortion, harmonic filters, and power quality which were not the main focus of this research, namely harmonic source detection. 82 papers were assessed for eligibility criteria (harmonic source detection method) and 18 papers were excluded as they did not meet the criteria. 64 papers were included in this study for qualitative synthesis and only 40 papers were included for quantitative synthesis as the criteria were

limited to research published during the period 2005 – May 2019 (as indicated in the results section in Table 3.4). Older papers were ignored as they were cited in the newer papers.

Stage 5: The selection of the research papers was based on inclusion and exclusion criteria to enhance the search as well as recover the most relevant literature on the topic. The inclusion criteria were based on the latest review conducted (Safargholi et al., 2018a), where only published journal articles and conference proceedings are used. This search excludes the following: (a) papers with the developed method out of the estimation and far from the three categorised methods based on the direction of active power flow, reactive power, and voltage-current ratio; (b) unpublished work; and (c) textbooks and web pages.

Stage 6: The findings were documented.

3.4. Categories of existing methods

The harmonic sources detection approaches proposed to depend on two groups: the distributed and synchronous (multi-point) measurement method, and the single-point measurement method (Swart et al., 1994; Li et al., 2016; Davis et al., 2000; Rens & Swart, 2001; Swart et al., 1996). Lin et al. (2018) note that the distributed and synchronous measurement method gives accurate information on the state of power system harmonics. However, it is difficult to implement and manage since its measurement instrument hardware and software components are complex and expensive. However, the single point measurement method is less expensive and its implementation is simple, although in some cases it does not provide accurate information regarding the state of power system harmonics. In medium and low voltage distribution systems, single-point measurements are still preferable, even though it is difficult or almost impossible to know the exact network impedance values. The literature shows that extensive research has been conducted since 1998 by bodies such as IEC, Cigré, IEEE, etc. to find an accurate method to detect the location of harmonic-emitting sources.

Harmonic source detections are categorised according to three methods as follows (Safargholi et al., 2018a):

i. The direction of active power flow
ii. Reactive power
iii. Voltage-current ratio

The author of this research conducted analysis and synthesis process. The existing methods based on the three categories are pointed out and analysed as per Figure 3.5. The shortcomings of each category are discussed in detail. The results are analysed according to the paper reviewed.

Among these methods, none is identified as accurate due to the shortcomings that researchers such as. Xu (2000) and Xu et al. (2003) have pointed out. Each method and technique has advantages and disadvantages; some of the common disadvantages include the difficulty and high cost of implementation. This literature review concentrates on the following: methods, shortcomings, and software used. There are several review papers based on harmonic source detection in general, although, as far as the author knows, there is no review paper focusing on a practical method that is easy to use in industry. Thus, to fill this research gap, a literature review based on pointing out the uncertainty regarding the impracticality of the published methods is required.

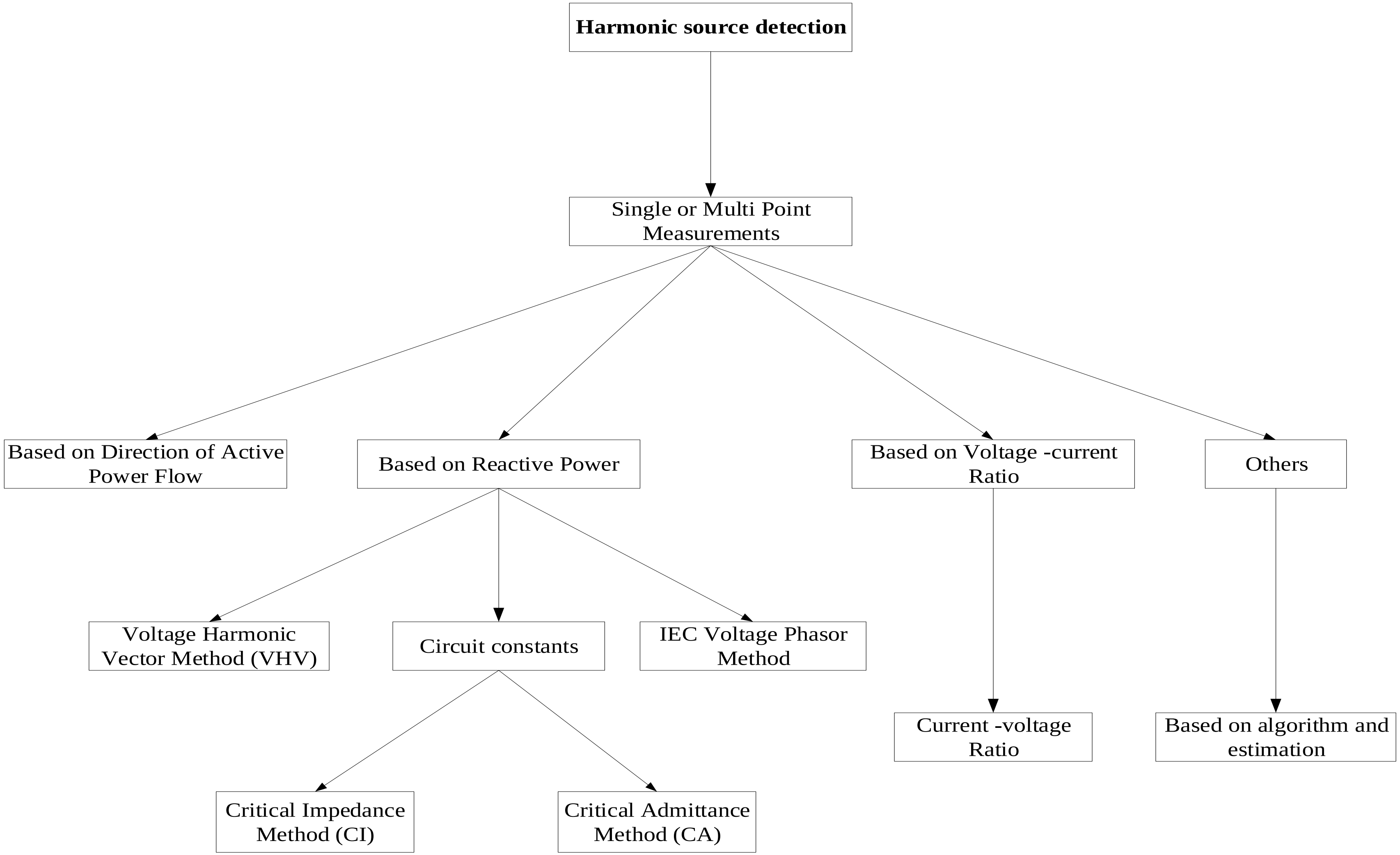


Figure 3.5: Harmonic source detection method block diagram

3.5. Dominant harmonic sources calculations

Most studies concentrated on the dominant harmonic source. This dominant harmonic source depends on two scenarios, which are Thevenin (larger equivalent harmonic voltage) and Norton (larger equivalent harmonic current) equivalent circuits. When the equivalent circuit is not indicated in the study, this can confuse the results as the equivalent circuit has different meanings. Safargholi et al. (2018b) demonstrated the confusion by giving an overview of the magnitude of the equivalent circuit of the harmonic voltage and/or current source. Safargholi et al. (2018b) concluded that where there is a larger magnitude current, there is a larger magnitude of the voltage or vice versa. The following sections explain the difference between the harmonic current source and harmonic voltage source in detail.

3.5.1. Harmonic current source

The Norton equivalent circuit shown in Figure 3.6 is used to investigate the harmonic current source. The circuit indicated in Figure 3.6 is simplified according to the superposition principle as indicated in Figure 3.7.

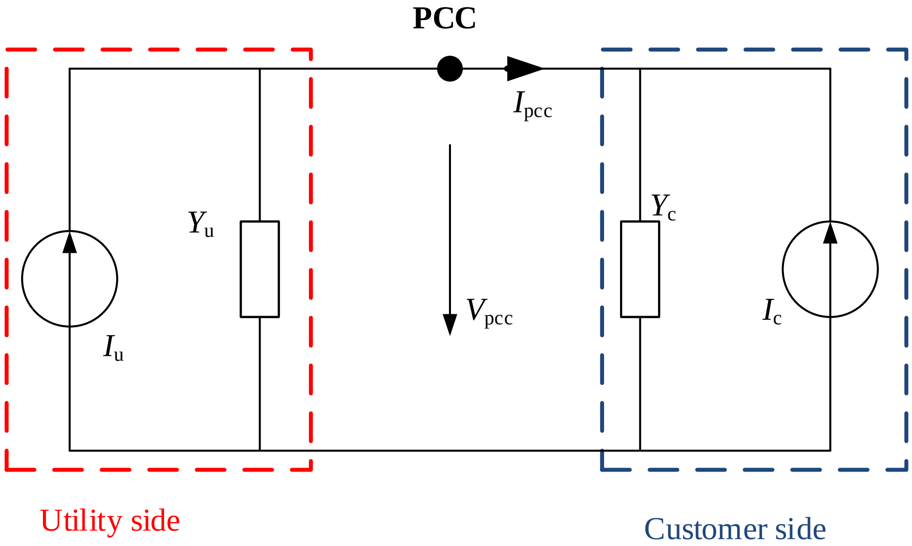


Figure 3.6: Norton equivalent circuit

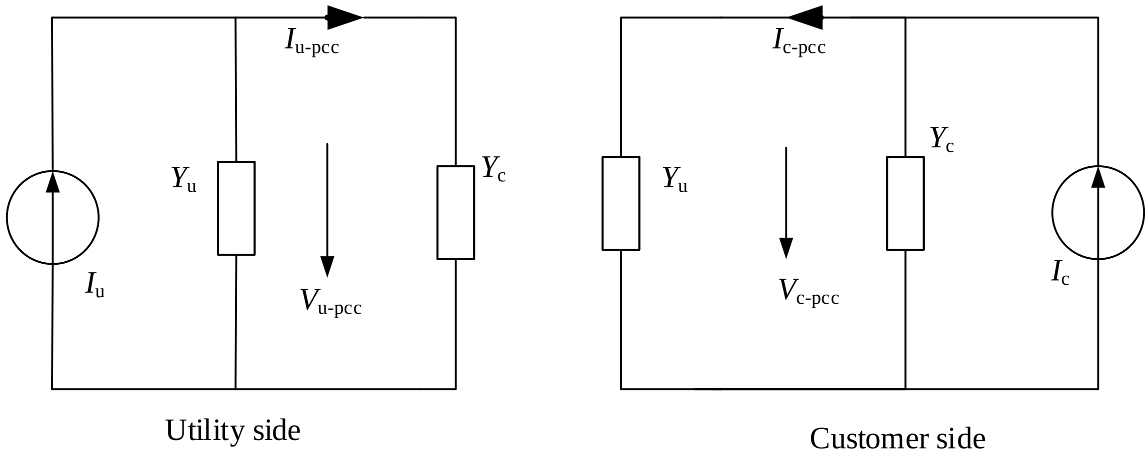


Figure 3.7: Norton equivalent circuit for harmonic voltage sources of two sides

To determine the voltage at the point of common coupling of the customer and utility, the following equations are used based on Figure 3.7:

$$V_{pcc} = V_{u-pcc} + V_{c-pcc} \tag{3.1}$$

$$V_{u-pcc} = \frac{I_u}{Y_u+Y_c} \tag{3.2}$$

$$V_{c-pcc} = \frac{-I_c}{Y_u+Y_c} \tag{3.3}$$

Combining (3.2) and (3.3) to obtain the following:

$$\frac{I_u}{I_c} = \frac{V_{u-pcc}}{V_{c-pcc}} \tag{3.4}$$

Therefore, Equation (3.4) indicates that the larger the magnitude of harmonic current, the higher the harmonic voltage contribution at the PCC. Thus, if it is known that the larger magnitude of the harmonic current is on the side where the harmonics are dominant, then that side also contributes a high harmonic voltage at the PCC. Table 3.2 gives the required current source input data and indicators for the different categories of harmonic source detection methods.

Table 3.2: Current source input data and indicators for the different categories of harmonic source detection methods

Method	Input Data	Indicator
The direction of active power flow	V_{pcc} , I_{pcc}	Sign of P_{pcc}
Reactive Power (Critical Admittance)	V_{pcc} , I_{pcc}, Y_c , Y_u	Sign of $Q_{t,u,i}$ $\|CA\|$
Current-voltage ratio	V_{pcc} , I_{pcc}, Y_c , Y_u	$G_{i,v}$

To define the indicators for the methods mentioned in Table 3.2 mathematically, the following formulae were used, according to Safargholi et al. (2018a):

3.5.1.1. The direction of active power flow method

$$P_{pcc} = Re\{V_{pcc} I^*_{pcc}\} \tag{3.5}$$

A harmonic active power at the PCC which is negative ($P_{pcc} < 0$) utility is a dominant harmonic current source, whereas if there is a positive harmonic active power at the PCC ($P_{pcc} > 0$), a customer is a dominant harmonic current source.

3.5.1.2. Reactive power method

According to Figure 3.6 the equivalent harmonic current source for the utility side is:

$$I_u = I_{pcc} - Y_u V_{pcc} \tag{3.6}$$

Equivalent harmonic admittance $Y_{tot} = Y_u + Y_c$ (3.7)

Transformation angle

$$\alpha = \arctan\left(\frac{\mathrm{Re}\{Y_{tot}\}}{\mathrm{Im}\{Y_{tot}\}}\right) \tag{3.8}$$

$$Q_{t,u,i} = \begin{cases} -[-\sin\alpha \quad \cos\alpha]\begin{bmatrix}\mathrm{Re}\{V_{pcc} I^*_u\} \\ \mathrm{Im}\{V_{pcc} I^*_u\}\end{bmatrix} & \mathrm{Im}\{Y_{tot}\} \geq 0, \\ +[-sin\,\alpha \quad cos\,\alpha]\begin{bmatrix}\mathrm{Re}\{V_{pcc} I^*_u\} \\ \mathrm{Im}\{V_{pcc} I^*_u\}\end{bmatrix} & \mathrm{Im}\{Y_{tot}\} < 0. \end{cases} \tag{3.9}$$

$$CA = 2\frac{Q_{t,u,i}}{V^2_{pcc}} \tag{3.10}$$

If $|CA| > Y_{tot.}$, utility side is dominant for the equivalent harmonic current source $\left(\frac{I_u}{I_c} > 1\right)$;

If $|CA| < Y_{tot.}$, is the same as $Q_{t,u,i} > 0$ customer side is dominant for the equivalent harmonic current source $\left(\frac{I_u}{I_c} < 1\right)$.

3.5.1.3. Current-voltage ratio method

$$G_{iv} = \frac{I_{pcc}}{V_{pcc}} \quad (3.11)$$

If $|G_{iv} + Y_c| > |G_{iv} + Y_u|$ the equivalent harmonic current source of the customer side is dominant $\left(\frac{I_u}{I_c} < 1\right)$; If $|G_{iv} + Y_c| < |G_{iv} + Y_u|$ the equivalent harmonic current source of the utility side is dominant $\left(\frac{I_u}{I_c} > 1\right)$.

3.5.2. Harmonic voltage source

The Thevenin equivalent circuit shown in Figure 3.8 is used to investigate the harmonic voltage source. The circuit indicated in Figure 3.8 is simplified according to the superposition principle as indicated in Figure 3.9.

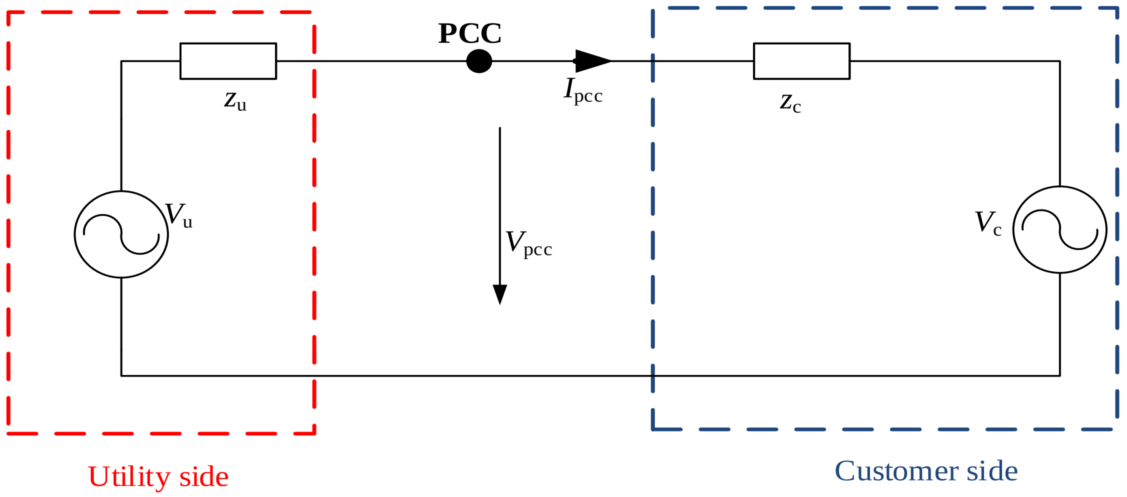


Figure 3.8: Thevenin equivalent circuit

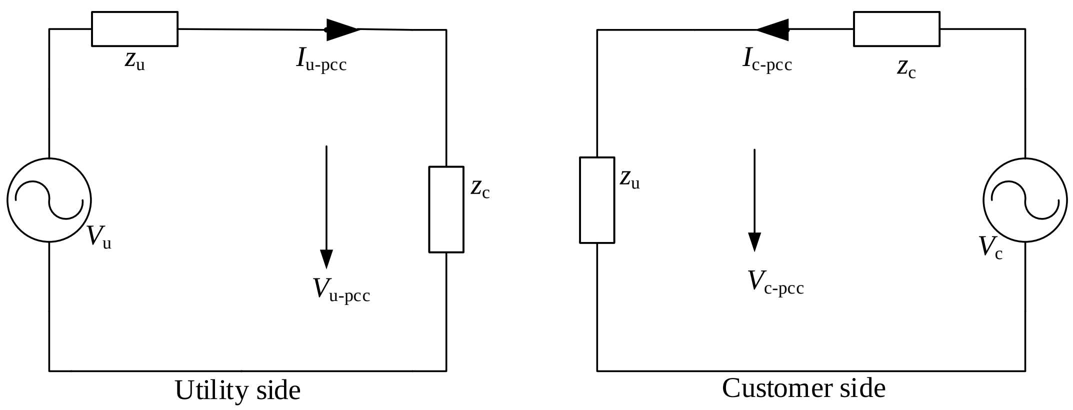


Figure 3.9: Thevenin equivalent circuit for harmonic current sources of the two sides

To determine the current at the point of common coupling of the customer and utility, the following equations are used, based on Figure 3.9:

$$I_{pcc} = -I_{c-pcc} + I_{u-pcc} \tag{3.12}$$

$$I_{u-pcc} = \frac{V_u}{Z_u + Z_c} \tag{3.13}$$

$$I_{c-pcc} = \frac{V_c}{Z_u + Z_c} \tag{3.14}$$

Combining (3.13) and (3.14) to obtain the following:

$$\frac{V_u}{V_c} = \frac{I_{u-pcc}}{I_{c-pcc}} \tag{3.15}$$

Therefore, Equation (3.15) indicates that the larger the magnitude of harmonic voltage, the higher the harmonic current contribution at the PCC. Thus, if it is known that the larger magnitude of harmonic voltage is on the side where the harmonics are dominant, then that side also contributes a high harmonic current at the PCC. Table 3.3 gives the required voltage source input data and indicators for the different categories of harmonic source detection methods.

Table 3.3: Voltage source input data and indicators for the categories of harmonic source detection methods

Method	**Input Data**	**Indicator**
The direction of active power flow	V_{pcc} , I_{pcc}	Sign of P_{pcc}
Reactive Power (Critical Impedance)	V_{pcc} , I_{pcc}, Z_c , Z_u	Sign of $Q_{t,uv}$ $\lvert CI \rvert$
Current-voltage ratio	V_{pcc} , I_{pcc}, Z_c , Z_u	$R_{v,i}$

To define the indicators for the methods mentioned in Table 3.3 mathematically, the following formulae were used, according to Safargholi et al. (2018a).

3.5.2.1. The direction of active power flow

Equation 3.5 is used in the harmonic current source and is applicable to be used for a harmonic voltage source. Therefore, if there is a harmonic active power at the PCC which is negative ($P_{pcc} < 0$), the utility is a dominant harmonic voltage source, whereas where there is a positive harmonic active power at the PCC ($P_{pcc} > 0$), a customer is the dominant harmonic voltage source.

3.5.2.2. Reactive power

According to Figure 3.8 equivalent harmonic voltage source for the utility side is:

$$V_u = V_{pcc} - Z_u I_{pcc} \tag{3.16}$$

Equivalent harmonic impedance $Z_{tot} = Z_u + Z_c$ (3.17)

Transformation angle

$$\beta = \arctan\left(\frac{\mathrm{Re}\{Z_{tot}\}}{\mathrm{Im}\{Z_{tot}\}}\right) \tag{3.18}$$

$$Q_{t,u,v} = \begin{cases} +[\sin\beta \quad \cos\beta]\begin{bmatrix}\mathrm{Re}\{V_u I_{pcc}^*\} \\ \mathrm{Im}\{V_u I_{pcc}^*\}\end{bmatrix} & \mathrm{Im}\{Z_{tot}\} \geq 0, \\ -[sin\,\beta \quad cos\,\beta]\begin{bmatrix}\mathrm{Re}\{V_u I_{pcc}^*\} \\ \mathrm{Im}\{V_u I_{pcc}^*\}\end{bmatrix} & \mathrm{Im}\{Z_{tot}\} < 0. \end{cases} \tag{3.19}$$

$$CI = 2\frac{Q_{t,u,v}}{I_{pcc}^2} \tag{3.20}$$

If $|CI| > Z_{tot.}$, the utility side is dominant for the equivalent harmonic voltage source $\left(\frac{V_u}{V_c} > 1\right)$; If $|CI| < Z_{tot.}$, is the same as $Q_{t,u,v} > 0$, the customer side is dominant for the equivalent harmonic voltage source $\left(\frac{V_u}{V_c} < 1\right)$.

3.5.2.3. Current-voltage ratio

$$R_{vi} = \frac{V_{pcc}}{I_{pcc}} \tag{3.21}$$

If $|R_{vi} + Z_c| > |R_{vi} + Z_u|$ the equivalent harmonic voltage source of the customer side is dominant $\left(\frac{V_u}{V_c} < 1\right)$; If $|R_{vi} + Z_c| < |R_{vi} + Z_u|$ the equivalent harmonic voltage source of the utility side is dominant $\left(\frac{V_u}{V_c} > 1\right)$.

3.6. Description of harmonic source detection methods

3.6.1. The direction of the active power flow method

In the early years, the researchers focused on locating the source that was producing the harmonics (Swart et al., 1996; Swart et al., 1994; Tanaka & Hirofumi, 1995). To identify the dominant side between the utility and the customer, the direction of active power flow at the PCC was used. Chupeng et al. (2016) stated that the method based on the active power direction is widely used as it gives a practical application in engineering, and that method is independent of the harmonic impedance of any party. Thus the calculation of the harmonic impedance is possible but it is not practical because harmonic impedance depends on the loading of the networks. Xu et al. (2018) proposed a revised method with certain restrictions for the direction of active power. The restrictions were developed based on the current and voltage measurements at the PCC and the impedance properties of the two sides. The determination of the dominant current harmonic source can be through the Norton equivalent circuit as shown in Figure 3.6, whereas for voltage harmonic sources it can be through the Thevenin equivalent circuit as shown in Figure 3.8. These equivalent circuits are only accurate when there is only one customer connected at the PCC, but as the distribution network is becoming more complex, there are multiple customers connected at the PCC. Therefore, it is not possible to represent these customers as one customer due to different load conditions as well as operation scenarios.
The active power at the PCC is calculated as follows (Xu et al., 2018):

$$P = \mathrm{Re}\left(V_{\mathrm{pcc}} I_{pcc}^{*}\right) = V_{\mathrm{pcc}} I_{\mathrm{pcc}} cos\varphi \tag{3.23}$$

Where, V_{pcc} is the harmonic voltage measured at the PCC, the term I_{pcc}^{*} is the complex conjugate of the harmonic current measured at the PCC I_{pcc}, and φ is the angle between V_{pcc} and I_{pcc}.

Xu et al. (2018) did not explain the order of harmonic voltage and harmonic current used in Equation (3.23). It was as well concluded that if $P > 0$, the dominant harmonic source is the utility side and if $P < 0$, the dominant harmonic source is the customer side. Xu et al. (2018) proved this method to be unreliable and proposed the impedance properties of the two parties (customer and utility), based on the actual measurement of voltage and current at the PCC. The accuracy of customer and utility harmonic impedance's phase angle is not a requirement for this method. Xu (2000) and Xu et al. (2003) found concrete proof that the power direction method is inaccurate and cannot be used for harmonic source detection, although it is the most commonly used method accepted by the industry because it is easy to implement and less expensive. The concept of superposition is contradicted by the direction of active power flow as the flow of harmonic power can be from either direction once the phase angle is greater than in 180º. Since the current phase angle between utility and customer(s) cannot be guaranteed to remain in a certain range, one can conclude that the method based on the direction of active power flow is not suitable for harmonic source detection (Xu, 2000).

Besides, Wang et al. (2018) indicated that there are quantitative and qualitative methods that could be used for the determination of harmonic contribution at the PCC. The quantitative method depends on the harmonic impedance measurements and calculation using the superposition principle method. Qualitative methods are known as power direction methods (active power, reactive power, and non-active power methods). Since the phase angle between a harmonic source both upstream and downstream of the PCC varies between 0° to 360°, when it is high, the method-based power direction cannot work effectively. Figure 3.10 indicates the direction of electrical power flow in a power system at different phases.

According to Figure 3.10, when the direction of the active power is supplied from the utility through the metering point to the load this means that the power is delivered and it has a positive sign. When the direction of active power flow is from the load which has a distributed energy source such as a rooftop Photovoltaic system through a metering point to the source, the power is received and it has a negative sign. If active power does not fall on any of the quadrants and only exists on the x-axis it is referred to as delivered or received, not lead or lag as the current and voltage.

In a traditional power system, the active power direction flow at the fundamental frequency (f_1) (50Hz) is normally flowing from the utility source to the load and it has a positive sign, as there are no disturbances that cause power quality issues. In modern smart grids, it is distributed energy sources and non-linear loads that inject harmonic current. The power system consists of harmonic frequencies (f_h).

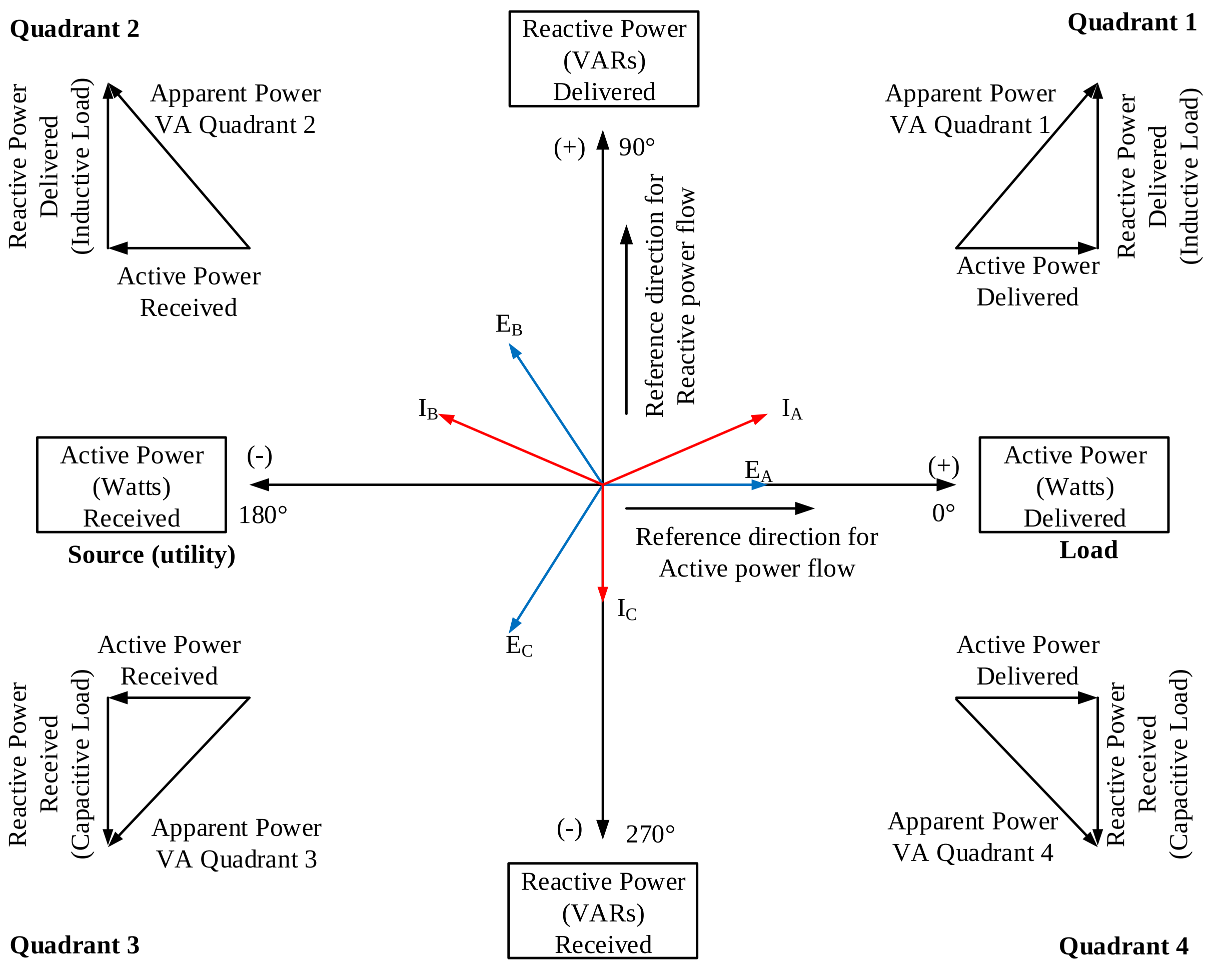


Figure 3.10: Direction of electrical power flow

3.6.2. Reactive power method

Pfajfar et al. (2008) and Pfajfar & Papič, (2011) agree that to detect the harmonic source, existing techniques have been applied to determine the harmonic contributions of the customer and the utility. The harmonic vector method has been proposed to determine the harmonic contributions of the utility and customer at the PCC based on the reference impedance. This method makes it possible without determining customer impedance to calculate the harmonic contributions and in resonance conditions, it evaluates the results better. In recent literature (Karimzadeh et al., 2016; Karimzadeh et al., 2015; Zhao & Yang, 2016) the independent component analysis (ICA) method was used, which requires the impedance on the customer's side to be higher than on the utility side. This is impractical when the network has filters or capacitors installed on the customer side. Karimzadeh et al. (2016) improved this method whereby some assumptions were removed.

Karimzadeh et al. (2016), Barbaro et al. (2007), Li et al. (2004), and Chen et al. (2004) did the qualitative analysis on determining the dominant harmonic source using the reactive power direction when the sum of reactive power is negative. The direction of reactive power flow gives a better similarity with the source magnitudes.

According to Figure 3.10, when the direction of the reactive power is being supplied from the source through the metering point to the load, this is referred to as delivered reactive power and it has a positive sign. When the reactive power flows from the load through a metering point to the source, this is referred to as received reactive power and it has a negative sign. If reactive power does not fall on any of the quadrants and only exists on the y-axis it is described either as delivered or received, not lead or lag as the current and voltage.

Xu et al. (2003) concluded that the direction of power flow is influenced by the polarity or phase angle difference between the two harmonic sources rather than the differences in magnitudes. Xu (2000), Xu et al. (2003), and Balci & Hocaoglu (2010) proposed techniques to quantify the harmonic sources with a set of superposition-based indices. Lin et al. (2005) presented a methodology that utilises a marginal number of connections and anticipates minimal computation duration for operation using a Cascade Correlation Network (CCN) design.

Li et al. (2004) used harmonic reactive power direction and critical impedance methods to evaluate the harmonic contribution and measurement at the PCC. It is difficult to detect the harmonic source in a power system with unbalanced supply conditions, due to the current and voltage affected by negative sequence components. Critical impedance methods are used through calculating harmonic reactive power generated by the utility and the equivalent impedance or admittance that consumes the reactive power. A dominant harmonic source can be estimated by comparing the utility and customer(s) merged impedances. Critical impedance methods and reactive power direction methods are similar in theory for calculating the utility and customer side voltages. When these methods indicate that the voltage at the customer side is greater than at the utility side this would mean that the customer side has a higher harmonic contribution at the PCC (Xu et al., 2003).

A novel method was presented by Xu & Liu (2000) to split the harmonic contribution of customers and utilities at the PCC which uses reference impedance and converts impedance changes into equivalent current source changes. These methods can be validated by field measurements. Power system harmonics are classified as supply or load harmonics depending on the origin. The harmonic impedance flowing in the power system depends on the source impedance. Hence, little modification in the impedance source is reflected in the current harmonic spectrum. Mazumdar et al. (2008) proposed a new method using artificial neural networks to separate and assess the influence of the source impedance change without interference with the load operation by using actual field data. This method requires voltages and current waveforms of single and/or three-phase loads to be measured at the PCC. Mazumdar et al. (2008) stated that to determine a true harmonic current of the customers, the supply voltage at the PCC has to be sinusoidal. It may be unfeasible to establish a pure sinusoidal voltage at the PCC since it requires performing switching of a customer to reduce the system impedance closer to zero to obtain a sinusoidal supply voltage.

Methods based on reactive power depend on the calculations of the customer(s) and utility harmonic impedance to determine the dominant contribution; this is mathematically possible by assuming the harmonic impedance is constant, although in an actual power system the harmonic impedance of the utility fluctuates. It affects the calculation of the dominant harmonic contribution. The harmonic impedance information needs to be accurate to have accurate information regarding the dominant harmonic source.

3.6.3. Voltage-current ratio method

A newly developed method was introduced using the voltage-current ratio for harmonic source detection at the PCC (Malekian, 2015). This method requires the measured voltage and current at the PCC as well as the utility and customer's equivalent impedance values. Malekian (2015) concluded that this does not only detect the harmonic source, but it also determines the contribution between the parties. Safargholi et al. (2018a) developed a current-voltage ratio for harmonic current source detection. This method requires the harmonic impedance of the utility and the customer, which is a challenging process.

3.7. Software

There are many different software packages that power utilities are using to conduct harmonic studies. Widely used tools are Matlab/Simulink as used in various references (Gül & Gündoğdu, 2015; Karimzadeh et al., 2016; Li et al., 2016; Lin et al., 2005; Karimzadeh et al., 2015; Lin et al., 2018; Stevanović & Petković, 2015), and PSCAD (Papic et al., 2019). Other general computation software is used such as MathCAD (Rens & Swart, 2001). The Monte Carlo mathematical method was used (Domagk et al., 2017) to model the probabilistic behaviour of the harmonics. The researcher was unable to find a simulation done using the DIgSILENT PowerFactory package for harmonic source detection. Various studies validate simulation results using the MAVOWatt 70 Power quality analyser. Unipower, Vectograph, and Impedograph power quality analysers can be used to validate the simulated results as well. Matlab that is widely used to validate the results of harmonic source detection is uncommonly used by most Southern Africa power utilities.

In this study, the reviewed articles are given in Table 3.4 by date of publication. Table 3.4 was used to derive the graph for the period of analysis since 2005, as specified in Figure 3.11.

Table 3.4: Fundamental Aspects of the reviewed papers

Harmonic source detection methods	**Reference**	**A fundamental aspect to be identified**
The direction of active power flow	(Xu et al., 2018; Peterson et al., 2017; Wang et al., 2018; Balci & Hocaoglu, 2010; Aiello et al., 2005; Brandon Peterson et al., 2015; Chupeng et al., 2016; B Peterson et al., 2015; Schau & Novitskiy, 2005; Cieslik, 2016)	• The input data required are the measured power or current and voltage at the PCC. • The sign of the power at the PCC indicates the contributor of the harmonic distortion. • The method is easy to implement and commercially viable. • Most of the existing instruments used for measurement in the industry give the total power and show the direction. • The methodology used is simple and does not require any switching of the load. • No assumption is needed. • The inaccuracy of the measurement output due to the incorrect setup of the measuring instruments.
Reactive Power	(Gül & Gündoğdu, 2015; Pfajfar & Papič, 2011; Cataliotti et al., 2008; Pfajfar et al., 2008; Li et al., 2016; Cataliotti & Cosentino, 2010a; Barbaro et al., 2007; Barbaro et al., 2006; Papic et al., 2019; Mazumdar et al., 2008; Santos et al., 2011; Karimzadeh et al., 2015; Karimzadeh et al., 2016; Lin et al., 2005; Lin et al., 2018; Zhao & Yang, 2015; Stevanović & Petković, 2015; Stevanović & Petković, 2011; Stevanović & Petković, 2014; Cataliotti & Cosentino, 2010b; Abdullah et al., 2014; Browne et al., 2009; Vaid et al., 2011; Špelko et al., 2018; Zhao & Yang, 2016)	• Assumption of customers and utility admittance and impedance cause it to be ineffective. • The inaccuracy of the measurement output. • Difficult to implement with multiple customers connected at the PCC. • To conduct the measurement of impedance, other customers need to be disconnected. • It is theoretically viable but not practical.
Voltage–current ratio	(Malekian, 2015; Safargholi et al., 2018a)	• Assumption of customers and utility admittance and impedance cause it to be ineffective. • The inaccuracy of the measurement output. • Difficult to implement with multiple customers connected at the PCC. • To conduct the measurement of impedance other customers need to be disconnected. • It is theoretically viable but not practical.
Others	(Ujile & Ding, 2016; Krishna & Sinha, 2018; Carta et al., 2019)	• Theoretically viable but not practical.

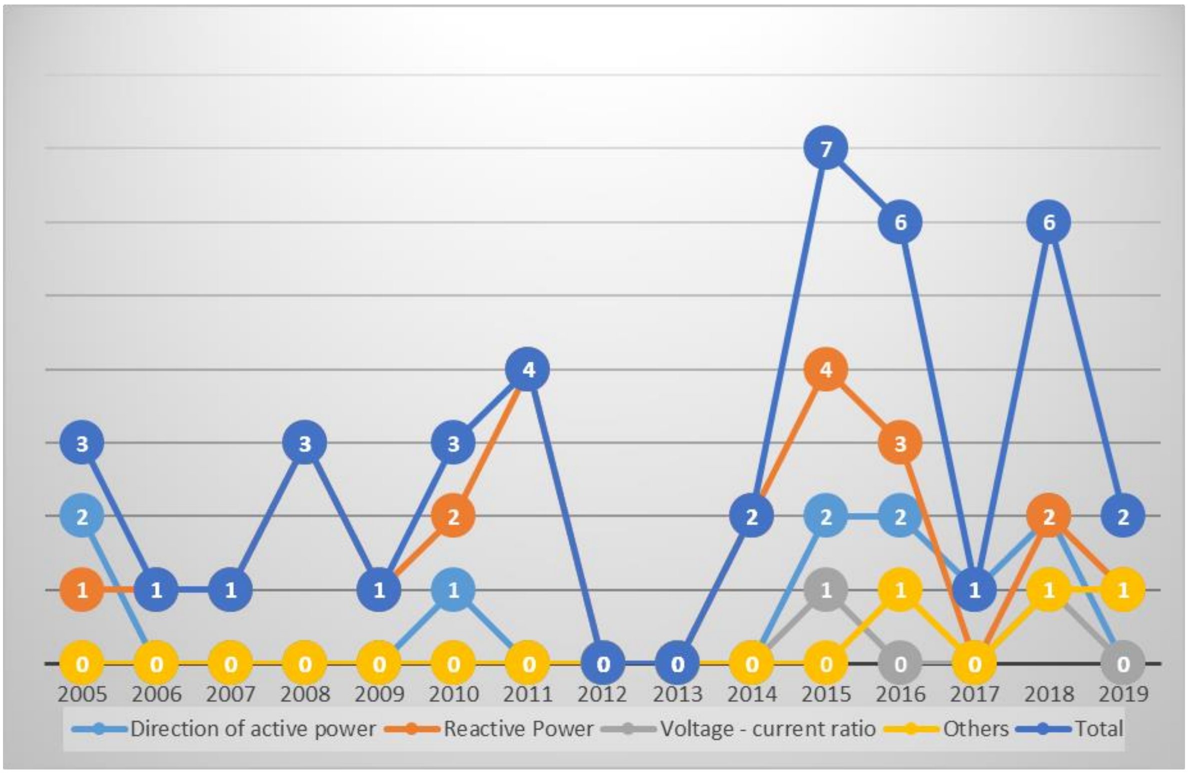


Figure 3.11: Aggregate number of papers used to review the three categories of harmonic source detection methods

According to Figure 3.11, harmonic source detection is still an active research point in the power system field and the number of publications about this topic has grown considerably in the period from 2005 – 2019. Among the 40 papers reviewed, there are more papers (25 papers) based on reactive power or non-active power compared to the other methods. Within this systematic literature review, it is noted that there is still no accurate method that is approved by international bodies such as IEEE, CIGRE, IEC to be used to give the practical and commercial results needed by the power utilities.

3.8. Theoretical framework (discussions, gaps, and future research work)

This section addresses the research gaps identified in the reviewed literature, the challenges for future research work, and proposes a framework for developing a more accurate and practical harmonic detection method.

3.8.1. Methods

The active power flow method is found to be theoretically inaccurate and unreliable to determine the source of harmonics in cases when both upstream and downstream of the metering point there is a source of harmonics (Xu et al., 2018). In this method, Xu et al. (2018) focused on the phase angle (δ) difference between the two harmonic sources as the main factor influencing the active power direction, while paying less attention to the magnitudes of voltage and current, which are important in a harmonic source detection problem. The characteristic of the circuit affects the direction of the power flow. This implies that the position or the point of measurement also influence harmonic source detection. Unlike active power that depends on the phase shift angle, reactive power depends on the magnitudes of the voltage sources, and this technique could be used as an indication of the dominant harmonic source. The direction of active or reactive power is affected by the harmonic source size and customer(s) impedances. Therefore, it is concluded that the power-direction-based methods are concluded to be unreliable.

It is also unknown how to use these methods when multiple customers are connected at the PCC as well as when multiple customers are Independent Power Producers (IPPs) using distributed generation sources. This case is not included in the surveyed literature. The contributions of the IPPs to the harmonic contents need to be determined. The active power flow formula used in Equation (3.24) needs to be defined as follows:

$$P_T = P_1 + P_{\mathrm{h}} \tag{3.24}$$

where P_1 is the power at the fundamental frequency andP_h is the total power for all the harmonic order parts of the network. $P_{\mathrm{h}} = P_2 + P_3 + P_5 + P_{nth} + \cdots$ is the sign of the harmonic power to be taken into consideration and the meaning to be understood. It is unknown how to determine whether the dominant will be determined per harmonic order or network, as it is possible to have a different harmonic source as per harmonic order and/or per even/odd or triplen harmonics.
A positive sign of total power $(P_T = P_1 + \sum P_h)$ means the harmonic source is from the utility side, while a negative sign of the total power means the harmonic source is from the customer's side, although it does not indicate which customer it is. It was concluded that the total power of each customer needs to be determined either through calculation or to be obtained from a software simulation. Thus, once the total power for each customer is determined this will give a better indication of which customer is the main contributor of harmonics. It was concluded that a customer with higher total power contributes more harmonics to the PCC.

Karimzadeh et al. (2016), Karimzadeh et al. (2015), and Zhao & Yang, (2015) indicate that the value of the impedance on the customer side is far larger than the utility when only one customer is connected at the PCC, therefore the reactive power method is not possible with multiple customers connected at the PCC and all of the loads are harmonic sources. This method depends either on the current, voltage, and harmonic impedance or the admittance of the utility and the customer as the input data. The harmonic impedance of the utility and the customers are challenges that vary depending on the load conditions and any other operation scenarios. The inaccuracies of harmonic impedance should always be taken into consideration, therefore this method based on reactive power cannot be used for practical and commercial purposes.

In the voltage-current ratio method, the time variation of harmonics has to be taken into consideration. It is highlighted in the literature that to determine and evaluate the contribution of the dominant harmonic source depends on computing the utility and the customer(s) impedance from the measured harmonic voltage and current at a PCC. In some cases, it is assumed that the background harmonic voltage is stable. These cases are not practical as the impedance of the distribution network varies depending on the instrument transformers' (voltage and current transformers) accuracies, whether they are programmed and calibrated correctly, and the load conditions.

Most of the reviewed harmonic detection methods are mathematically correct. However, for those methods to be implemented, a certain strategic plan needs to be in place as the network of supply might require some profiling or switching off certain sections to verify the network parameters. Assessment of resonance conditions is not part of most of the reviewed methods, whereas this scenario is of high importance because during the resonance condition the harmonic distortion rises. In a practical situation, voltage and current harmonics can be a combination of positive, negative, and zero sequences, which needs to be achieved in simulation as well.

This systematic literature review enabled the author to select and propose a modified harmonic detection method based on the direction of active power flow, where shortcomings of previous detection strategies need to be considered. According to the synthesis of the literature, the direction of the active power flow method is the only method that gives practical results, and without any input data being assumed. A proposed method should be tested using the IEEE PES benchmark test system with renewable energy generators connected at the PCC as well as energy producers and consumers with mixed non-linear loads and distributed generators which form a microgrid. The direction of the active power flow method helps engineers solve the practical issues as they arise. However, modifications are needed to cater to the entire challenges are currently face a power system with multiple customers connected at the PCC.

It is identified that the harmonic source detection is a major concern for most power utilities, thus future research areas should formulate a strategic plan with different scenarios of the power system to reduce the harmonic content for the certain customer(s) at the PCC. The analysis of the power quality indexes which are part of the international standards should be re-evaluated and checked to determine whether the limits identified to cover the shortcomings of the literature when it comes to harmonic source content. Studies on harmonic source detection should include the resonance condition as well as the unbalanced networks, which consist of sequence components (positive, negative, and zero sequences). It is also required to develop new adapted Norton or Thevenin equivalent circuits to include the new phenomena that are present in modern practical power systems. Determination and discussion in detail of the harmonic mitigation actions are required between the two parties that have harmonic content higher than the prescribed harmonic limits stated in the international standards. To prevent the cost of purchasing and installation of harmonic filters and design effective harmonic mitigation, one needs a practical solution to detect harmonic sources and thereafter to monitor and effectively manage harmonic distortion at the PCC. This is a cost-effective methodology for both the utilities and the customers.

Important parameters in using a modified harmonic detection method based on the direction of active power flow are fundamental power (P_1) and harmonic power (P_h). Figure 3.12 shows a flowchart presenting the framework for the proposed method to identify the harmonic source at the PCC with multiple customers. It is worthwhile for the power utilities to invest in limiting the harmonic content of their customers. Utilities do allow the harmonic level as per the electricity supply agreement. The utilities should monitor the harmonic levels at the PCC not to exceed the prescribed limits specified in the electricity supply agreement to reduce the harmonic effects to the grid. When the power system is monitored well and harmonics are maintained within the limits prescribed by the national and international standard, harmonic source detection cannot be a challenge. Figure 3.13 describes the harmonic monitoring management process.

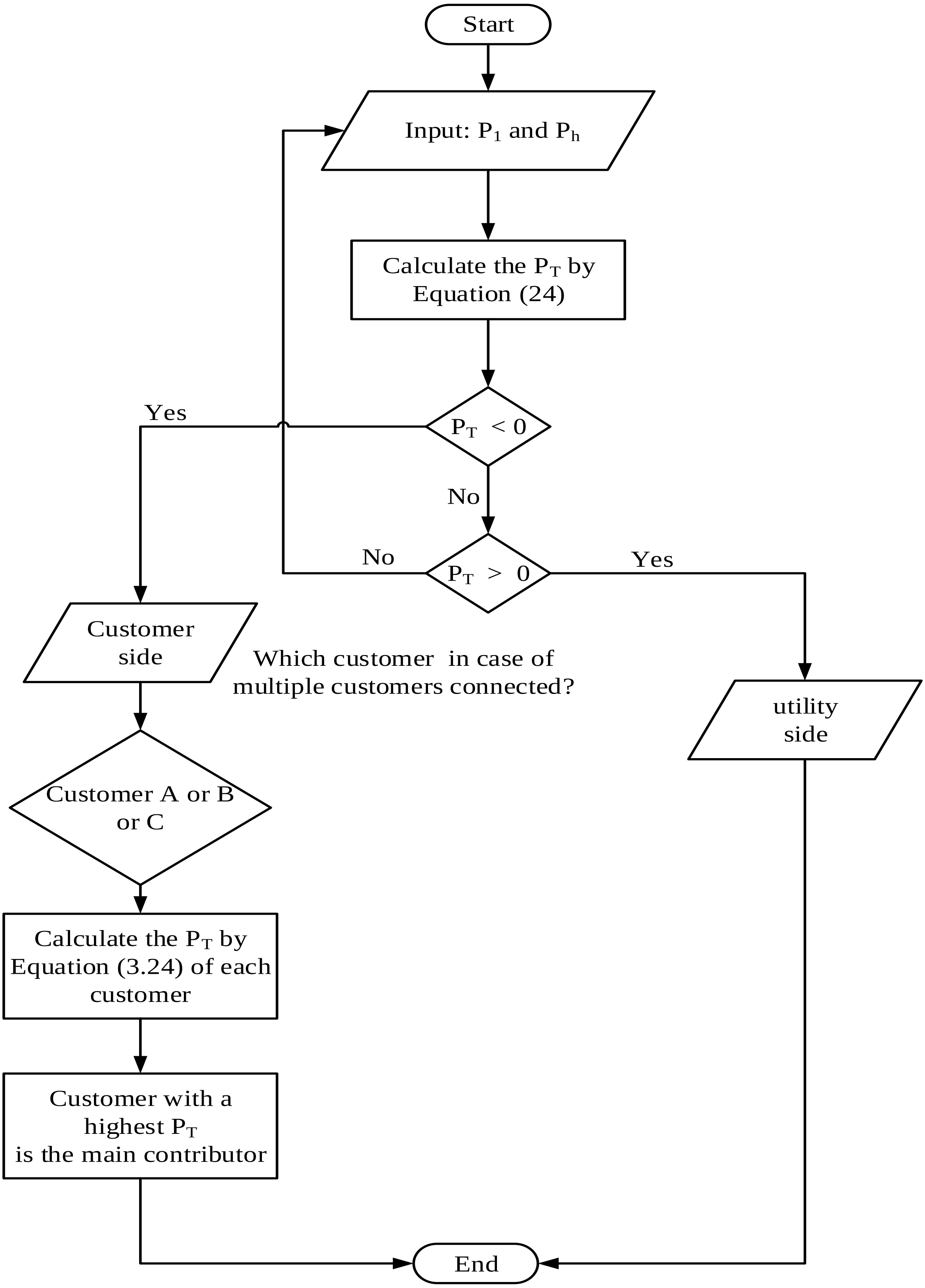


Figure 3.12: Flowchart of the method based on a direction of active power flow for identifying the harmonic source

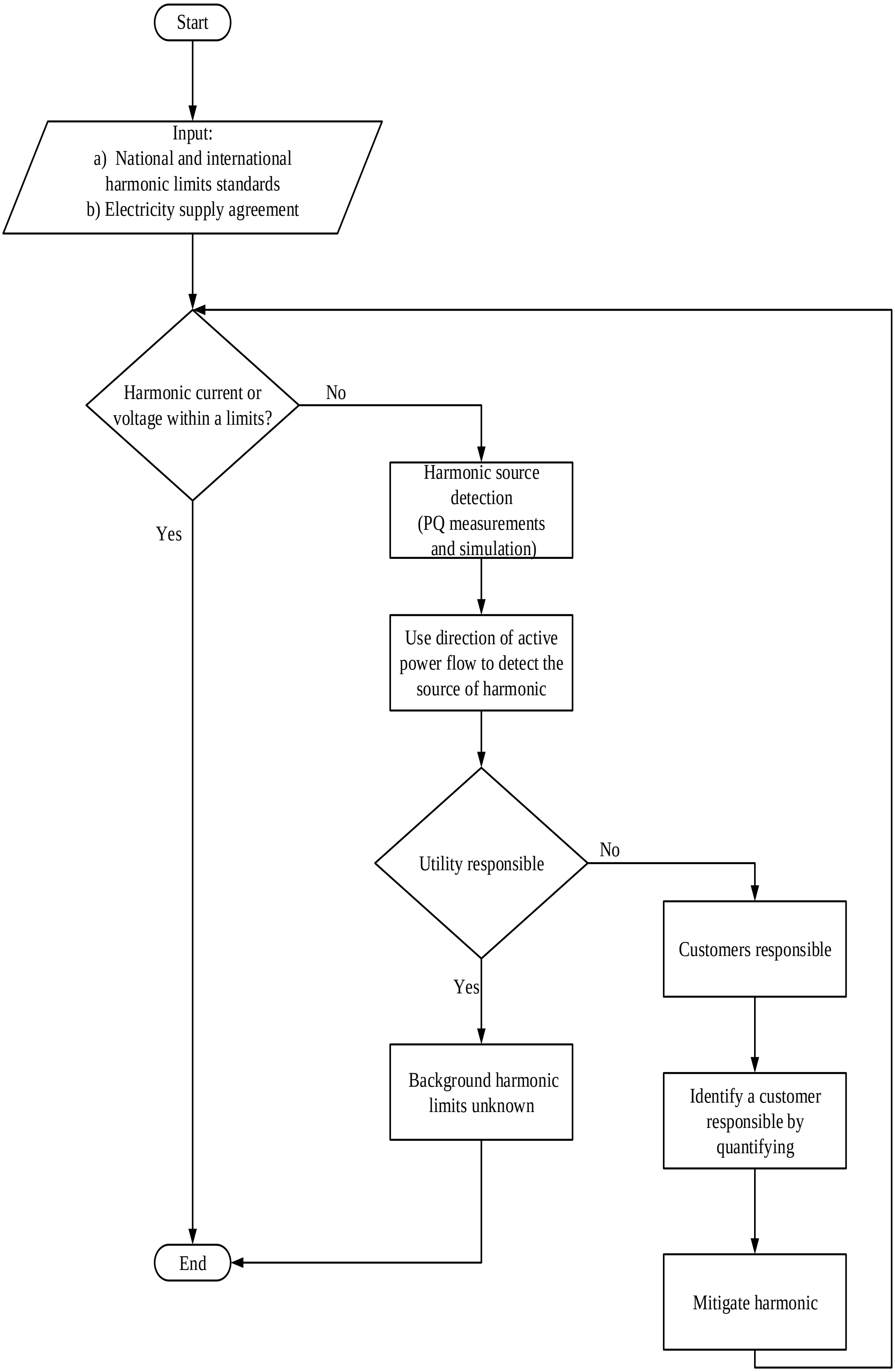


Figure 3.13: Harmonic Monitoring Management

3.8.2. Relevant software

Most researchers used a mathematical model to calculate the harmonic source content and many algorithms are given on how to determine the harmonic source detection. The method based on the direction of active power flow is the only method that gives a practical overview, and it needs modification to fill the gaps identified in this systematic review. Most researchers use the MATLAB/Simulink to validate their mathematical model. This software, however, is not commonly used by most Southern Africa power utilities. Most Southern Africa power utilities use DIgSILENT for their harmonic analysis during the planning phase to connect new customers at the PCC. DIgSILENT software indicates the direction of power per harmonic order which can be a good sign for determining the harmonic contribution. Measurements of actual data on harmonics give a better indication of the harmonic content of the power system compared to the simulation and mathematical model. The author recommends the use of the measurements of the harmonic content at the PCC where multiple customers are connected using the power quality analysers such as Unipower and Vectograph and/or Impedograph. Thereafter, DIgSILENT should be used to simulate the network with the actual harmonic content of each customer. Finally, it would be interesting if more research on harmonic source detection were to use the test system such as the IEEE PES given by Papic et al. (2019) and test the mathematical model provided in literature as this would give a better understanding of the topic and allow results to be compared on the same basis.

3.9. Summary

The main purpose of this thesis was to demonstrate an up-to-date outline of methods used in harmonic source detection at the PCC. The three categories of harmonic source detection methods are the direction of the active power flow method, reactive power method, and voltage-current ratio method. The shortcoming of the methods was discussed, and the most common software packages used by the researchers for simulation in the field were indicated. The mathematical models of different methods were analysed.

The systematic literature review methodology used for this analysis enabled the author to discover and categorize the existing literature, analyse and combine data, and develop clear conclusions of what is known and is unknown about the topic by classifying the interdependence between the reviewed papers. In the research areas, the research gaps were identified and future research areas were proposed. The analysis of this chapter presented guidelines to researchers who are new in the study of harmonic source detection. The research questions raised can present a focus for experienced researchers and engineers within the studied areas.

In this review, it was highlighted how the operation of a modern power system has changed with the integration of renewable energy generators. This causes challenges for power quality, mainly harmonic distortion. Harmonic distortion affects the electrical equipment which forms the power system. A modified harmonic source detection method based on the direction of active power flow was proposed to cater to multiple harmonic customers connected at the PCC. The harmonic monitoring management process was defined. The use of Norton and Thevenin equivalent circuit can no longer combine the customers at the PCC as one because of different operation scenarios, thus in this chapter, it was proposed to adopt these equivalent circuits. Besides, software applications were reviewed: it was noticed that researchers have mostly used Matlab/Simulink software packages and different test systems during simulation, thus in this chapter it was proposed to use DIgSILENT PowerFactory, as it is widely used by most utilities. It is advisable to use the actual measurement data during simulation to obtain accurate results. Additionally, it is beneficial to use the IEEE PES benchmark test system for harmonic source detection, for researchers to better compare the results of different methods.

CHAPTER 4: CONTRIBUTION TOWARDS HARMONIC DISTORTION

4.1. Introduction

Harmonic distortion is a known challenge for power quality. There are currently many researchers investigating this topic. This thesis contributes towards harmonic distortion is to develop new adapted Thevenin and Norton equivalent circuits to cater to practical power system needs. Most researchers used the existing equivalent circuits in the development of harmonic source detection methods. A mathematical model is included in this chapter. Another contribution is the development of a harmonic monitoring management system in terms of a flow chart.

4.2. New adapted equivalent circuits

Traditionally, a power system was designed with only one customer connected at the point of common coupling (PCC). A contemporary power system has multiple customers connected to the PCC. The customers cannot be represented as one because of different operating and load conditions. The equivalent circuits were designed to represent the customer connected at the PCC which no longer holds. Therefore, it is important to develop adapted Norton and Thevenin equivalent circuits that include the new phenomena of a modern power system. The existing equivalent circuits were adapted based on the number of customers connected at the PCC, which should be able to increase or decrease. Two case studies are investigated with single and three customers connected in Chapter 6. This was achieved by calculation of the current and voltage at the PCC with single and three customers. The voltage and current at the PCC differ between the two case studies for each equivalent circuit. Therefore, the newly adapted circuits demonstrated that several customers cannot be represented as one. Thus, it is recommended that for harmonic source detection the new adapted circuits should be used.

4.2.1. Background

Power systems have changed drastically due to increases in the power demand of countries worldwide. As the population is increasing, there is growth and development in certain countries and investors are interested in investing in such countries. While it was common to have only one customer connected at the PCC (Xu et al., 2003), it is very rare to find only one customer connected at the PCC in the new era. New phenomena arose whereby multiple customers are connected at the PCC. These customers have different operations and load conditions (Sinvula et al., 2019a) and cannot be represented as a single customer. Thevenin and Norton's equivalent circuits were used in electrical engineering for different circuit analyses. These equivalent circuits were used to determine the dominant harmonic source (Chupeng et al., 2016; Safargholi et al., 2018b; Xu et al., 2003; Wang et al., 2018; Xu et al., 2018; Safargholi et al., 2018a; Cieslik, 2016). Thus, these equivalent circuits need to be modified to accommodate and represent a true practical power system and enable it to be used for harmonic source detection. The disturbance of harmonics can come from either the customer(s) or the utility side. The harmonic impedance of each side (customers or utility) should be determined to use this method. Determination of the harmonic impedance can only be possible through measurement and assumptions, although the harmonic impedance varies depending on the loads and operation of the network. Thus, to represent customers connected at the PCC as one means that the harmonic impedance was assumed. Once the equivalent circuits were adapted, they could be used for the harmonic frequencies part of the network. It is important to determine the source of harmonics once the current and voltage distortion were detected as part of the power system. These adapted equivalent circuits could be used for circuit analysis apart from harmonic source detection.

4.2.2. Methodology

The existing Thevenin and Norton equivalent circuits were used to developing adapted equivalent circuits. The mathematical model was developed and validated with the application of case studies. Figure 4.1 indicated the method used to develop the new adapted equivalent circuits.

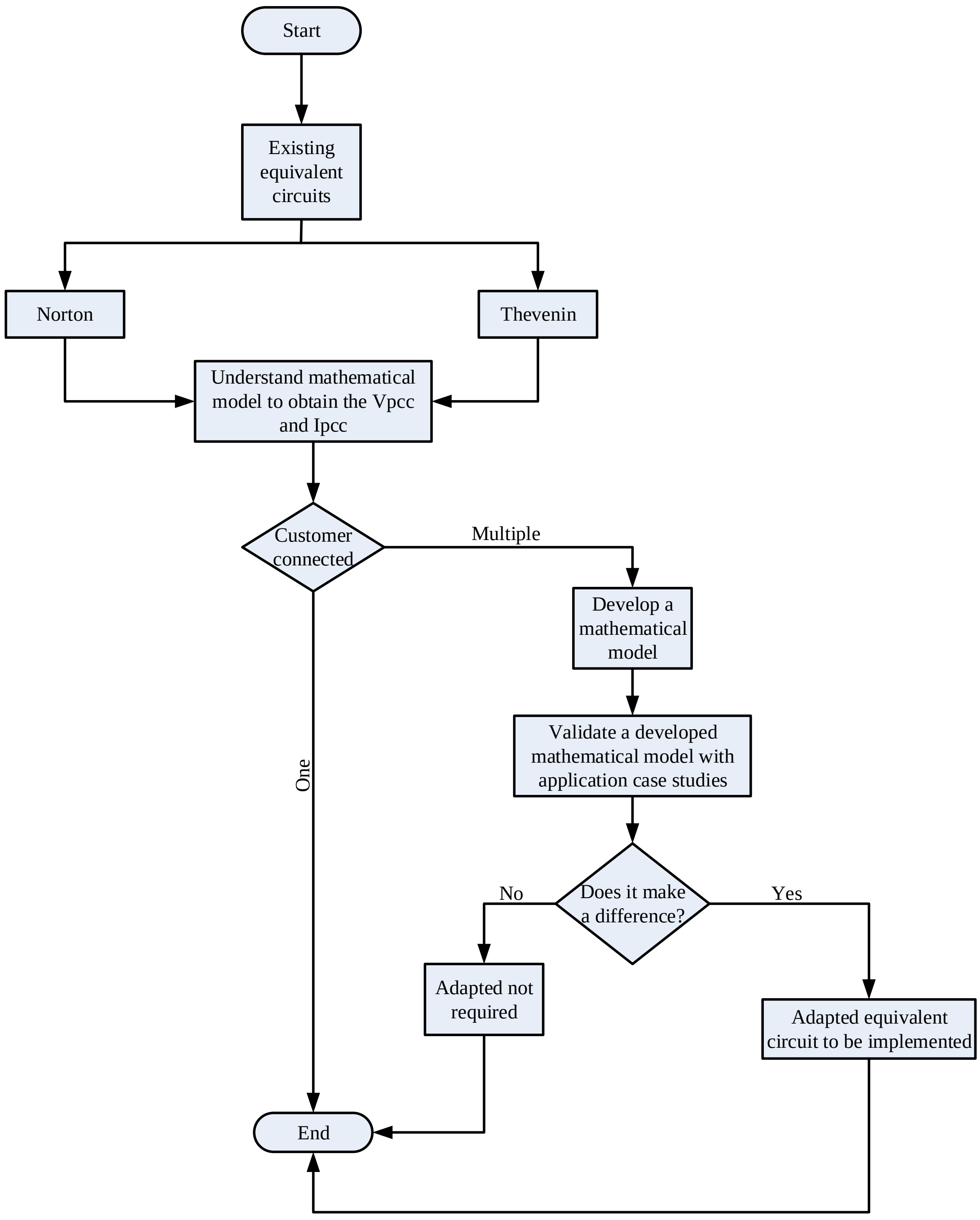


Figure 4.1: Flowchart used to modify the equivalent circuit

4.2.3. Mathematical model

The mathematical model was based on the first principle of the superposition theorem.

4.2.3.1. Norton equivalent circuit

The Norton equivalent circuit (larger harmonic current source) was used to determine the harmonic current source as shown in Figure 3.6 and Figure 3.7 of Subsection 3.5.1 in Chapter 3.

i. Single customer

The voltage at the point of common coupling of the customer and utility was determined using the formulae as specified in Equation 3.1 – Equation 3.4 of Subsection 3.5.1 in Chapter 3. Thus, to determine the current at the PCC the Equation 4.1 was used.

$$I_{pcc} = I_{u-pcc} - I_{c-pcc} \tag{4.1}$$

$$I_{u-pcc} = I_u - (V_{u-pcc} \times Y_u) \tag{4.2}$$

$$I_{c-pcc} = -I_c - (V_{c-pcc} \times Y_c) \tag{4.3}$$

ii. Multiple customers

Figure 4.2 and Figure 4.3 indicate the Norton equivalent circuit with three customers connected at the PCC.

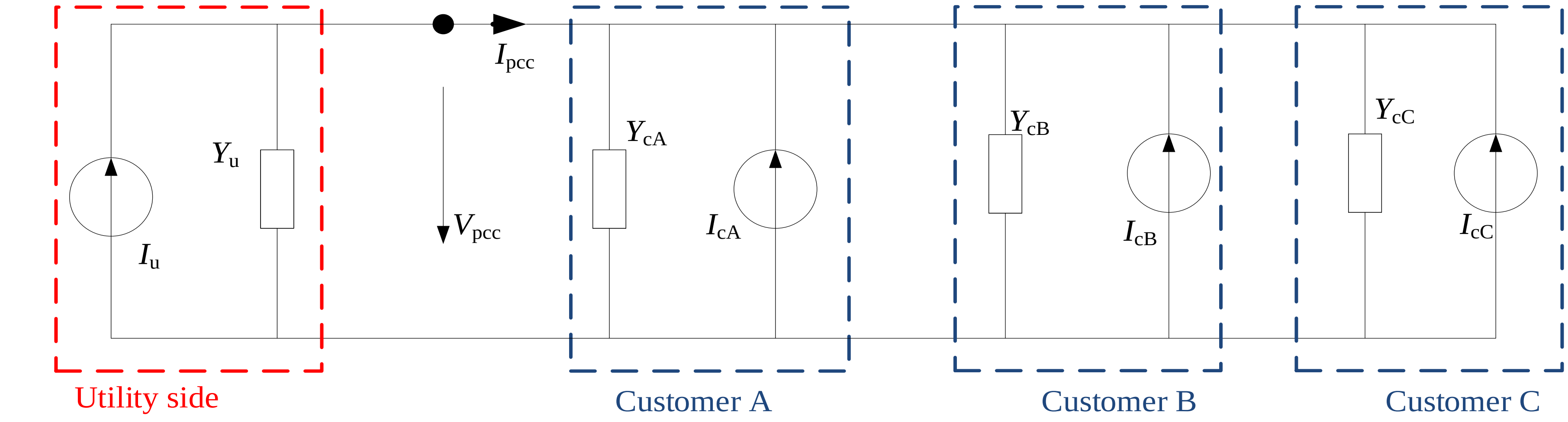


Figure 4.2: Norton equivalent circuit with three customers connected at the PCC

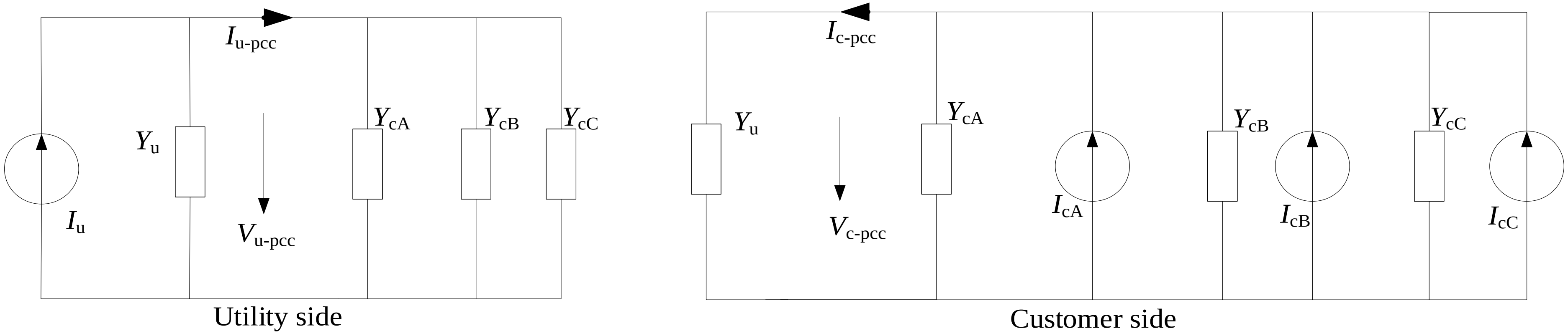


Figure 4.3: Norton equivalent circuit for harmonic voltage contribution of two sides representing three customers

Equations (4.4) to (4.10) represent the new mathematical model to calculate the voltage and current at the PCC when multiple customers are connected.

$$V_{pcc} = V_{u-pcc} + V_{c-pcc} \tag{4.4}$$

$$V_{u-pcc} = \frac{I_u}{(Y_u+Y_{cA})+(Y_u+Y_{cB})+(Y_u+Y_{cC})} \tag{4.5}$$

$$V_{c-pcc} = \frac{-(I_{cC}+I_{cB}+I_{cA})}{(Y_u+Y_{cA})+(Y_u+Y_{cB})+(Y_u+Y_{cC})} \tag{4.6}$$

Combining (4.5) and (4.6) to obtain the Equation (4.7)

$$\frac{I_u}{I_{cA}+I_{cB}+I_{cC}} = \frac{V_{u-pcc}}{V_{c-pcc}} \tag{4.7}$$

$$I_{pcc} = I_{u-pcc} - I_{c-pcc} \tag{4.8}$$

$$I_{u-pcc} = I_u - \left(V_{u-pcc} \times Y_u\right) \tag{4.9}$$

$$I_{c-pcc} = \left(-I_{cC} - \left(V_{c-pcc} \times Y_{cC}\right)\right) + \left(-I_{cB} - \left(V_{c-pcc} \times Y_{cB}\right)\right) + \left(-I_{cA} - \left(V_{c-pcc} \times Y_{cA}\right)\right) \tag{4.10}$$

4.2.3.2. Thevenin equivalent circuit

An equivalent circuit (larger harmonic voltage source) was used to determine the harmonic voltage source as shown in Figure 3.8 and Figure 3.9 of subsection 3.5.2 in Chapter 3.

i. Single customer

The current at the point of common coupling of the customer and utility was determined using the formulae as specified in Equation 3.12 – Equation 3.15 of Subsection 3.5.2 in Chapter 3. Thus, to determine the voltage at the PCC the Equation 4.11 was used.

$$V_{pcc} = V_{u-pcc} + V_{c-pcc} \tag{4.11}$$

$$V_{u-pcc} = V_u - \left(I_{u-pcc} \times Z_u\right) \tag{4.12}$$

$$V_{c-pcc} = V_c - \left(I_{c-pcc} \times Z_c\right) \tag{4.13}$$

ii. Multiple customers

Figure 4.4 and Figure 4.5 indicate the Thevenin equivalent circuit with three customers connected at the PCC.

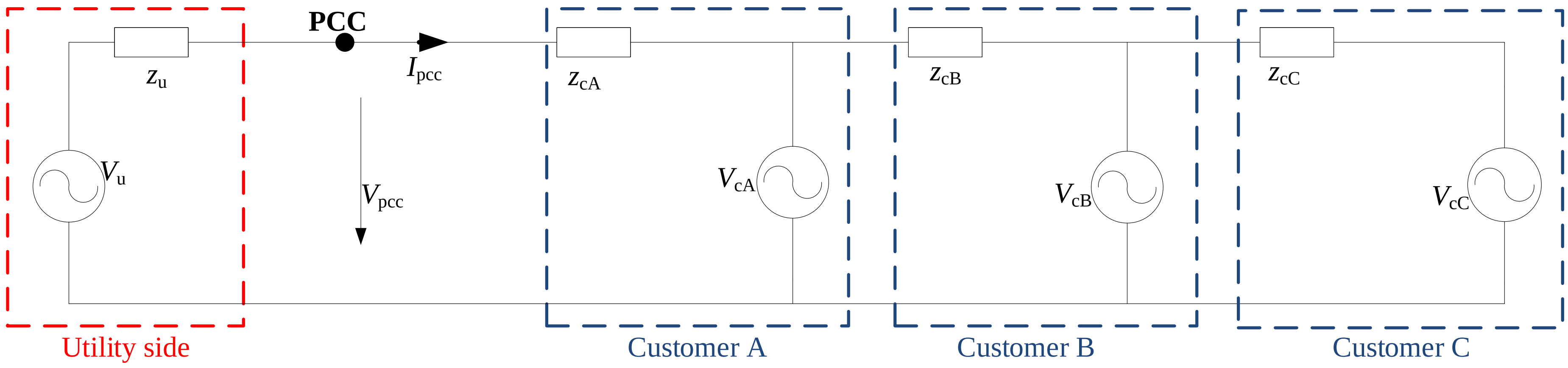


Figure 4.4: Thevenin equivalent circuit with three customers connected at the PCC

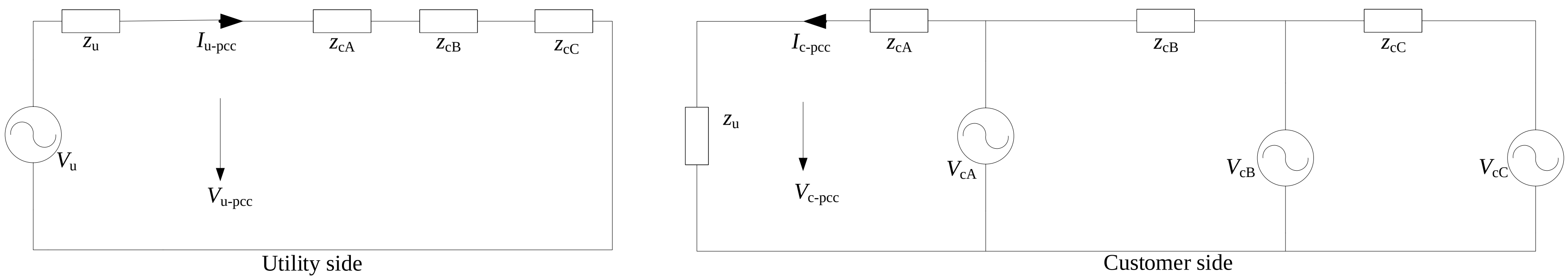


Figure 4.5: Thevenin equivalent circuit for the harmonic current contribution of two sides representing three customers

$$I_{pcc} = -I_{c-pcc} + I_{u-pcc} \tag{4.14}$$

$$I_{u-pcc} = \frac{V_u}{(Z_u+Z_{cA})+(Z_u+Z_{cB})+(Z_u+Z_{cC})} \tag{4.15}$$

$$I_{c-pcc} = \frac{V_{cA}=V_{cB}=V_{cC}}{(Z_u+Z_{cA})+(Z_u+Z_{cB})+(Z_u+Z_{cC})} \tag{4.16}$$

Combining (4.15) and (4.16) obtains the following equation; in parallel the voltage is equal.

$$\frac{V_u}{V_{cA}=V_{cB}=V_{cC}} = \frac{I_{u-pcc}}{I_{c-pcc}} \tag{4.17}$$

$$V_{pcc} = V_{u-pcc} + V_{c-pcc} \tag{4.18}$$

$$V_{u-pcc} = V_u - \left(I_{u-pcc} \times Z_u\right) \tag{4.19}$$

$$V_{c-pcc} = (V_{cC} = V_{cB} = V_{cA}) - \left(\begin{matrix}\left(I_{c-pcc} \times Z_{cC}\right) + \\ \left(I_{c-pcc} \times Z_{cB}\right) + \left(I_{c-pcc} \times Z_{cA}\right)\end{matrix}\right) \tag{4.20}$$

This mathematical model can be done for any number of customers (cN) connected at the PCC. It important for each customer to be represented separately as it is in the practical power system. The mathematical model showed the difference in formulae when multiple customers were connected at the PCC for each equivalent circuit. This was validated in the application case studies in Chapter 6.

4.3. Harmonic monitoring management system

The excessive total harmonic distortion measured at the PCC raises the need to develop a harmonic monitoring management system that can assist the power utilities to manage the electricity supply agreement with the industrial customers. The contractual agreements between the utilities and the customers should consist of the harmonic limits of each party. The harmonic distortion data measured by power quality analysers that are connected at different points in the network are used to check whether the customer or utility is within the limits as specified in the contractual agreement. The harmonic monitoring management system was developed using a flowchart indicated in Figure 4.10. The utilities need to follow the developed system and monitoring should be done monthly to avoid the uncertainty of different operation and load conditions. The outcome of the monitoring should be presented to the customers quarterly for harmonic mitigation and information purposes. Therefore, the system assisted the utilities and customers to detect the source of harmonic distortion and discuss the mitigation factors needed. Also, the challenges of identifying the methods for harmonic source detection was resolved.

4.3.1. Background

Many studies are concerned about the power quality problem and how it can be solved. Different solutions on how to mitigate harmonic distortion have been proposed and implemented in the power system (Zobaa, 2006; Babu & Manikandan, 2017; Attia & Fahmy, 2010). Although different approaches of harmonic distortion mitigation have been ongoing, there is a shortcoming in the literature on how harmonic distortion can be managed at the point of common coupling (PCC) through a contractual relationship between the utilities and the customers. Currently, the contractual Electricity Supply Agreement (ESA) between the utilities and the customers places little emphasis on power quality. The utility must emphasise more the continuity of power supply to the customers as the quality of power supplied by the utilities is a concern to the customers.

The responsibility of power quality must be well defined in the contracts. The contracts should address issues concerning power quality in a way that is understood by all parties. There are different national and international standards with limits for harmonic distortion (current and voltage distortion) (IEC Std. 61000-3-6, 2013; IEEE Std 519-2014, 2014; NRS 048-4:2009, 2009; IEEE Std 1159.3™-2003, 2003; IEEE Std 1159™-2009, 2009). Although limits are set in the standards, it should be interpreted in the ESA as well.

Harmonic distortion has effects on the power system equipment. The harmonic distortion effects depend on the sequence components' type of harmonics that are present at the PCC. Positive and negative sequence harmonics cause the heating of the conductors and the power transformers (Babu & Manikandan, 2017). The negative sequence harmonics can cause the induction motors to run in the reverse direction; whereas the zero-sequence harmonics cause neutral currents which can be larger than phase currents (Babu & Manikandan, 2017). Due to the negative effects that harmonics can cause, both parties need to participate in drawing up a contract agreement.

Traditionally, utilities believed that harmonics were caused by the customer only, which is no longer true as it was found that utilities have background harmonics. The utilities need to specify on the contracts the percent of harmonic distortion each customer can inject into the national grid. The background harmonics at the PCC should be known by the utilities and this information should be given to the customers who are applying for the electricity supply at that point. There should be a clause in the contracts specifying the percentage of total harmonic distortion the customer will be exposed to, for the customers to take into consideration in the design of their equipment. The total current/voltage harmonic distortion is well defined on the standards (NRS 048-4:2009, 2009; IEEE Std 519-2014, 2014; IEC Std. 61000-3-6, 2013) according to the voltage level at the PCC. It is a concern on how to apportion the total current harmonic distortion in case multiple customers are connected at the PCC.

The legal side of contracts on power quality should be defined similarly to the Notified Maximum Demand (NMD). In case of dispute, methods should be put in place on how to solve the power quality disputes. Power quality measurement methodology should be included in the contract. All involved parties must agree on the equipment to be used for measurement. Power quality must no longer be ignored for electricity supply agreements between the utilities and the customers. There is a need to develop the concept and process to be followed by power quality engineers and commercial engineers when drawing up power quality as part of the ESA. This concept and process were demonstrated using the contracts from two different utilities within Southern Africa. When utilities take measurements and verify the harmonic limit based on the limit set out in the ESA, this ensures that the customer knows who is responsible and which harmonic order is dominant. Today's power quality analysers can measure the harmonic distortion of each harmonic order that forms part of the network.

It is important to propose a harmonic monitoring management system which could be used during the planning phase and setting up of an electricity supply agreement between the utility and customers. It is also pointed out that the customer's harmonic content needs to be a part of the required document which forms part of the application for electricity supply. The harmonic limit allowed at the PCC should be one of the determining factors for the number of customers allowed at a certain PCC. The NMD is currently a yearly exercise for customers to notify the utility regarding any changes in their operations. However, the harmonic limit has become a concern whereby the customer has to notify the utility once they increase the loads that are categorized as a harmonic source. Whether the harmonic content should be a yearly exercise that a customer should notify the utility about is still under investigation.

4.3.2. Methodology for monitoring and managing harmonic distortion

A power system with harmonic distortions that are not monitored accurately can cause a challenge of harmonic source detection between the utility and the customers. The harmonic monitoring management system was developed using a flowchart that described all the procedures to be followed by the utilities during the planning phase of drafting the electricity supply agreement. The system was developed based on the national and international standards that specify the harmonic limits. The method and calculation of harmonic apportioning is not part of this thesis. The harmonic monitoring management is determined by national and international harmonic standards and electricity supply agreement as indicated in Figure 4.6.

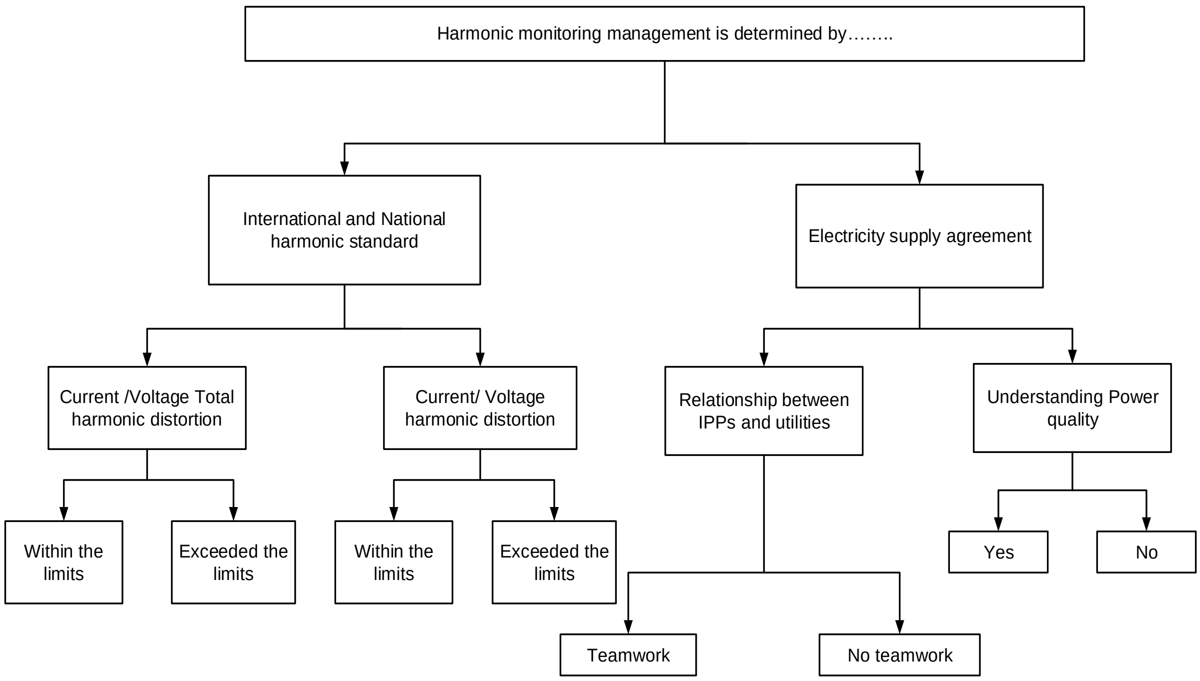


Figure 4.6: Dendrogram deductive research design for harmonic monitoring management

This approach is based on the practical challenges of a scenario where three customers with different operating load conditions are connected at the PCC. The PCC has a higher total harmonic distortion that exceeds the limit specified by the standards. This harmonic distortion is affecting the equipment of the customers, it is difficult to identify the source of the harmonics at that point and there is no limit set in the electricity supply agreement. Therefore, it is ideal for the harmonic limits to be set during the planning phase and be part of the ESA from the initial stage. It is difficult to change the ESA at a later stage, once the challenges become a reality as customers might not have the same understanding at that time.

As shown in Figure 2.5 about emission evaluation procedure, how emission limits are addressed in contracts is categorised in three stages. These stages only specify the harmonic limit of the three different customers and the utility's harmonic limit is ignored as nothing is documented regarding it. However, the utility's background harmonics need to be monitored and well documented with a specific limit set as part of the ESA. Figure 2.5 is modified to accommodate the utility's background harmonics from upstream of the network to be specified according to standard procedures. Stage 1 on the customer side is also modified to have a specified contractual limit according to the standard procedures as the load owner can decide to change the equipment or the operation procedures without increasing the notified maximum demand of the load. At present, customers could install a rooftop solar PV system to reduce their electricity bill from the utility. This can change the harmonic parameter of the specific load.

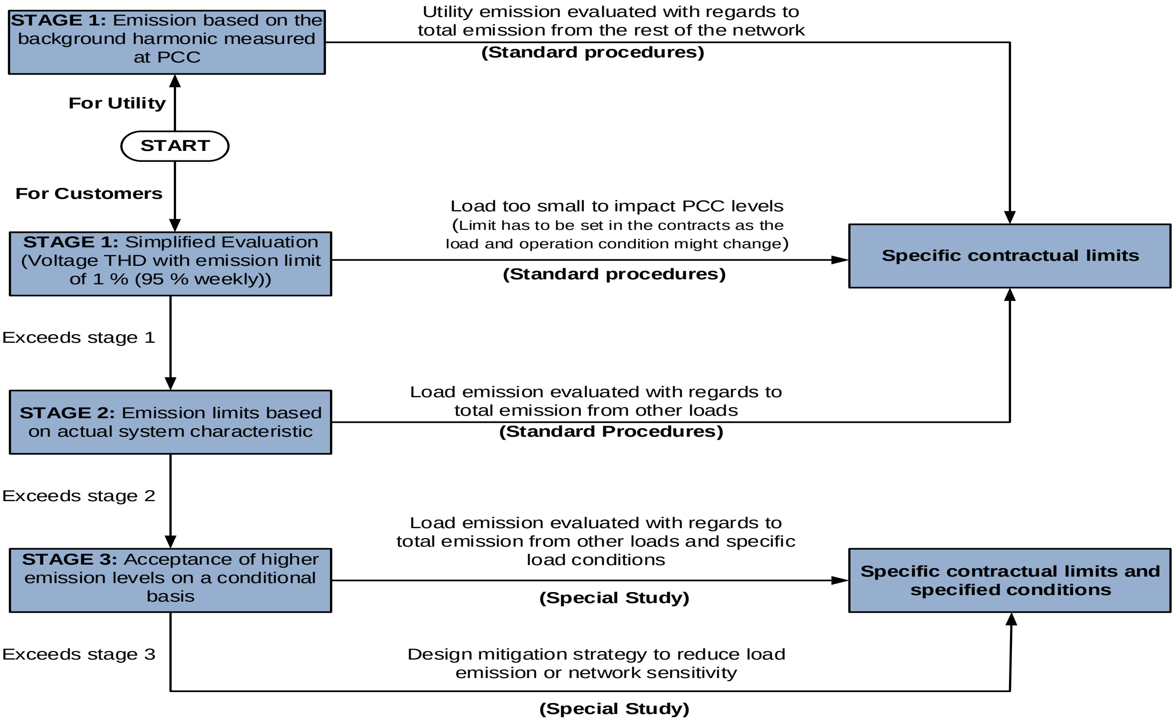


Figure 4.7: Illustration of the emission evaluation procedure, and how emission limits are addressed in contracts for both parties

4.3.3. Harmonic monitoring management stages

Three stages need to be used for the development of the harmonic monitoring management system.

4.3.3.1. Stage 1: Problem identification

It is a challenge to identify the source of harmonics at the PCC where multiple customers are connected. Utilities still face challenges in identifying customers responsible for harmonic contents in the network due to inadequate specifications/terms in the electricity supply agreement. A clear specification of harmonic limits for each customer needs to be known and be part of the ESA. A contract can be used to solve the problems of harmonic content if defined properly. Once each customer is given a specified harmonic limit of current distortion they can inject at the PCC that can be measured to determine the discrepancy and notify the customer in writing to remedy the problem once identified. This can be treated similarly to the notified maximum demand (NMD). Customers must adhere to the NMD as there are penalties involved that are non-negotiable. The utility must be serious about harmonic limits as they bring about more challenges if not managed and monitored correctly.

4.3.3.2. Stage 2: Objective to solve the problem

The harmonic limit contents must be clearly stated in the contracts and understood by all parties. Measurement guidelines must be developed and agreed upon before the contract is signed. Measures must be put in place defining the processes to be followed once one of the parties fails to honour the contract. National and international standards must always be used as guidelines when specifying the harmonic contents. Harmonic limits at the PCC must be defined in the contracts according to the standards. Limits must be set per customer to resolve the issue of harmonic contents. Therefore, in solving the problem defined in stage 1, the following questions need to be attended to:

i. what can be done to identify the harmonic contents?;
ii. who is the party responsible for the harmonic contents at the PCC?;
iii. what are the measurement principles of the harmonic contents per customer?;
iv. what are the harmonic content limits per customer/utility and PCC?; and
v. how will the limits be achieved?

4.3.3.3. Stage 3: Solution

When the measured harmonic content at the PCC is exceeded, three types of the solution should be taken into consideration by both parties i.e. utilities and customers.

4.3.3.3.1. Technical solution

Measurements need to be taken by both parties for a certain period agreed upon in the contract. The position of equipment must be decided, where the main measurement and backup measurement should be taken. Measuring equipment agreed upon in the contract should be correctly calibrated by an approved and registered company. Care should be taken that any equipment connected at the secondary winding of the voltage transducer does not generate harmonic currents. All customers with distributed power generators as well as renewable energy sources that inject harmonic current in the network which affect the harmonic voltage at the PCC should be treated similarly. When a party is found to have harmonic content exceeding the specified harmonic limit within the ESA for a consecutive period of three months is identified, that party has to be notified in writing each month. The responsible party should be given three months to mitigate its contribution by providing a harmonic filter, or any other mitigation methods, and bearing the costs thereof. As the designing of harmonic mitigation can be a long process, the responsible party has to be responsible for the financial solution until mitigation takes place and the harmonic content is within the limit set. By so doing parties, involved will be serious about adhering to the condition specified under the ESA. New applicants for electricity supply should be notified of the complications involved once the ESA conditions are not adhered to by giving an example of the existing contracts regarding harmonic content and exceeding the limits.

4.3.3.3.2. Financial solution

It should be stated in the contract agreement that the party who is responsible should need to pay penalties after three consecutive months of exceeding harmonic limits. The penalty payment should be processed similarly to the NMD. The process of calculating the penalties is not part of this thesis, as this is something that the national regulatory body of a specific country must agree upon with the utility. Utilities should clarify in the contracts what should happen to other customers connected at the same PCC if their equipment has been affected by the poor quality of supply (QoS). The utilities have to be responsible to manage the network in such a manner as to ensure that voltage distortion remains within the contracted limits and adheres to the power quality standards prescribed by the electricity regulatory body of the specific country. In cases whereby the harmonic content which exceeds the limits is from the utility itself, the same process should be followed to remedy the problem.

4.3.3.3.3. Legal solution

There should be a clause in the contract agreement that states, in case the limits of harmonic distortion are exceeded and disputes arise, the process in which the disputes should be dealt with. In the contract, it should be stated that the complaints from the customer should be in writing and this complaint letter should be kept for a minimum of three years.

Figure 4.8 indicates the three main stages of how to manage the harmonic contents to be used in developing a harmonic monitoring management system.

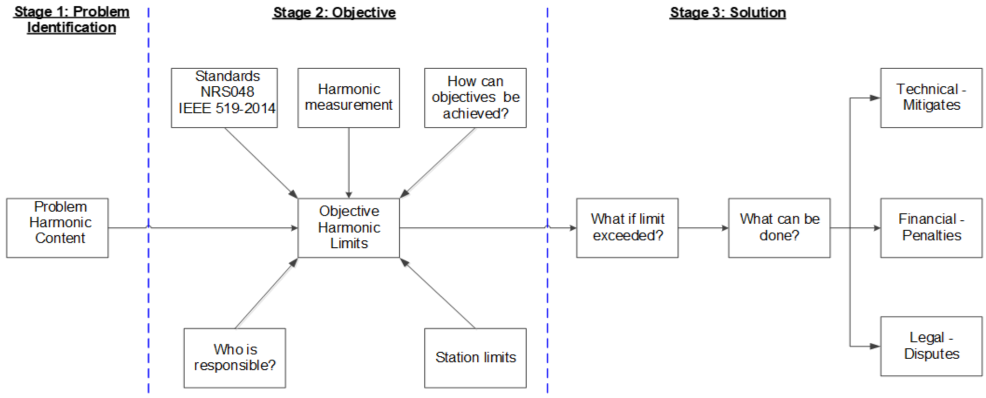


Figure 4.8: Concept of how to manage harmonic content

The utility must take measurements of the voltage harmonic distortion at the PCC before any customer is connected at that point. Once the background harmonics at the PCC are known, during the planning phase an overview is given of the remaining percentage that needs to be apportioned to the applications of the customers who are to be connected at that point. It can also indicate how many customers can be connected to the PCC. Today, the main factors that contribute to deciding the number of customers to be connected at the PCC are the transformer capacity, and the maximum current carrying capacity of the conductor and its clamps. In most cases, the utility can upgrade the transformer to a transformer with a higher capacity. For instance, a 10 MVA transformer can be replaced with a 20 MVA transformer with the same voltage to cater to the number of customers to be connected. In the case of the conductor, one with a higher maximum current capacity is used to transfer the higher current. For instance, the centipede conductor with a current capacity of 647 A at 75 °C can be replaced with a Bull conductor with a current-carrying capacity at 75 °C of 986 A. It is crucial to consider the total voltage harmonic distortion of the PCC as a limiting factor for the number of customers to be connected at the PCC.

The value of background harmonics should be noted in the electricity supply agreement (ESA) contract and the limit should be set as well for the utility. The utility should be responsible to ensure that it is within the specified harmonic limits set. This guideline should be based on the national and international standards to apportion the harmonic limits set. Involved parties should ensure that their harmonic contents are within the limit set. This should imply that whenever the customer changes the operation condition, it will enable the party involved to take the precautionary measure of designing and installing the harmonic mitigation procedures to ensure that the percentage is within the harmonic limit.

4.3.4. Contract agreement development

The five stages for the development of a contract agreement are specified in Figure 4.9.

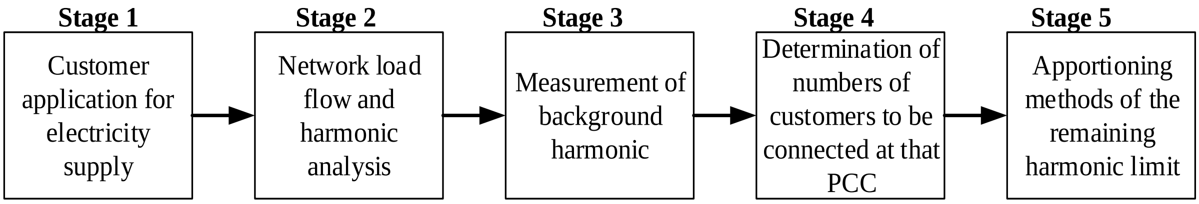


Figure 4.9: Five stages for the development of contract agreement

These stages are described in detail as follows:

i. **Stage 1** – The customer approaches the power utility with the application for electricity supply, with their determined maximum demand required. It should become a requirement for the application to have the customer's harmonic content and the types of the load forming part of their plant. If this information is not part of the existing utility electricity supply application, the utility must review and amend the document. It is also important that the customers are notified by the utility to provide all the necessary information to have a comprehensive power quality analysis and obtain an accurately specified harmonic limit.

ii. **Stage 2** - The planning engineers conduct the network load flow to check which part of the network has the capacity required and can be connected considering the closest point in the network, transformers capacity, etc. Once the point of connection is identified the power quality engineers need to determine the harmonic content of the customer. The power quality engineers should conduct the harmonic load flow analysis and suggest to the customers the specified harmonic limit based on the apportioning method that needs to be agreed.

iii. **Stage 3** - The background harmonics at the PCC must be determined using the peak percentage recorded for the past twelve months' period from the Unipower/Vectograph data. For example, if the peak background harmonics is identified to be 1 %, then it is feasible to give a background harmonic limit of ≤1.5 %. It should be noted that the peak background harmonics is under no-load conditions, and born in mind when apportioning the specified harmonic limit of the utility at the PCC. The background harmonics might increase under load conditions.

iv. **Stage 4** - The utility forecast engineers should determine and provide the load forecast for the next five years. This indicates the number of customers to be connected at a certain PCC.

v. **Stage 5** - The apportioning method of the harmonic content should be determined by the utility for each customer and this depends on the data they have provided to the power utility. Customers should provide all the necessary information to help the utility to determine realistic and accurate harmonic limits. For example, if a customer's harmonic content at full load indicates 1.5 % then the utility can allow the customer to inject a harmonic limit of ≤ 2 %.

4.3.5. Harmonic monitoring framework

The framework of the harmonic monitoring management system is given in Figure 4.10. The payment of a penalty is applied to each party who is responsible for harmonic content higher than the allowable or agreed-upon limit in the contract. The fees for the penalty should be regulated by the national regulatory body where this methodology is to be applied. Thus, with this in place, both parties will take responsibility for their harmonic content seriously. The current research challenge of harmonic source detection will be resolved due to the penalties involved.

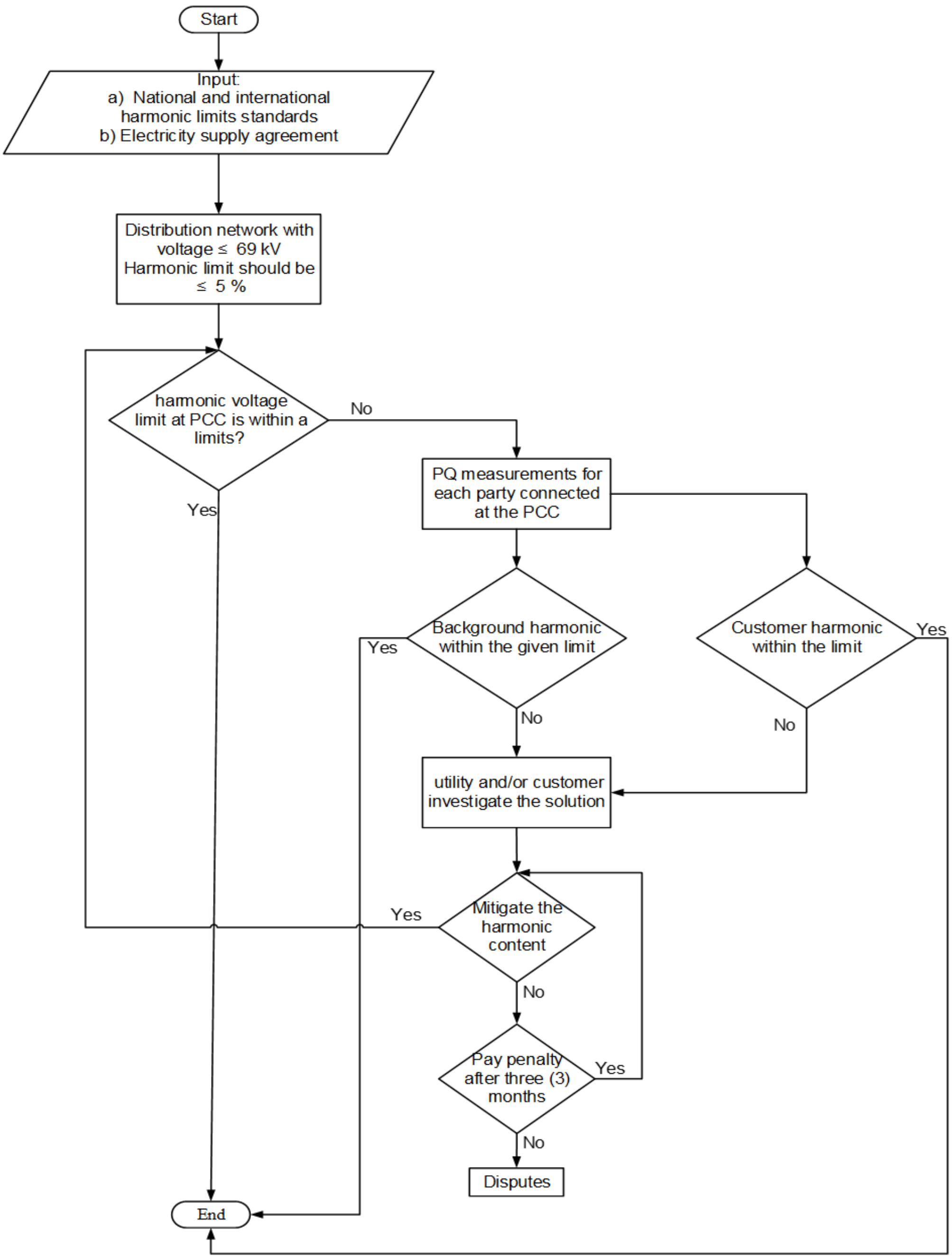


Figure 4.10: Harmonic monitoring management system

4.3.6. Case study explanation of the methodology

A radial distribution network with a step-down transformer 132/66kV initiates this study, where three customers are connected at the PCC (Bus 2) as indicated in Figure 4.11. Customers have different operating and load conditions. These customers applied for electricity supply at different periods over 15 years. These customers are faced with challenges of harmonic distortion at the PCC. These customers are blaming one another for harmonic distortion effects that cause malfunctioning of their equipment. Thus, it becomes a challenge for the utility as no harmonic limits are specified in the ESA of each customer. Once a dispute is declared, it becomes a challenge to manage as there is a grey area in the ESA.

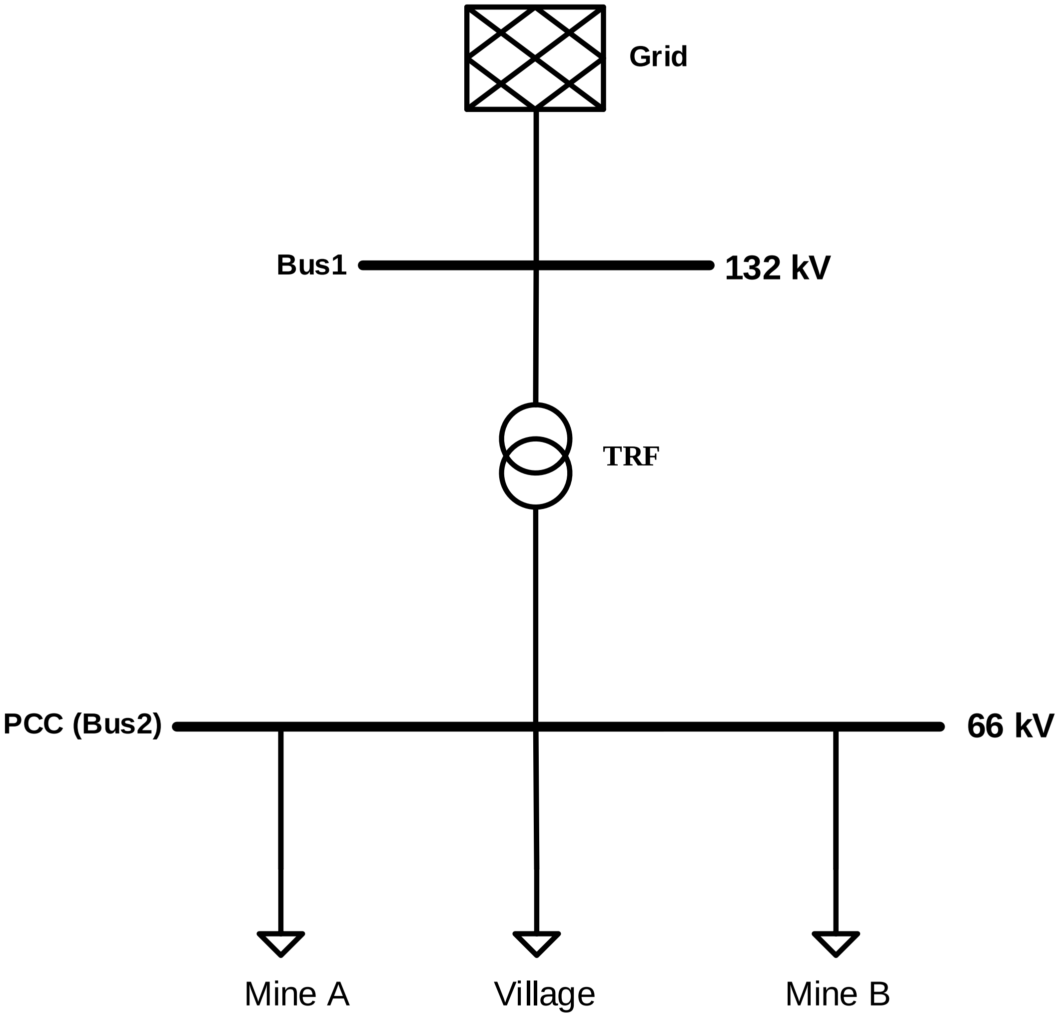


Figure 4.11: Radial distribution network

The three major customers connected to the distribution network had different operating conditions at the beginning than they do currently. Thus, if the harmonic limit is not set in the ESA it becomes complicated for the utility to manage the harmonic content. Table 4.1 indicates the year the customers applied for electricity supply from the utility, the percentage of total harmonic distortion (THD) obtained once the power quality engineers conducted the harmonic analysis using DIgSILENT, and the total harmonic distortion agreed upon by the two parties and stipulated in the Electricity Supply Agreement (ESA) as per stages indicated in Figure 4.7. It should be noted that if no harmonic limit forms part of ESA, new customers can be added at the same PCC which can cause the PCC's total harmonic distortion to exceed its limit, as customers can inject any percentage. For instance, in 2005 when a village applied for the electricity, initially no solar PV farm was present. Thus, if the THD limit was initially set at zero, after the installation of the solar PV farm, the THD would start to exceed the harmonic limit as set by the standards. Setting a harmonic limit as part of the ESA is beneficial to the utility. The negotiation for harmonic mitigation will be easier if the stakeholders involved have understood the details as part of the ESA. If the utility measured an average peak background harmonic without load at 0.5 %. Therefore, it is advised to set the harmonic limit of the background harmonic to ≤1 %.

$$\%VTHD_{set\ on\ ESA} = \%VTHD + \%\ allowable \tag{4.21}$$

Where: $\%VTHD$ is a measured or simulated harmonic content of the utility or customer and the % allowable was 0.5 %

Table 4.1: Data for customers connected at the PCC

Customer Name	**Year of application for ESA**	**%THD noticed using DIgSILENT**	**%THD set on the ESA**
Village	2005	0	≤ 0.5
Mine A	2007	1.5	≤ 2
Mine B	2011	1	≤1.5

All customers need to be given the harmonic limits in their ESA as the operation and load might change within the period. For example, a village in Table 4.1 could not inject any harmonic current at the PCC according to a study done in 2005 during the application process. Today most villages use distributed generators that can inject harmonic current in the system. Thus, customers should discuss their five-year plan of operations. The total harmonic distortion that is noticed using the simulation in DIgSILENT is when the plant is operating at full load as per design, as this is the worst-case scenario. The recommended total voltage harmonic distortion limit, according to IEEE 519-2014, should not exceed 5%, and the individual voltage harmonic distortion limit should not exceed 3%, according to the categories of 1 kV < V ≤ 69 kV as indicated in Table 2.6 of the radial distribution network as in Figure 4.11 with Bus 2 (PCC) of 66kV.

It is a challenge to all parties when there are customers connected at the PCC without set harmonic limits included in the ESA. It is not practically possible to switch off the customers connected at the PCC for a certain period to measure the background harmonic levels. Thus, to assign harmonic limits to the existing customers, the utility and customers must agree upon a limit. The utility must notify the customers of the benefits that it can bring once the harmonic limits are known. This is a process that can take a long time to be solved as a new ESA needs to be signed.

4.4. Modified harmonic source detection method

Active power flow direction is a common method used by most industries to determine the flow of harmonics in the distribution network and for data monitoring analysis. This method is integrated into most power quality analysers and in commercial software. It is important to examine the harmonic power flow direction method and quantify the size of the harmonic contribution of each harmonic source connected at the Point of Connection (PoC). The harmonic power flow depends on the flow of harmonic current within the power system. It can be that the harmonic sources have negative power at a harmonic frequency which means it injects the harmonic current, even though the dominant contribution might only be from one or two harmonic sources. Thus, the load with the highest percentage of individual and total harmonic distortion is the dominant contributor to harmonics. DIgSILENT gives the contribution of each load connected at the PoC by indicating the percentage of total harmonic distortion. It is also possible to identify which harmonic order is the major contributor to the total harmonic distortion of an individual customer. The active power flow direction method is the practical and commercial method used in the industries as it gives logical results and does not depends on any assumed parameters. This gives a solution for ongoing harmonic source detection research. It is recommended to use DIgSILENT, as it indicates the direction of harmonic active power flow and quantifies the harmonic content within the network.

4.4.1. Background

Harmonic distortion is supposed to be monitored and managed within the limits as prescribed in the standards. These individual and total harmonic distortion limits of the voltage and current should form part of the ESA and be understood by all parties involved in drawing up the contract. In most scenarios, the individual and total harmonic distortion exceed the limit and this motivated the researcher to investigate a method to identify the harmonic source. Traditionally, it is known that harmonics exist because of the non-linear loads that are part of the customer network. Apart from the non-linear loads, the phenomenon of penetration of renewable energy sources which is drastically increasing to form part of the power system is a source of harmonics. The power system is becoming smart because of the introduction of electronic equipment/devices. However, this changes as the utilities can contribute to the harmonics that are measured at the PCC due to the background harmonics that flow from any side of the network. The background harmonic can no longer be ignored in the investigation of harmonic source identification. Current ongoing studies on harmonic source detection are mainly focused on determining the source of harmonic distortion between the customer and utility. This does not represent a practical power system as it is uncommon to have only one customer connected at the PCC. The dominant source of harmonics needs to be identified whether it is upstream (utility side) or downstream (customers side). When the harmonic source is from the customers' side then further investigation should take place to identify the individual customer responsible. There is a shortcoming in the literature to determine the harmonic source between the multiple customers connected at the PCC. This is required to form part of the modified direction of the active power flow method.

4.4.2. Methodology

It is known that at the fundamental frequency the active power flows from the source to the loads. This source traditionally refers to the utility grid, which no longer holds as the source can be the utility grid and renewable energy sources which are downstream of the power system on the customer side as shown in Figure 4.12. The fundamental frequency power can be either upstream (utility grid) or downstream (renewable energy source). At the harmonic frequency, the harmonic active power can also flow from either side, upstream (utility through background harmonics), and downstream (customers with harmonic source loads). It is important to note that the direction of active harmonic power can be different at different harmonic frequencies. Thus, at the combined frequency (fundamental and harmonic frequency) the total active power of the power system flow depends on the dominant harmonic source.

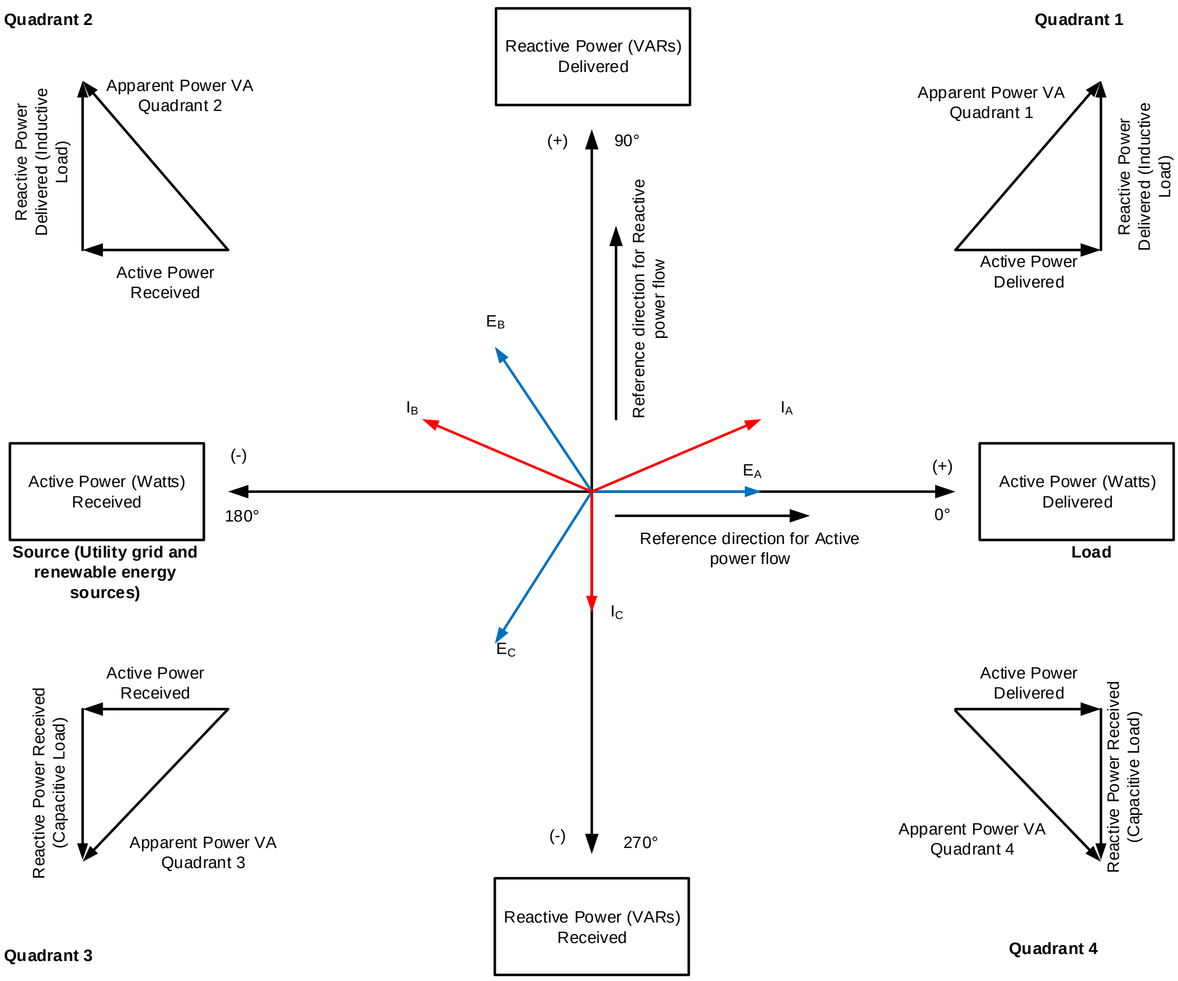


Figure 4.12: Direction of electrical power flow with the integration of RES at the fundamental frequency

New applications for electricity supply should be treated with the developed harmonic monitoring management system to avoid future complications. In the future, the monitoring should be conducted accordingly and harmonic distortion becomes part of the tariff that contributors need to be charged. However, harmonic source detection research is minimally discussed in the electrical engineering field. The process to deal with the new applications needs to be formalised by each country's regulator. These show that for the existing customers without the harmonic limit as part of the ESA, the harmonic source detection method is still required. This is because the utility can't disconnect their sensitive customers such as mining industries to conduct measurement and review of their ESA to implement a harmonic monitoring management system.

The modification of the direction of active power flow has to be conducted in three stages as follows, which are formulated in Figure 4.13 – Figure 4.15:

i. identify the side of the harmonic source and quantify each side's contribution;
ii. identify the contributor in case of the customer side and quantify each customer; and
iii. prove the dominant harmonic order of the contributor.

4.4.3. Active power definition

The sign of active power should be considered when calculating the total active power at the combined frequency. The total active power of the non-linear loads and renewable energy generators is affected by the harmonics compared to the total active power of linear loads. A non-linear load and RES draw fundamental power (P_1) and inject harmonic power (P_h); the harmonic power can be in either direction. Similarly, for linear load, harmonic power (P_h), is not exactly at the same phase as the fundamental power (P_1), thus, the direction of active power flow is used (Zhao et al., 2017). When harmonic distortion is present in the network, the power should include harmonic power with its flow of directions either positive or negative (Zhao et al., 2017). This will result in a total power (P_T) to be either one of Equation (4.22) – (4.23) as for non-linear loads or RES and linear load. These equations calculate the total active power at the combined frequency:

$$\text{total active power}, P_T = P_1 - \sum P_h \tag{4.22}$$

$$P_T = P_1 + \sum P_h \tag{4.23}$$

Harmonic power (P_h), is obtained by Equation 4.24, where θ_h is voltage angle and $\emptyset_h$ is the current angle.

$$P_h = \sum_{h=1}^{\infty} V_h I_h \cos(\theta_h - \emptyset_h) \tag{4.24}$$

The harmonic order or characteristic harmonics (hch) that are part of the network depend on the size of the rectifiers. The rectifiers are based on the pulse number. For instance, the determination of the dominant harmonics for a 12-pulse rectifier is achieved by Equation 4.25.

$$h = (n \times p) \pm 1 \rightarrow n^{th} \,\&\, m^{th} \; harmonics \tag{4.25}$$

where n is integers (1, 2, 3, 4…) and p is the rectifier pulse number. Thus, the characteristic harmonics of the 12-pulse rectifier can be obtained using equation 4.25 as follows:

$$h = (1 \times 12) \pm 1 \rightarrow 11^{th} \,\&\, 13^{th} \; harmonics$$
$$h = (2 \times 12) \pm 1 \rightarrow 23^{th} \,\&\, 25^{th} \; harmonics$$
$$h = (3 \times 12) \pm 1 \rightarrow 35^{th} \,\&\, 37^{th} \; harmonics$$
$$h = (4 \times 12) \pm 1 \rightarrow 47^{th} \,\&\, 49^{th} \; harmonics$$
$$h = (n \times 12) \pm 1 \rightarrow n^{th} \,\&\, m^{th} \; harmonics$$

4.4.4. The direction of active power flow stages

The positive sign of the active power at harmonic frequency means the load is not a harmonic source and is absorbing harmonic power. The negative sign of the active power at the harmonic frequency means the load or utility is injecting the harmonics into the power system. It should be noted that any load or utility can have a negative harmonic power but it is not a dominant harmonic source of the network. The dominant harmonic source depends on the criteria as set in Figure 4.13. In the DIgSILENT simulation as well as measurement done by the Unipower power quality analyser, the %ITHD given is not per harmonic frequency but is for the combined harmonic frequency of the specific load. To gain a better understanding, the %HD changes as per the harmonic frequency and this indicates the dominant harmonic frequency of each load connected in the network. The distortion diagram gives the overview of the dominant harmonic frequency present at the PCC and this can be compared with the harmonic limit of specific standards such as IEEE 519 (2014), and IEC 61000–3–6 (2013). It is important to verify the distortion diagram to ensure the individual harmonic frequencies are within the limit as the total harmonic distortion at the PCC can be within the limit while the individual harmonic distortion exceeds the specified limit. Thus, it is possible also to have a lower harmonic frequency within the limit while the higher harmonic frequency like 21^{st}, 23^{rd}, 25^{th}, etc exceeds the limit. The power quality data obtained from the harmonic analysers should be understood and analysed to limit the effects of harmonics on the lead equipment such as transformers and induction machines. The three stages of modification of the practical and commercial harmonic source method based on the direction of active power flows are given in terms of the flowcharts:

i. identify the side of the harmonic source and quantify each side's contribution;

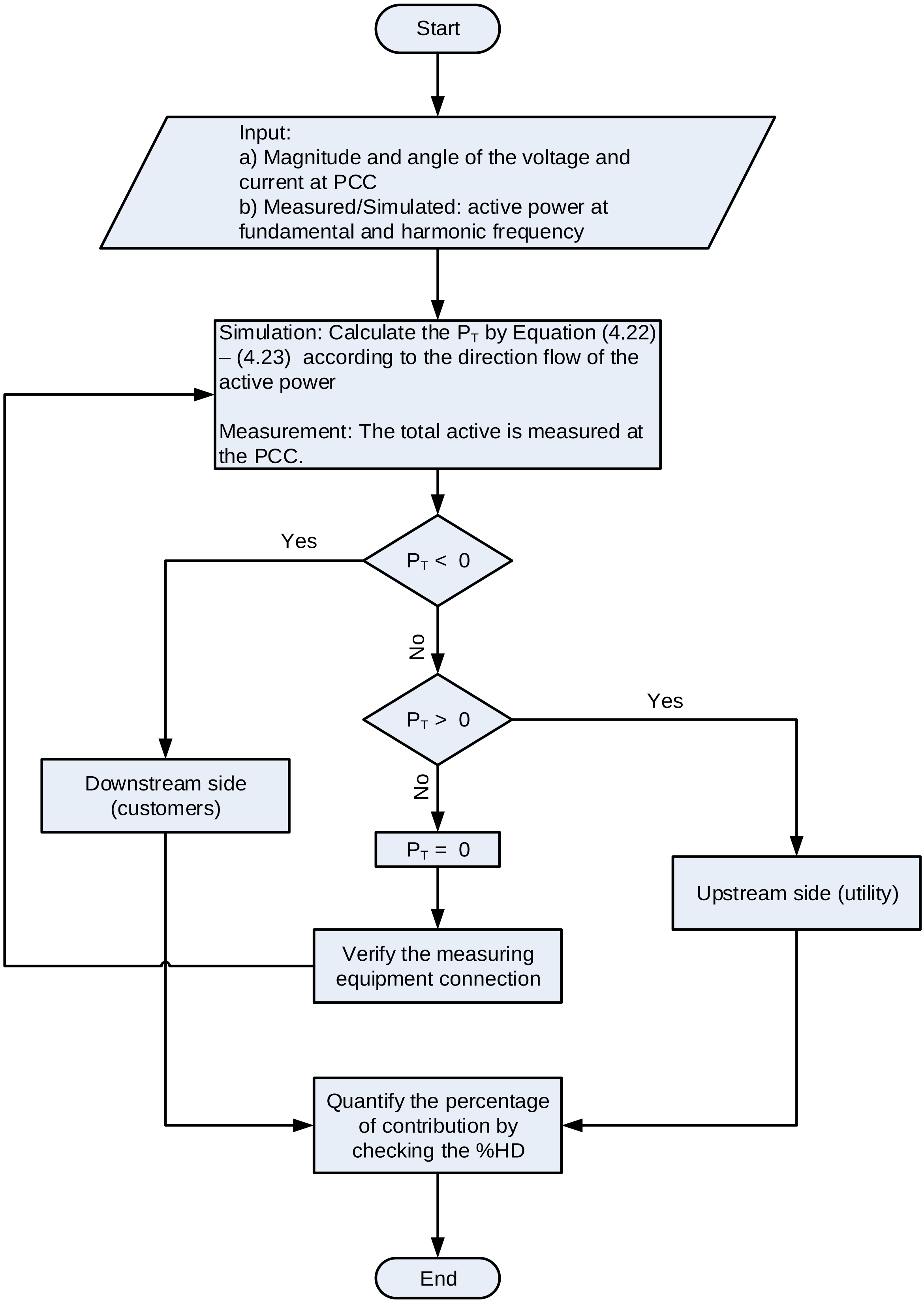


Figure 4.13: Flowchart to identify the network harmonic source side

The total active power at the combined frequency used in this flow chart should consider the sign in the calculations. This could give a completion of harmonic source detection when only one customer is connected at the PCC. In today's network, the next flowchart Figure 4.14 is important.

ii. Identify the contributor in case of the customer side and quantify each customer; and

There are multiple customers connected at the PCC, thus it is vital to identify which customer among them is a harmonic contributor.

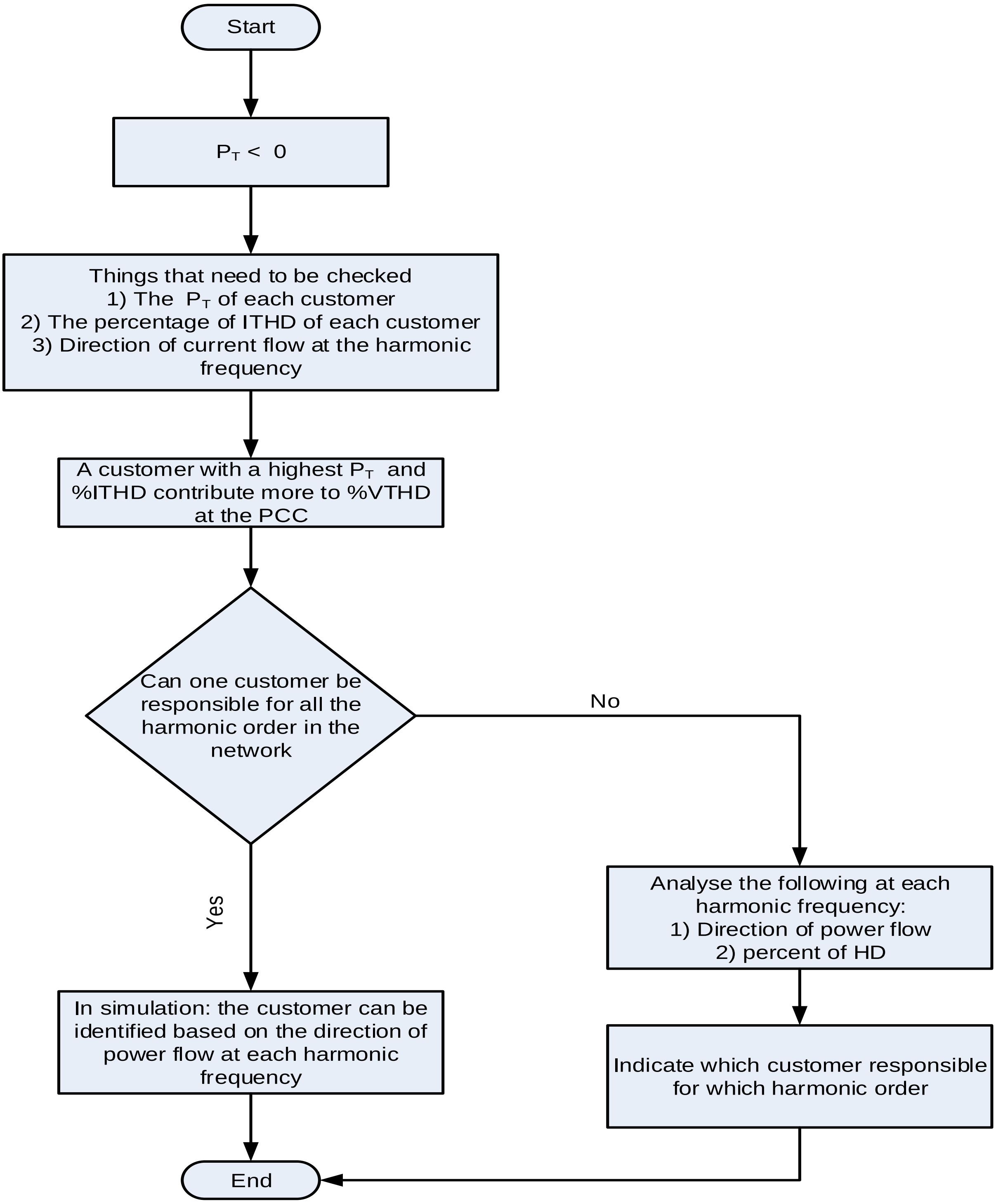


Figure 4.14: Flowchart to identify the harmonic contributor customer

iii. prove the dominant harmonic order of the contributor.

Harmonic distortion is mostly investigated based on the voltage total harmonic distortion at the PCC as specified in the standard. It is good to provide insight into the contribution of each harmonic frequency of the network for a better understanding of the effects network equipment might be faced with based on the dominant harmonic frequency that exists and forms part of the network. By identifying the dominant harmonic order that exceeds the specified limits, it gives an overview of harmonic mitigation required to minimize the percentage of individual harmonic distortion.

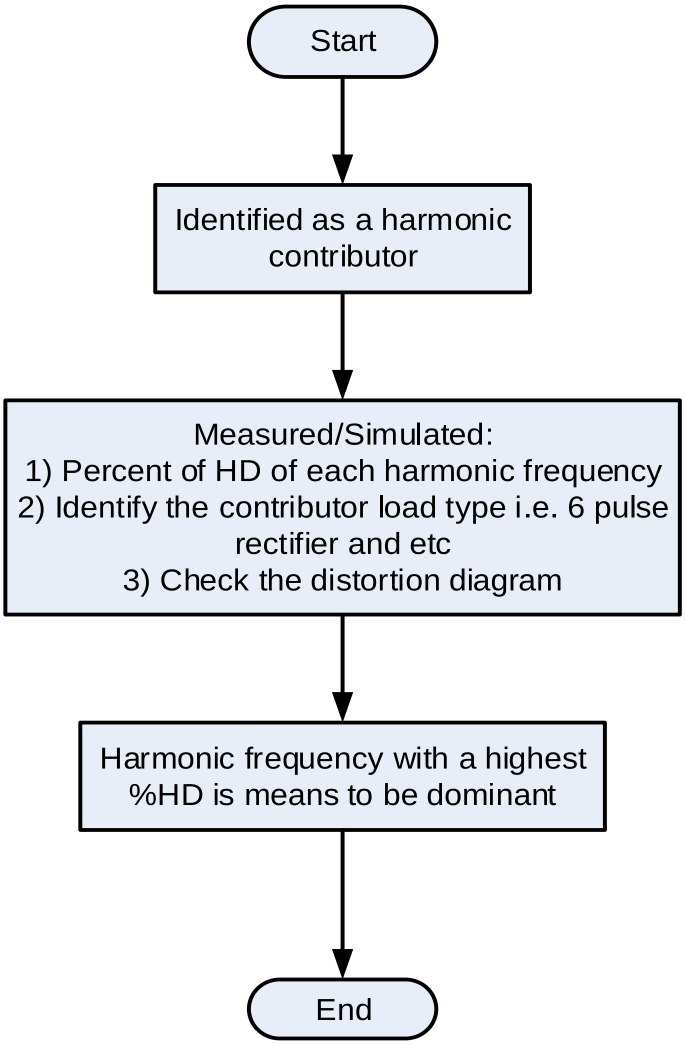


Figure 4.15: Flowchart to identify the dominant harmonic frequency

To determine the harmonic source, the meaning of active power is summarised in Table 4.2 – Table 4.3.

Table 4.2: Harmonic source meaning based on the total power at the PCC

	Equation	Sign	Harmonic source
Total Power	$P_{T\_Pcc} > 0$	Positive	utility
	$P_{T\_Pcc} < 0$	Negative	customer

Table 4.3: Harmonic source meaning based on the individual harmonic power at the PCC from the upstream and downstream of the network

	Equation		Sign	Harmonic source
Power of individual harmonic	Upstream	$P_{Pcc} > 0$	Positive	Customer
		$P_{Pcc} < 0$	Negative	Utility
	Downstream	$P_{Pcc} > 0$	Positive	utility
		$P_{Pcc} < 0$	Negative	Customer

The meaning of individual harmonic power for utility grid or RES and customer (load) is determined in Table 4.4–Table 4.5.

Table 4.4: Meaning of the individual harmonic power at the utility grid or RES

	Equation	Sign	Generating/Absorbing
Power of individual harmonic at the utility Grid or RES	$P_h > 0$	Positive	generating
	$P_h < 0$	Negative	absorbing

Table 4.5: Meaning of the individual harmonic power at the customer or load

	Equation	Sign	Generating/Absorbing
Power of individual harmonic at the customer or load	$P_h > 0$	Positive	absorbing
	$P_h < 0$	Negative	generating

4.5. Summary

This chapter began with the Norton and Thevenin equivalent circuits that are known and widely used in the engineering field for circuit analysis. These equivalent circuits have been used by most researchers for harmonic source detection studies by using the superposition theorem. The existing and known equivalent circuits do not represent power systems today as they have multiple customers connected at the PCC. The existing equivalent circuits were adapted in a mathematical model to represent the practical power system. The adapted equivalent circuits could be used for engineering circuit analysis and it is not recommended to be used for harmonic source detection because of assumptions of the harmonic impedance of the utility and customers. The harmonic impedance is not constant and cannot give correct information regarding the determination of the dominant harmonic source. There are two main processes for harmonic source detection which were described as follows: firstly, for all new applications to the utility for electricity supply, the developed harmonic monitoring management system should be used. Secondly, for existing customers with limited power quality criteria as part of the ESA, the three developed criteria for the modification of harmonic source detection methods based on the direction of active power flow should be applied. Case studies will be developed in Chapter 5 to validate the developed methodology.

CHAPTER 5: MODELLING OF POWER SYSTEM EQUIPMENT IN DIgSILENT

5.1. Introduction

This is an overview of the different electrical network equipment, as they are modelled in DIgSILENT PowerFactory. The equipment data were given to enable the repetition of the case studies in the future. The mathematical model of certain equipment is highlighted. A comparison of the benchmark IEEE PES test system with and without RES is described.

5.2. DIgSILENT

The DIgSILENT software package was used for simulation investigations and to demonstrate the effectiveness of the modified method developed for harmonic source detection at the PCC where multiple customers are connected. DIgSILENT has a one-line integrated graphic user interface It comprises the network drawing functions, modelling, and features enabling power system analyses to be conducted. This software package can show the direction of active power, and generate results of certain parameters at different frequencies. It can conduct the load flow, harmonics, and dynamic analysis as well as motor starting, to mention a few of its capabilities. Thus, it is an effective software package that most commercial industries use and it is best for harmonic source detection as it gives the individual and total harmonic distortion of the current and voltage at different points in the network.

5.3. Case studies

Three main case studies are modelled with different scenarios to validate the mathematical model and modified harmonic source detection framework given in Chapter 4.

5.3.1. Benchmark IEEE PES test system

This network was simulated in PSCAD as described in a journal article by Papic et al. (2019) and is adapted in DIgSILENT. There were differences in modelling, thus the equipment modelling was explained in detail in Table 5.1. Three case studies were simulated as shown in Table 5.1 and the source of harmonics was identified and its contribution quantified. Lastly, case study C as given in Table 5.1 was simulated besides the use of renewable energy sources. The RES used was a 5 MW Wind turbine generator connected at MV and a 1MW solar PV at LV 3.

Table 5.1: Parameters of the three case studies

The element of the network	Case study A	Case study B	Case study C
Customer 1 (PCC 1)			
Thyristor rectifier 1 (harmonic source)	Alpha order: $\alpha = 12°$, $L_{coup} = 0.1$ mH, $R_{DC} = 1.0\ \Omega$	Alpha order: $\alpha = 12°$, $L_{coup} = 0.1$ mH, $R_{DC} = 1.0\ \Omega$	Alpha order: $\alpha = 12°$, $L_{coup} = 0.1$ mH, $R_{DC} = 1.0\ \Omega$
Capacitor bank	ON, $C_{LV} = 1407.493\mu F$ ($Q = 0.234$ MVAr) C_{LV} delta connected	ON, $C_{LV} = 1407.493\mu F$ ($Q = 0.234$ MVAr) C_{LV} delta connected	ON, $C_{LV} = 1431.553\mu F$ ($Q = 0.238$ MVAr) C_{LV} delta connected
Power factor (PF) at the PCC 1	$PF = 0.981$	$PF = 0.981$	$PF = 0.982$
Customer 2 (PCC 2)			
Thyristor rectifier 2 (harmonic source)	OFF	OFF	Alpha order: $\alpha = 12°$, $L_{coup} = 0.1$ mH, $R_{DC} = 1.0\ \Omega$
Linear load	OFF	OFF	$R_{L3} = 1\ \Omega$ $L_{L3} = 0.01H$ $P = 160$ kW $Q = 51$ kVAr
Capacitor bank	OFF	OFF	ON, $C_{PHF} = 1016.446\mu F$ $L_{PHF} = 0.451mH$ $R_{PHF} = 0.0067\Omega$ ($Q = 0.177$ MVAr) C_{PHF} delta connected
Power factor (PF) at the PCC 2	/	/	0.993
Customer 3 (PCC 3)			
Induction motor	Terminal IM voltage (L2- L1): $U = 408.33\ V$, $\varphi = 25.72°$ $P = 200kW$ $Q = 96\ kVAr$ $(PF = 0.9)$	Terminal IM voltage (L2- L1): $U = 393.95\ V$, $\varphi = 21.94°$ $P = 600kW$ $Q = 291\ kVAr$ $(PF = 0.9)$	Terminal IM voltage (L2 - L1): $U = 411.10\ V$, $\varphi = 25.58°$ $P = 200kW$ $Q = 96\ kVAr$ $(PF = 0.9)$
Capacitor bank	ON, $C_{LV} = 336.836\mu F$ ($Q = 0.056$ MVAr) C_{LV} delta connected	ON, $C_{LV} = 980.433\mu F$ ($Q = 0.163$ MVAr) C_{LV} delta connected	ON, $C_{LV} = 330.8216\mu F$ ($Q = 0.055$ MVAr) C_{LV} delta connected
Power factor (PF) at the PCC 3	$PF = 0.969$	$PF = 0.947$	$PF = 0.970$
Equivalent load			
Linear load	$R_{MV} = 180\ \Omega$ $L_{MV} = 2H$ $P = 7.15$ MW $Q = 2.09MVAr$	$R_{MV} = 180\ \Omega$ $L_{MV} = 2H$ $P = 7.13$ MW $Q = 2.08MVAr$	$R_{MV} = 180\ \Omega$, $L_{MV} = 2H$ $P = 7.24$ MW, $Q = 2.11$ MVAr
MV capacitor bank			
Capacitor bank	OFF	OFF	ON, $C_{MV} = 8.75\mu F$ ($Q = 1.21$ MVAr), star connected $L_{CMV} = 0.5mH$ $-$inrush reactor $R_{CMV} = 0.3638\ \Omega$
HV/MV transformer			
Conditions on the MV side of the transformer	$P = 7.56\ MW$ $Q = 2.14\ MVAr$ $PF = 0.962$	$P = 7.95\ MW$ $Q = 2.29\ MVAr$ $PF = 0.961$	$P = 8.09\ MW$ $Q = 1.02\ MVAr$ $PF = 0.992$

To maintain the power factor at the PCC, the following formula is used for the power factor correction. This value is indicated under the capacitor bank per customer as indicated in Table 5.1.

$$Q = P(\tan\delta - \tan\varphi) \tag{5.1}$$

Where Q is the value of the capacitor bank to be used for the power factor correction, P is the input power at the transformer that feeds the specific PCC,

δ is the $\cos^{-1}(\text{PF which is at that busbar before PFC})$, and
φ is the $\cos^{-1}(\text{PF which need to be part of the busbar})$.

To model the equivalent MV load with resistance and inductance, in DIgSILENT a different mathematical calculation is used as follows:

i. the active (P) and reactive (Q) power are known
ii. determine the apparent power (S) as $S = \sqrt{P^2 + Q^2}$ (5.2)
iii. determine the PF: $PF = \frac{P}{S}$ (5.3)
iv. determine the base impedance: $Z_{base} = \frac{kV^2}{MVA_{3\emptyset}}$ (5.4)
v. determine impedance in ohms, as it is indicated that it comprises parallel resistance and inductor in the delta connection:

$$Z_{parallel(\Omega)} = \frac{1}{\frac{1}{Z_R}+\frac{1}{Z_L}} \tag{5.5}$$

vi. determine the impedance in per unit: $Z_{p.u.} = \frac{Z_\Omega}{Z_{base}}$ (5.6)

To control and maintain the active and reactive power as well as the power factor of the transformer MV side can be achieved using the static generator for reactive power compensation as a plant category.

To control the terminal voltage (L2-L1) and its angle of the induction motor, this can be achieved by setting the angle as shown in Figure 5.1.

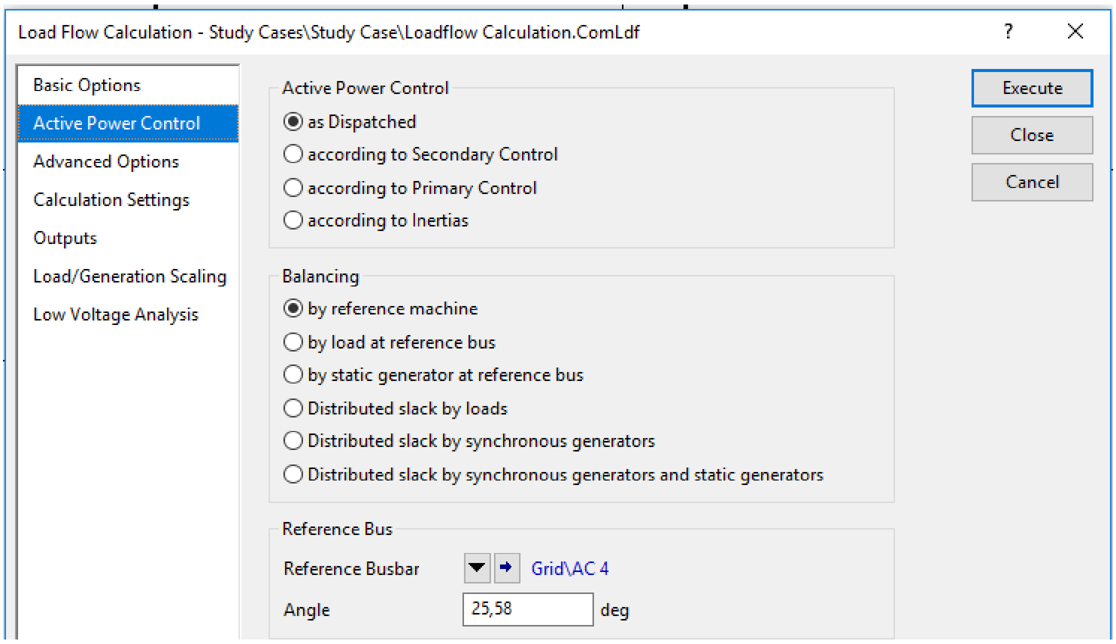


Figure 5.1: Control for the induction motor terminal angle

Figure 5.2 indicated the 110 kV grid with the short-circuit power of $S_{sc} = 3200\,\text{MVA}$ with X/R the ratio of 10. The voltage of the grid was set to 1 p.u. The transformer and line data were stipulated in Appendix B in Table B.1 and Table B.2 respectively. The HV/MV transformer TR4 was grounded on the MV side using an 80 Ω resistor for the limitation of single-phase fault currents. The background harmonic spectrum used is given by IEEE PES as provided in Appendix B in Table B.3. Table B.4 gave the voltage level of the busbars and terminals.

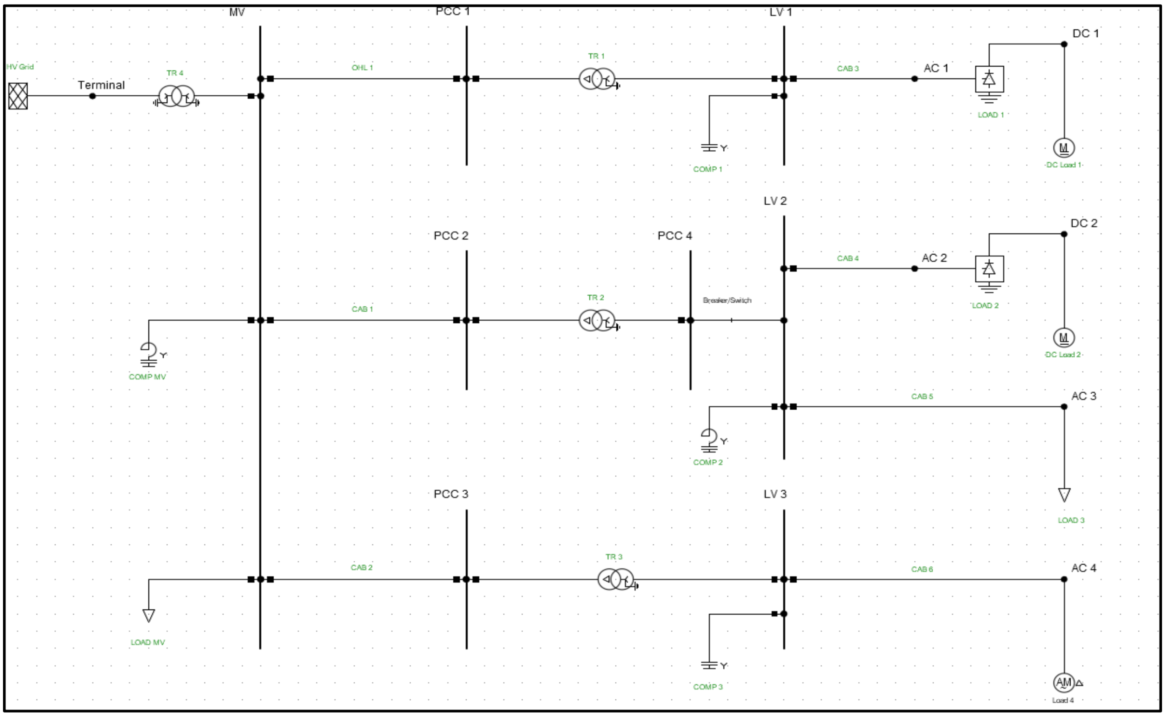


Figure 5.2: Benchmark IEEE PES test system

5.3.1.1. Wind turbine generator modelling

A three-phase 5MW Wind turbine generator was modelled with a nominal apparent power rating of 5.556MVA and a power factor of 0.9. The wind turbine was connected at the 0.4kV LV wind busbar and supplied by a 5.6 MVA 20/0.4kV transformer with a Dyn5 vector group. This transformer had a positive sequence and zero sequence impedance of 6% and 3% respectively. It had copper losses of 5.6kW. The wind generator was connected at this point as the network was tested for the overloading of cables and transformers. The harmonic spectrum of the model should be made available for better results of the harmonic distortion. In this case, the wind turbine generator was modelled without the harmonic spectrum as the model was obtained from the DIgSILENT library. However, the model had the fully rated converter control for the following: Wind Turbine Generator (WTG) 5MW, slow frequency measurement, PQ controller, PQ LV, voltage measurement, current controller, current measurement, phase-locked loop (PLL), and over frequency power reduction. The schematic diagram of the wind turbine generator was indicated in Figure 5.3. A built-in model was used for this research, which is a standard electrical component model that already exists in the DIgSILENT library.

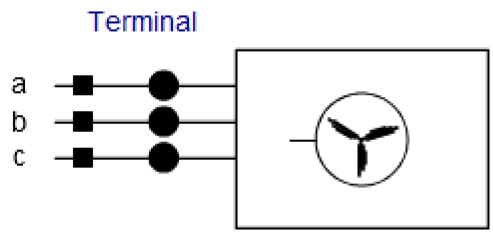


Figure 5.3: Schematic diagram of the wind turbine generator

The composite frame model of the *FullyRatedConv Control* WTG is given in Figure 5.4. To ensure that the measuring devices are connected correctly, the measurement devices were connected either to the terminal or to the cubicle that connects the generator to the terminal. The frame description of the *FullyRatedConv Control* WTG was to reduce the power; in case of electrical over frequency, the active power reduction slot was used. PLL, PQ, Vac, and Iac are for fast voltage angle, active and reactive power, and current and AC voltage measuring devices respectively. For over frequency power reduction, the Slow FrequMeas was used to measure the frequency. The current controller and PQ control were used to calculate from current reference a voltage signal for the static generator and to control the active and reactive power via the rotor current.

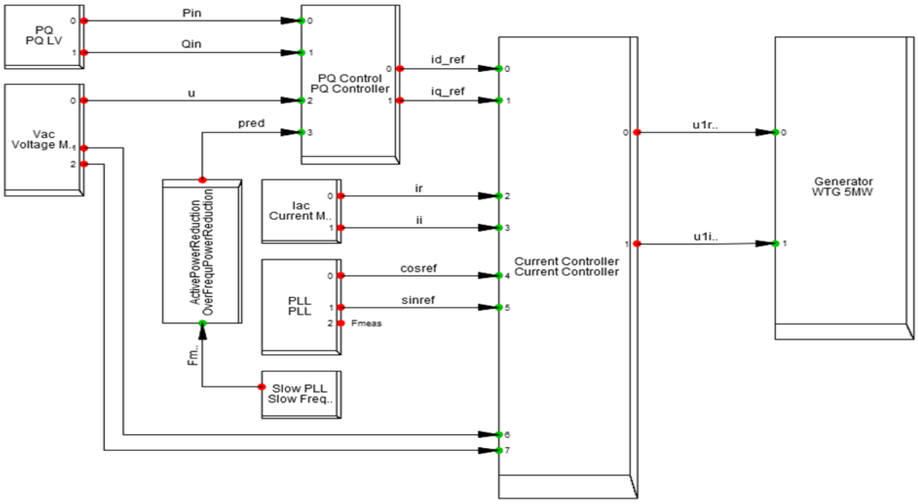


Figure 5.4: Composite Frame of the *FullyRatedConv Control* WTG

Certain parameters can be changed to adapt the model such as the number of parallel machines, the nominal power required, and nominal AC voltage. It was possible to customise the model. To change the active power reduction during over frequency six parameters need to be changed: frequency which triggers the active power reduction, the frequency which ends the active power reduction, the gradient of the active power reduction, PT1 filter for frequency measurement, gradient limitation for active power reduction, and gradient limitation for active power increase. The over-frequency power reduction was a control that uses the frame-block shown in Figure 5.5.

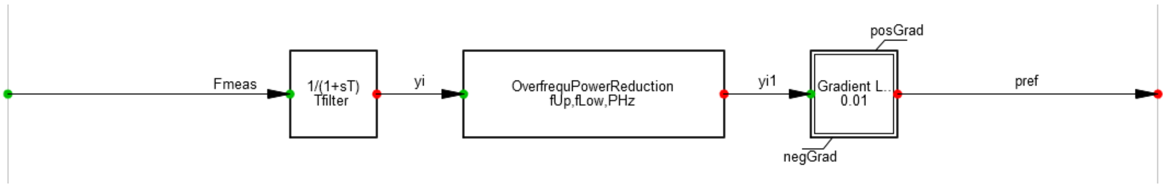


Figure 5.5: Over Frequency Power Reduction Control

The active and reactive power control and current controller were done based on the frame shown in Figure 5.6 and Figure 5.7. These blocks were part of the model in the DIgSILENT.

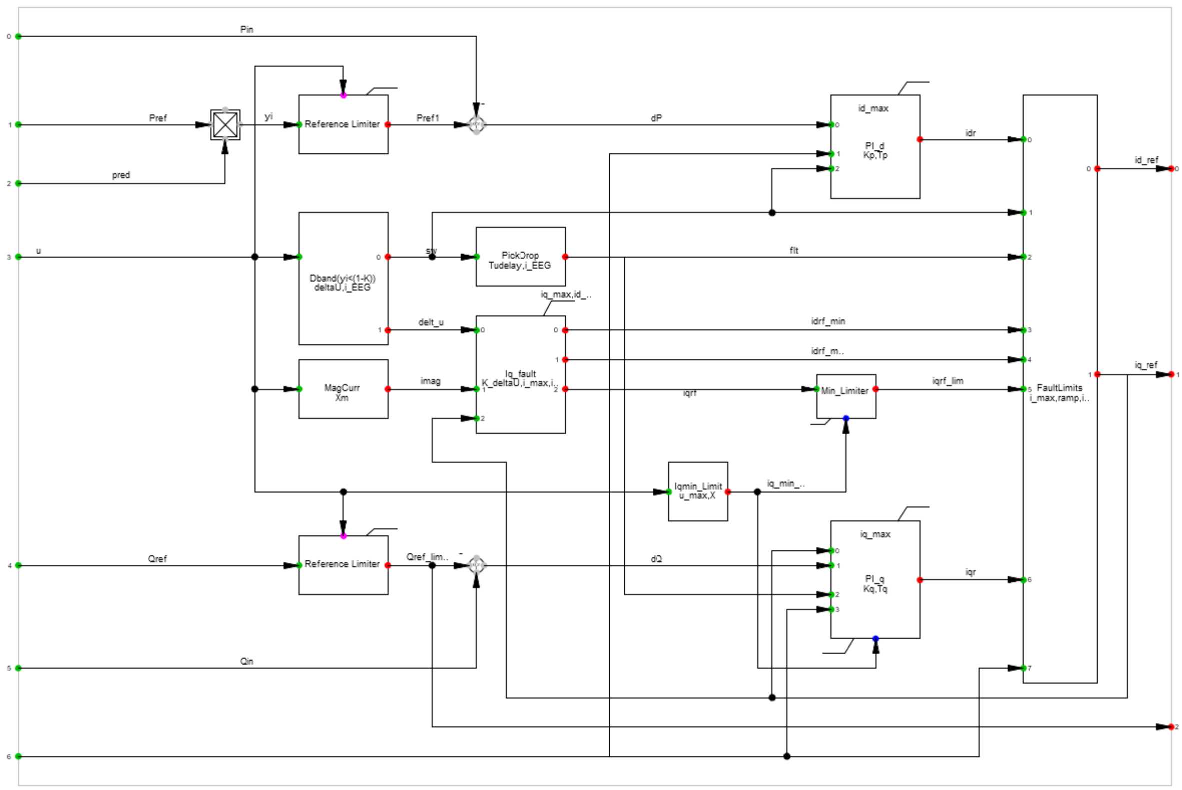


Figure 5.6: PQ control frame

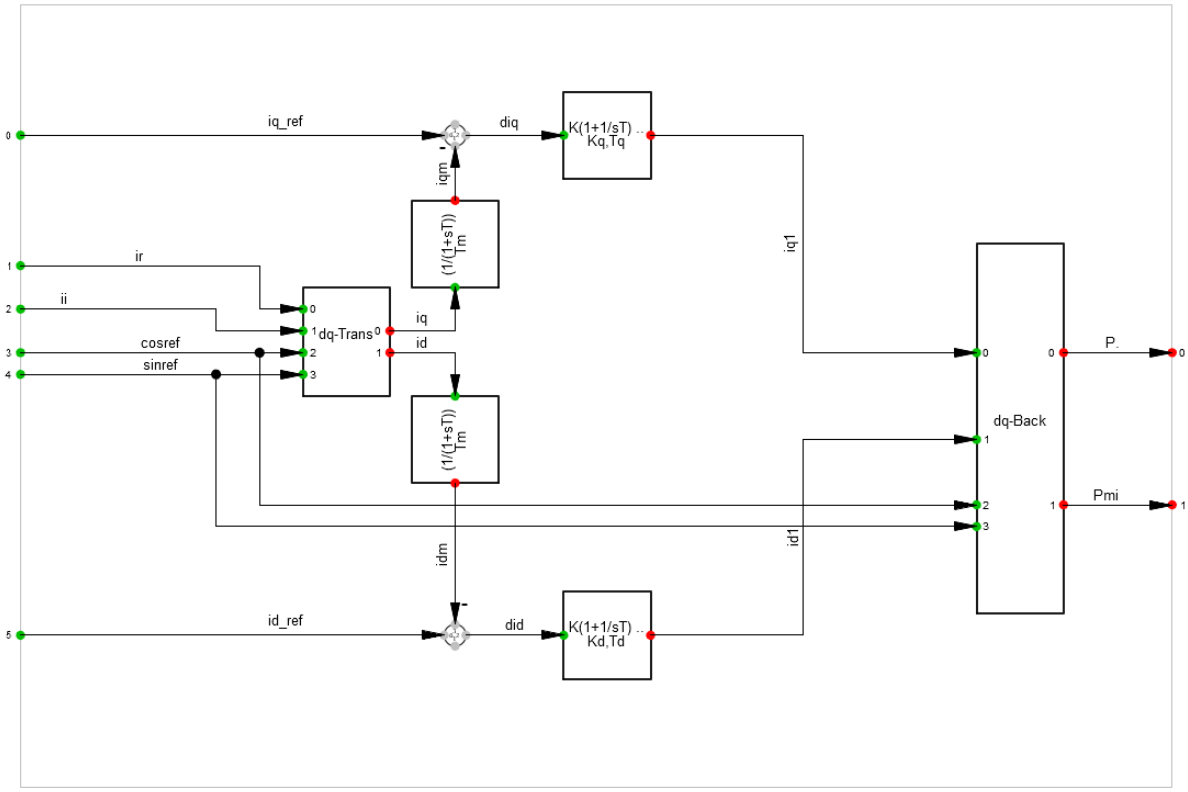


Figure 5.7: Current controller frame

There were some wind turbine generator models available in DIgSILENT such as Double Fed Induction Generator (DFIG), FullyRatedConv WTG, VarRotor Resist WTG, IEC 61400-

27-1 WT Type, and WECC WTG Type. The model selected to be incorporated in this model was the FullyRatedConv WTG.

5.3.1.2. Solar PV farm modelling

A 1 MW solar PV farm that was connected at LV 3 busbar was a three-phase photovoltaic system with a nominal apparent power of 1111 kVA and a power factor of 0.9. The schematic diagram of the solar PV is shown in Figure 5.8.

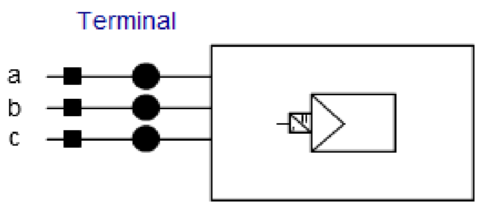


Figure 5.8: Schematic diagram of the solar PV

The composite frame of the solar PV is given in Figure 5.9. The following slots were considered to be part of the model. For example, the static generator, the photovoltaic model for the PV array, DC busbar and capacitor model and its controller, power measurement for active and reactive power, AC voltage for measurement, PLL for phase measurement, active power reduction, slow frequency measurement, solar radiation, temperature, and measurement of solar radiation and temperature.

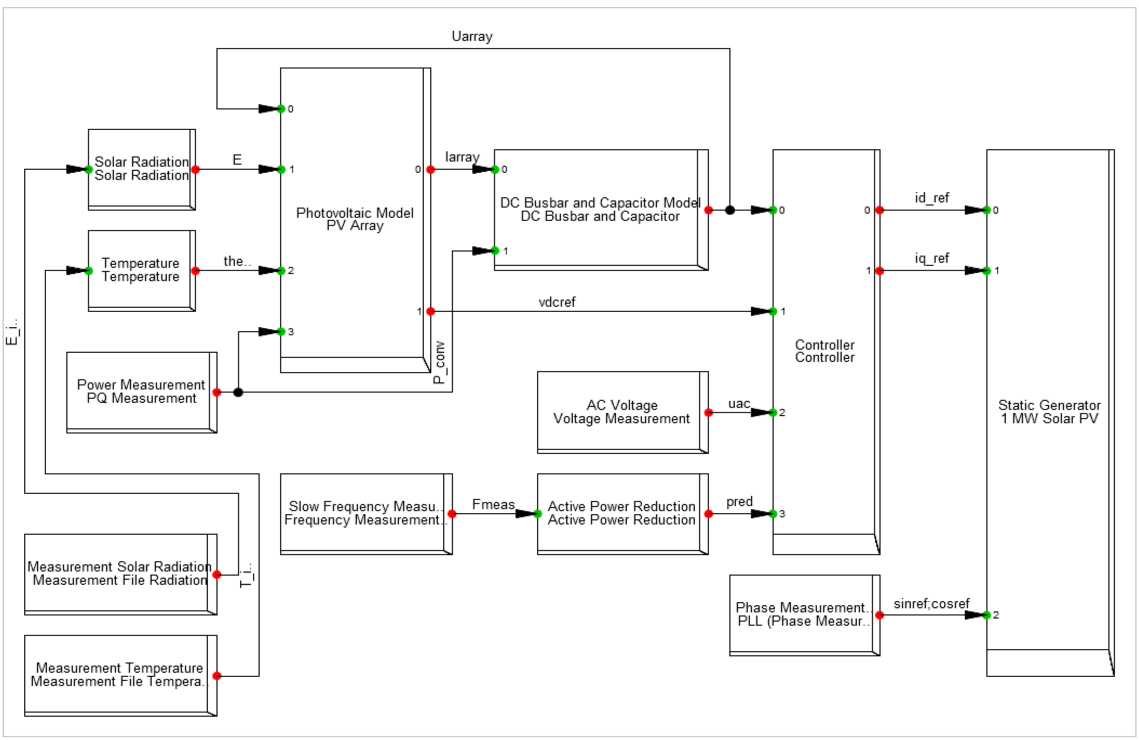


Figure 5.9: Composite frame of the PV system

The PV active power reduction and its controller frames were given in Figure 5.10 and Figure 5.11.

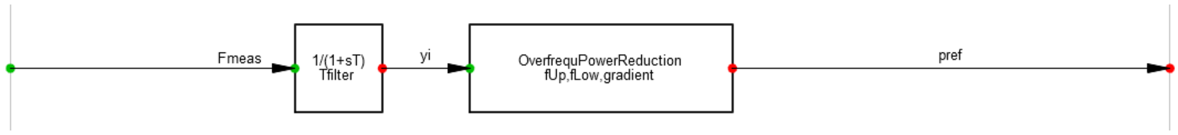


Figure 5.10: Active power reduction of the Photovoltaic

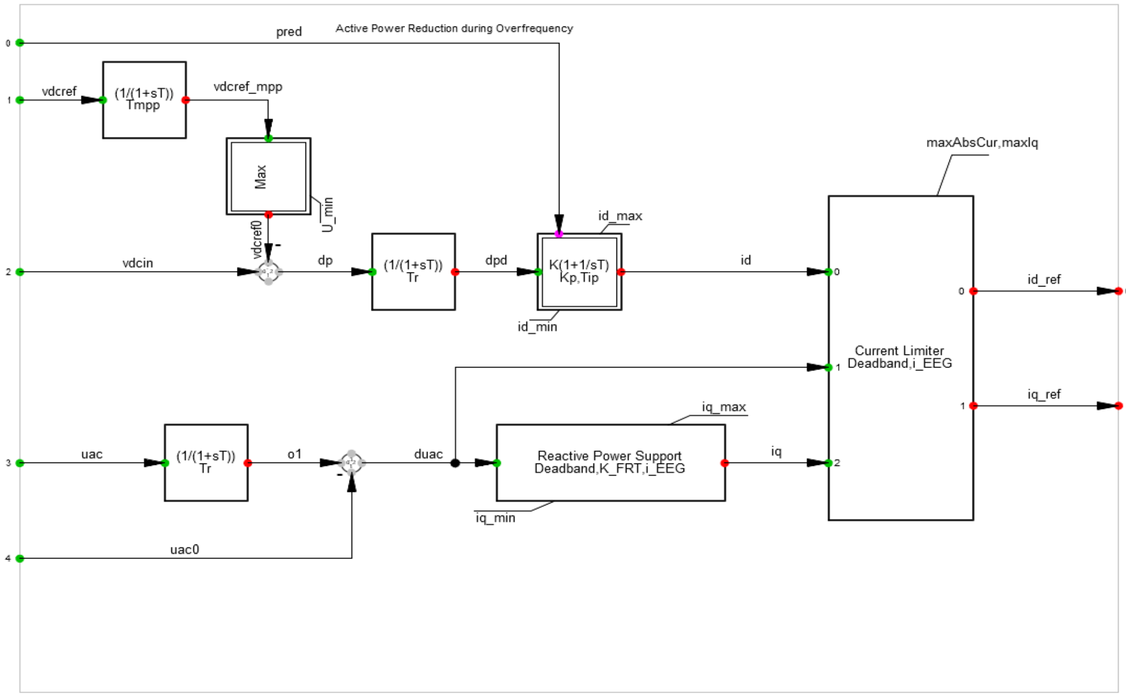


Figure 5.11: Controller for active power reduction

For the DC busbar and capacitor, the model shown in Figure 5.12 is used to measure the DC current. The input and output of the PV array were given in Figure 5.13.

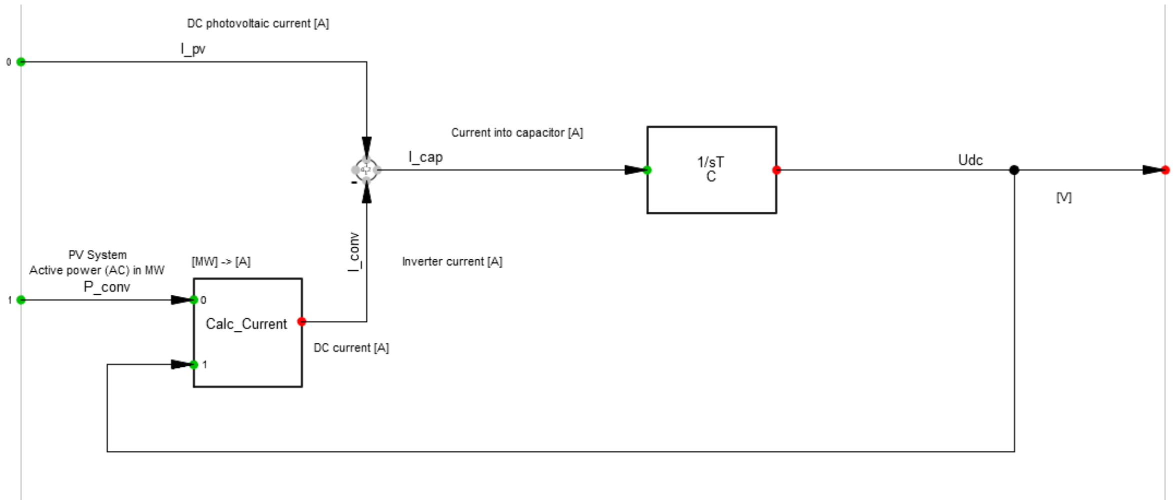


Figure 5.12: Model for the DC busbar and capacitor for the PV

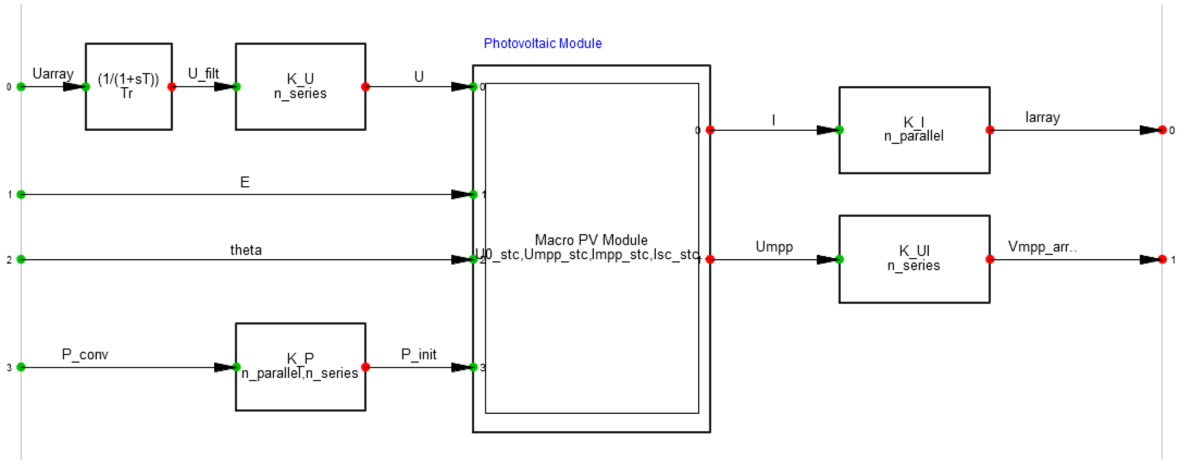


Figure 5.13: The input and output of the PV module Array

5.3.2. The radial distribution network for new adapted equivalent circuits

The radial distribution network shown in Figure 5.14 is modelled in DIgSILENT to give the difference used for representing the customer at the point of common coupling.

This network consists of an 11 kV voltage source with a step-down transformer (TR 1) stepping from 11 kV Bus 1 to 0.4 kV Bus 2. There were three customers connected to the PCC (Bus 2). The features of these customers were summarised in Table 5.2

Table 5.2: Technical data of the different customers

Customer	Technical data
Customer A	Linear load (impedance model 1) $S = 2\ MVA$ $PF = 0.8$
Customer B	Three-phase 6-pulse diode rectifier connected at the DC machine $Rated\ AC\ voltage = 0.42\ kV$ $Rated\ DC\ voltage = 0.55\ kV$ $Rated\ Active\ power = 0.55\ MW$ DC machine has: $Rated\ mechanical\ power = 4000\ kW$ $Nominal\ speed = 1200\ rpm$ $Efficiency = 90\ \%$ $Separately\ excited\ machines$
Customer C	Three-phase solar PV $Nominal\ apparent\ power = 1134\ kVA$ $Number\ of\ parallel\ inverter = 2$

These customers in Figure 5.14 have different operating conditions. For example, customer B and customer C were modelled as a harmonic source whereas customer A was a normal linear load with impedance. The six-pulse rectifier was modelled with an idealised six-pulse-bridge harmonic spectrum with a maximum harmonic order of 31. The voltage source and solar PV were modelled with an ideal voltage and current harmonic spectrum respectively.

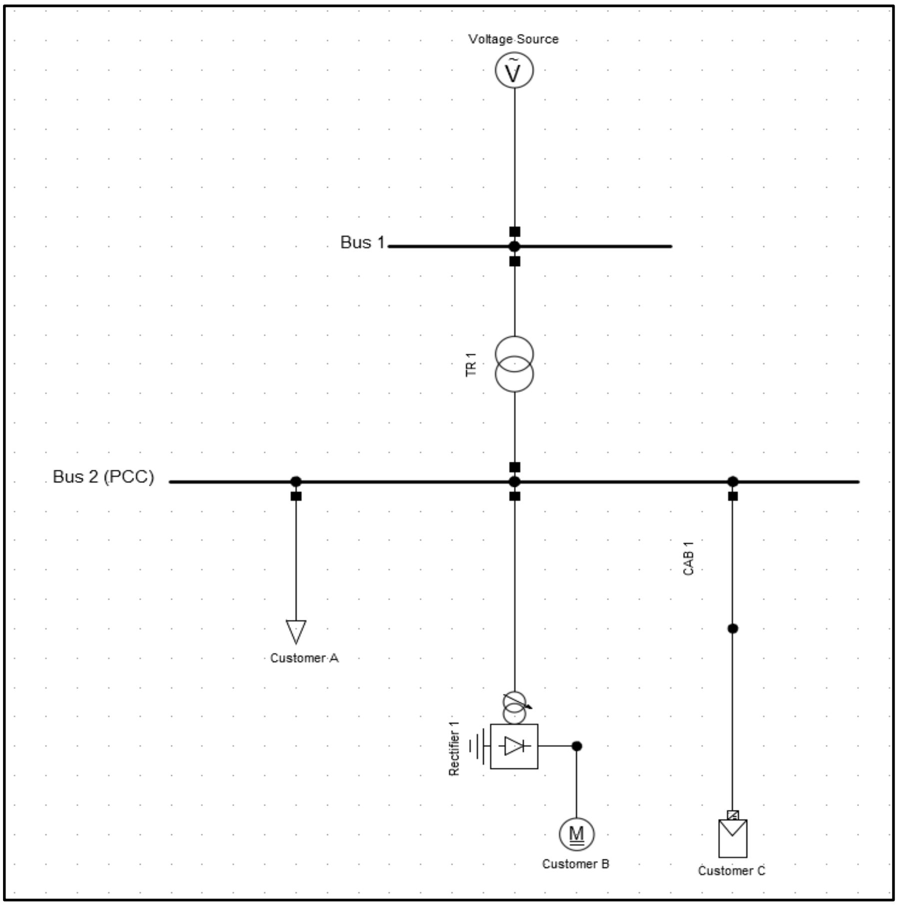


Figure 5.14: Radial distribution network

5.3.3. Industrial network

This was an industrial network consisting of two zinc mining industries, 5 MW solar PV, and different commercial loads. Figure B.1 under Appendix B indicates the 400kV slack bus with short-circuit power of $S_{sc} = 10\,000\ \mathrm{MVA}$, short-circuit current of $S_{sc} = 14.43\ \mathrm{kA}$ and $\mathrm{X/R}$ the ratio of 10. The voltage of the grid was set to 1 p.u. The frequency dependencies for the resistance and reactance of the positive sequence components were obtained through conducting a frequency sweep or frequency scan. This parameter was part of the grid model. The transformers, lines, cables, and load data were stipulated in Appendix B in Table B.5, Table B.6, Table B.7, and Table B.8 respectively.

5.3.3.1. Transformer modelling

The data used in modelling were as per transformers at the site and this information was gathered during a data collection phase in August 2018. The Obib TR 1 & 2 and the rectifier transformers were three-winding transformers and the rest of the transformers within the network were two winding transformers. In the network modelled the two and three-winding transformers were three-phase.

5.3.3.1.1. Three-winding transformers

The three-winding transformers were modelled according to the DIgSILENT positive-sequence model of a 3-winding transformer, with the taps modelled at the star point as indicated in Figure 5.15.

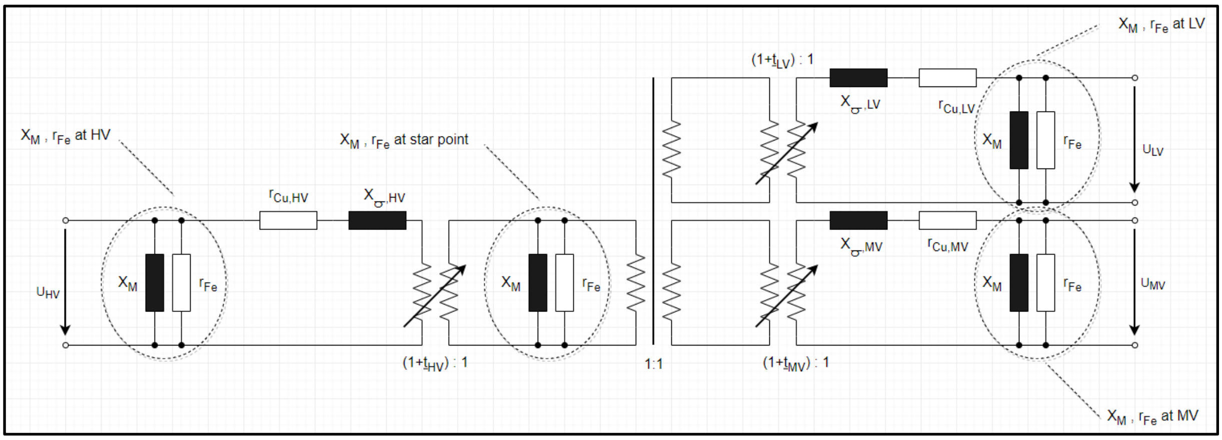


Figure 5.15: Positive sequence three-winding transformer model with tap modelled at the star point

Where: X_M and r_{Fe} are magnetisation reactance and the iron loss resistance respectively at all three windings HV, MV and LV. r_{Cu} and X_σ are HV, MV and LV copper resistance and leakage reactance respectively.

The positive and negative sequences were modelled the same in DIgSILENT, except the zero sequence. This network consists of transformers with different vector groups, namely YNynd1, Yynyn6, and Dyn1yn7. Its drawing model is given in Figure B. 2–Figure B. 4. The magnetising impedance was neglected when the transformer had delta winding because in a practical situation this impedance was short-circuited by the delta winding impedance.

5.3.3.1.2. Two-winding transformers

The two-winding transformers in the network have a vector group of YNd or Dyn. The positive/negative sequence model of the two-winding three-phase transformer was indicated in Figure 5.16. The magnetising current of a zero sequence depends on the size of the physical characteristics of the transformer core and its vector group. The model for the zero-sequence equivalent circuit was represented in Figure 5.17.

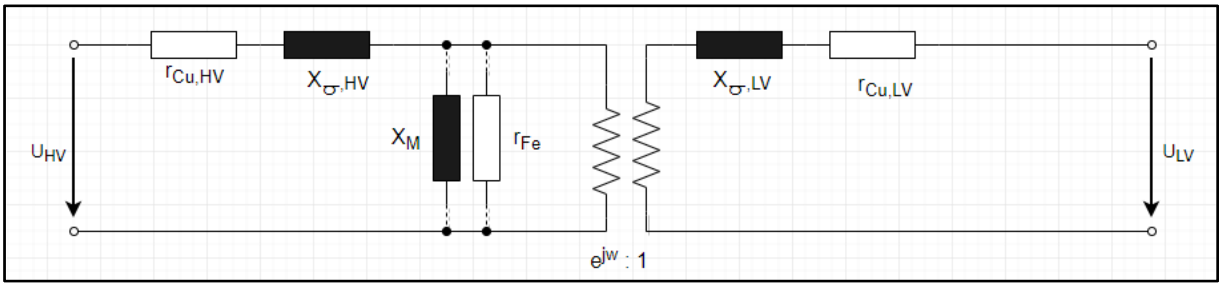


Figure 5.16: Positive sequence (per-unit) equivalent circuit of the two-winding transformer

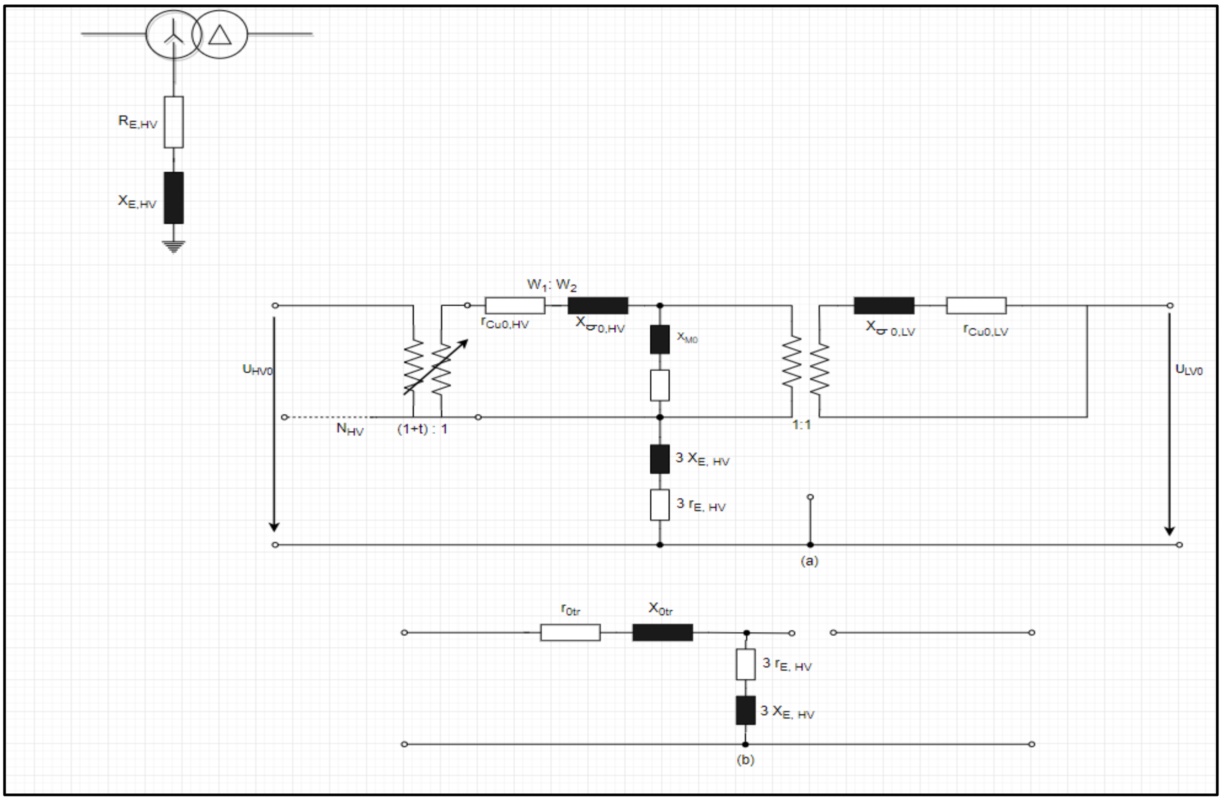


Figure 5.17: Zero sequence equivalent circuit of a Yd-transformer with HV side tap changer
(a) detailed representation (b) simplified representation

5.3.3.2. Overhead lines

The three-phase aluminum conductor with neutral was modelled as a lumped parameter (PI) and as a solid conductor with its matrix of resistance and reactance per phase. The number of earth wires depends on the conductor type. The geometrical parameters were used as input mode. The conductor type of the line circuit and earth were modelled as Figure 5.18 and Figure 5.19 respectively. The parameter used to model such as the nominal current, bundle spacing, DC resistance at 20 ˚C, GMR, etc. were obtained from the technical datasheet for Pelican conductor. The other aluminum conductor used in this network was a Hare, which was modelled as a three-phase line.

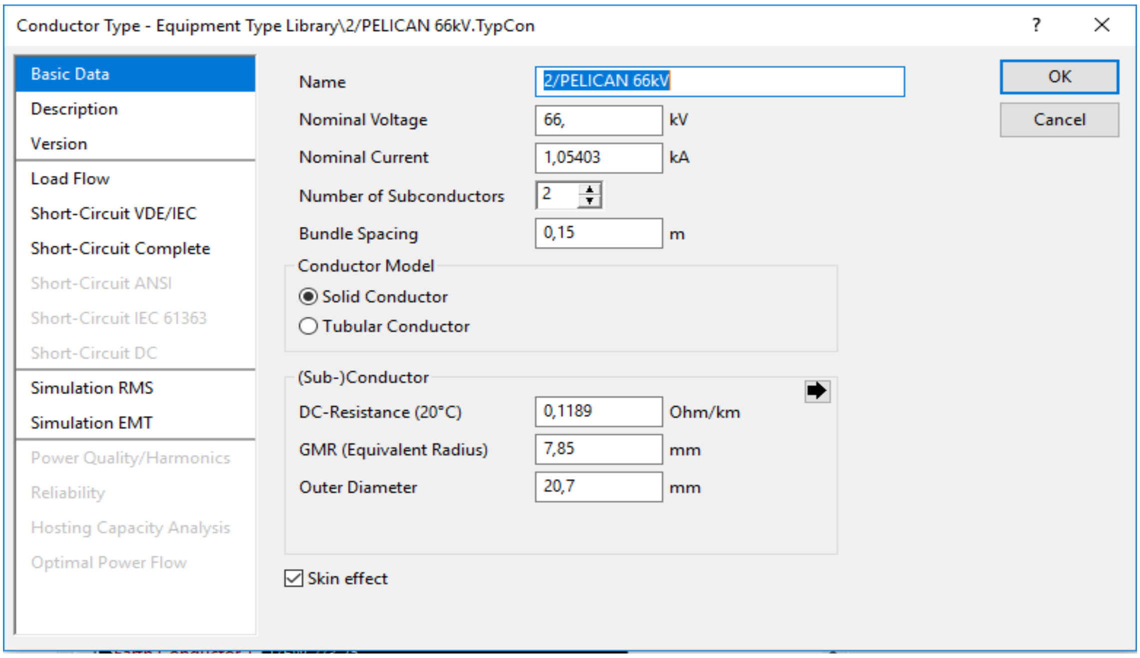


Figure 5.18: Three-phase line conductor type data

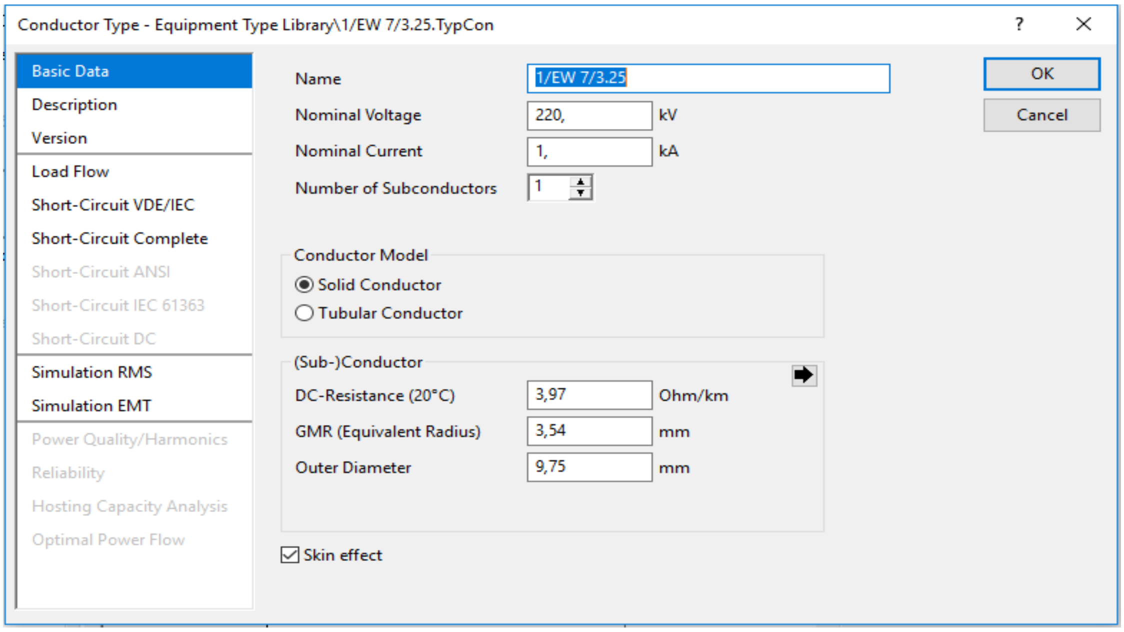


Figure 5.19: Three-phase earth conductor type data

To obtain the nominal voltage of the earth wire/conductor as shown in Figure 5.19, the following formula was used:

$$V_{rated} = \frac{V_{HV(TR)}}{\sqrt{3}} \tag{5.7}$$

The Pelican conductor was modelled using a three-phase four-wire system and earth, the three-phase line, neutral and earth conductor as stipulated in Figure 5.20. This showed that at the utility the earth/neutral conductor was at zero potential whereas on the customer side (load) the earth/neutral conductor was separated to allow the return path to the ground.

$$\underline{Z}_{RWBN} = \begin{bmatrix} \underline{Z}_s & \underline{Z}_m & \underline{Z}_m & \underline{Z}_{pn} \\ \underline{Z}_m & \underline{Z}_s & \underline{Z}_m & \underline{Z}_{pn} \\ \underline{Z}_m & \underline{Z}_m & \underline{Z}_s & \underline{Z}_{pn} \\ \underline{Z}_{pn} & \underline{Z}_{pn} & \underline{Z}_{pn} & \underline{Z}_n \end{bmatrix} \tag{5.8}$$

$$\underline{Y}_{RWBN} = \begin{bmatrix} \underline{Y}_s & \underline{Y}_m & Y_m & Y_{pn} \\ \underline{Y}_m & \underline{Y}_s & Y_m & \underline{Y}_{pn} \\ Y_m & \underline{Y}_m & \underline{Y}_s & \underline{Y}_{pn} \\ \underline{Y}_{pn} & \underline{Y}_{pn} & \underline{Y}_{pn} & \underline{Y}_n \end{bmatrix} \tag{5.9}$$

Where: admittance is the inverse of impedance; $\underline{Z}_s$ and $\underline{Y}_s$ are the sum of the impedance value connected to the corresponding phase; the inverse of $\underline{Z}_s$. $\underline{Z}_m$ is the impedance value between the two phases; $\underline{Z}_{pn}$ is the impedance between the phase and neutral conductors; and $\underline{Z}_n$ is the impedance value of a neutral conductor.

$$\underline{Z}_s = \frac{1}{3}\left(\underline{Z}_0 + 2\left(\underline{Z}_1\right)\right) \tag{5.10}$$

Where: $\underline{Z}_0$ zero sequence impedance and $\underline{Z}_1$ positive sequence impedance. The positive sequence should be multiplied by two because the positive and negative sequence impedance value was the same.

$$\underline{Z}_m = \frac{1}{3}\left(\underline{Z}_0 - \underline{Z}_1\right) \tag{5.11}$$

In this model the zero and positive sequence, impedance is given in terms of resistance and reactance at each phase. For instance, the positive sequence impedance:

$$\underline{Z}_1 = R + jX \tag{5.12}$$

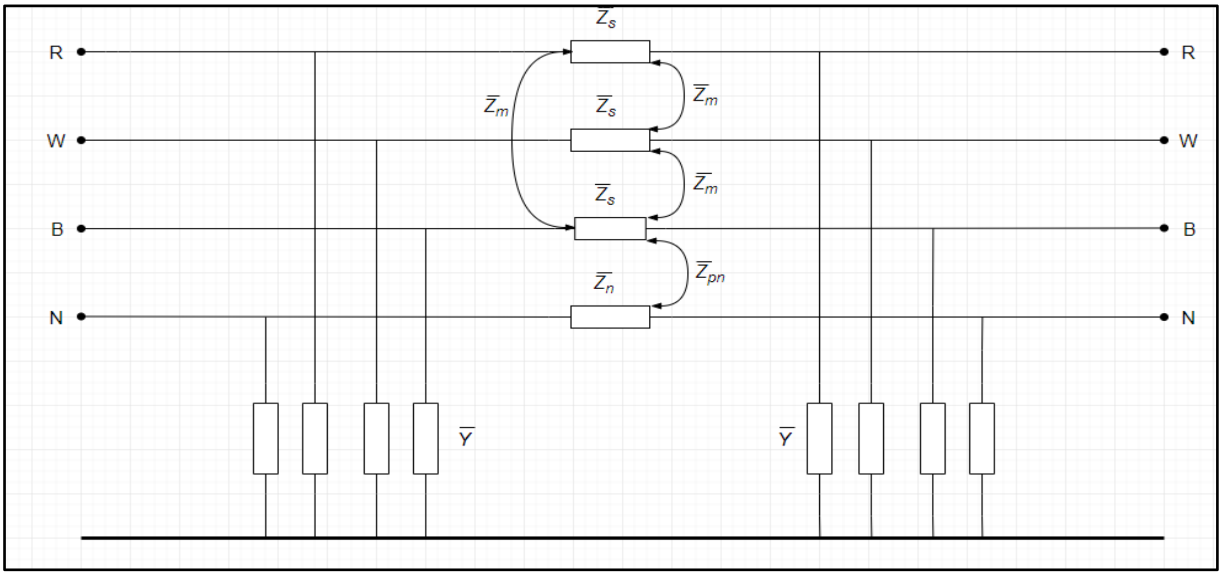


Figure 5.20: Equivalent circuit of the three-phase four-wire system with a neutral conductor

5.3.3.3. Cables

The three-phase cable in Table B.7 has a nominal voltage of 11 kV, copper conductor 120 mm^2 three core XLPE IS(0.1) PVC SWA PVC BLK/RED VULTEX. It was manufactured by Aberdare cable with a resistance of 0.1961 Ω/km, the inductance of 0.313 mH/km, and capacitance of 0.347 μF/km. These parameters per length were for positive and negative sequences. The zero-sequence parameter per length of resistance was 1.0932 Ω/km and inductance 0.216 mH/km. The length of the cable differs as stipulated in Table B.7. The parameter per length of sequence components as part of the technical datasheet obtained from Aberdare Cables. The cross-section diagram of a cable as shown in Figure 5.21.

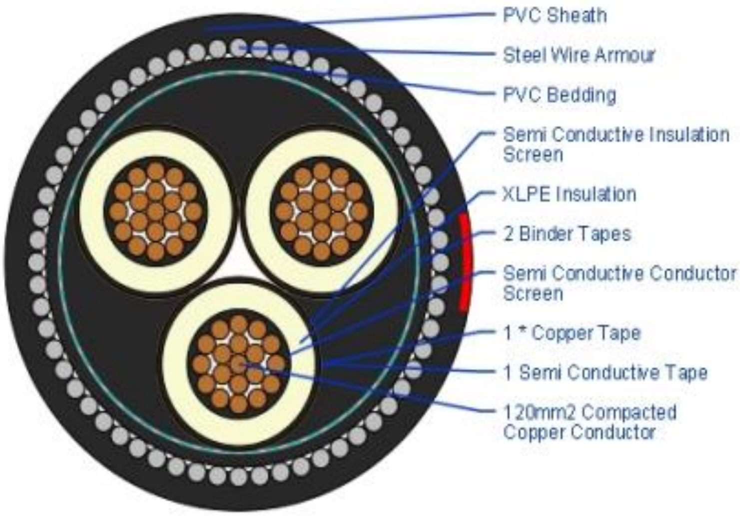


Figure 5.21: 120mm^2 Copper XLPE Cross-section diagram
Adapted from Aberdare Cables (2019)

5.3.3.4. Linear load

The linear load was modelled as impedance model 1, where the active power and its power factor was known. The parameter of the linear load is given in Table B.8

5.3.3.5. Rectifiers

The model of the rectifier is given in Figure 5.22.

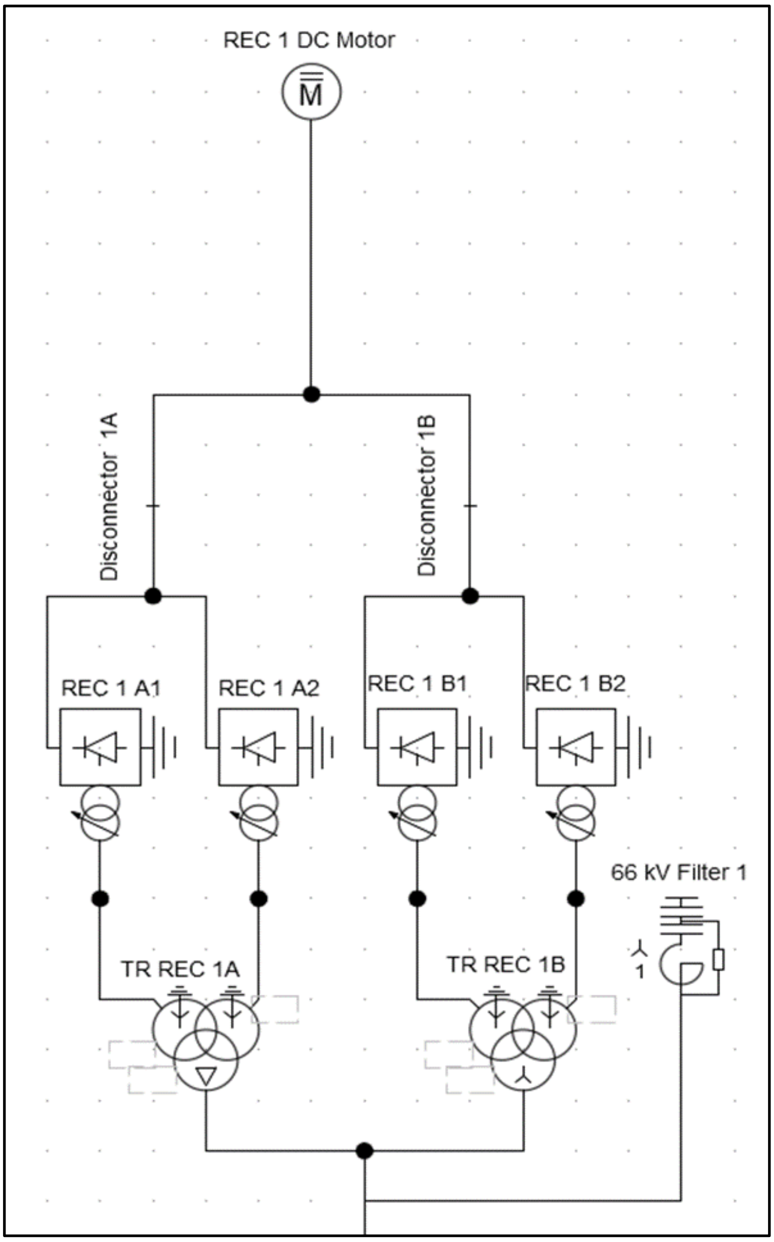


Figure 5.22: Rectifier model in DIgSILENT

TR-REC 1A and TR-REC 1B were three-phase rectifier transformers manufactured by ABB PowerTech Transformers in 2002 in operation for more than 15 years. This model shown in Figure 5.22 represents only one rectifier, as they were modelled the same and both rectifiers should be in operation. REC 1 A1 and REC 1 B1 were modelled the same and control the DC voltage whereas REC 1 A2 and REC 1 B2 control the current. The rectifiers were 12-pulse thyristor rectifiers with a 20.35 MW DC motor at a nominal voltage of 0.37 kV DC and rated DC current of 55 kA. The rectifier had a built-in transformer to regulate the maximum and minimum tap position. Each rectifier had a 66 kV harmonic filter for power factor correction and harmonic control. The harmonic spectrum for the 12-pulse thyristor rectifier used in this model was from the DIgSILENT library, as indicated in Table B.9.

5.3.3.6. Harmonic filters

The 66 kV harmonic filters should be in operation at all times. As shown in Figure 5.22, the size of a 66 kV Filter 1 was an 11 MVAr modelled as shunt filter type R-L-C1-C2-Rp. The layout parameter for the filter as indicated in Figure B.5 under Appendix B. There also two 11kV second-order harmonic filters. A second-order harmonic filter was widely used because it provides a low impedance to enable moderation of a wide range of frequencies. It consists of a capacitor in series with a parallel combination of a reactor and a resistor. The layout parameter of this filter is given in Figure B.6 under Appendix B. The data of the harmonic filters part of the industrial network was summarised in Table B.10.

5.3.3.7. Asynchronous machines

The asynchronous machine data is given in Table B.11 whereby the 11kV machines were wound type or slip ring induction motor. The Rosh Pinah Zinc mine had five compressors, two connected at 0.525 kV underground, and three connected at 0.4 kV underground. Only three compressors should be on at a time, thus the two connected at the 0.525 kV underground was out of service as shown in Figure B.1.

5.3.3.8. Variable Speed Drives (VSDs)

There were five industrial fans situated underground for cooling purposes, which was controlled by the variable speed drives that control the speed and the torque of the AC induction motors. The VSDs also reduce the starting transients for the induction motors that were used for pumps or fans. The VSD model was represented by a rectifier, DC capacitor, and pulse width modulation (PWM) connecting to a three-phase induction motor. It was very crucial to model the VSDs accurately for harmonic analysis due to the harmonic current generated by the rectifiers.

The active power of the DC system was calculated by:

$$P_{DC} = V_{DC} \times I_{DC} \tag{5.13}$$

The commutation reactance (X_{cr}) was vital as it causes the DC voltage drop, which was subtracted from a nominal DC voltage.

$$\Delta V_{DC} = \frac{3}{\pi} X_{cr} \times I_{DC} \tag{5.14}$$

These equations were used in the calculations of six-pulse three-phase diode rectifiers or three-phase line commutated thyristor-controlled rectifiers.

$$V_{DC} = 1.35 \times V_{LL} - \Delta V_{DC} \tag{5.15}$$

Where: V_{LL} is the line-to-line voltage. To calculate the AC voltage, the following formulae were used:

$$V_{LL} = \frac{\sqrt{3}}{2\sqrt{2}} V_{DC} = 0.612 V_{DC} \tag{5.16}$$

$$V_{rms} = \frac{1}{\sqrt{2}} V_{DC} = 0.707 V_{DC} \tag{5.17}$$

The rectifier was modelled as a current source load with an ideal six-pulse rectifier harmonic spectrum; this keeps the DC voltage constant. The VSD dynamic simulation model is given in Figure 5.23.

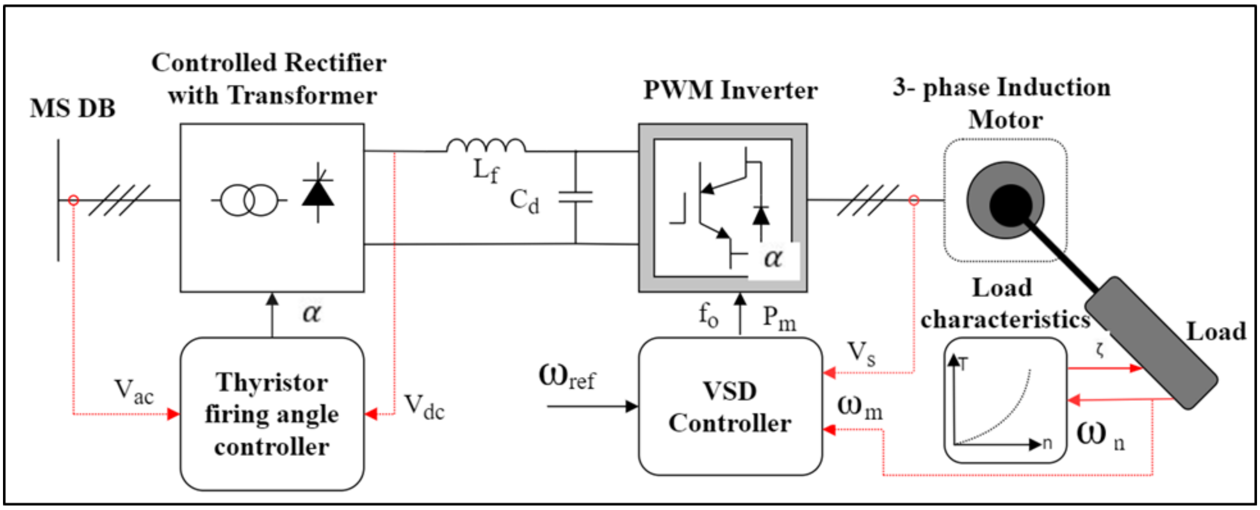


Figure 5.23: VSD driven motor load dynamic simulation model
Adapted from Meegahapola & Robinson (2016)

The graphic design of the VSD in the DIgSILENT is given in Figure 5.24. The composite model of a VSD was created from the frame definition *VSD_V/f_PWM* as indicated in Figure 5.25.

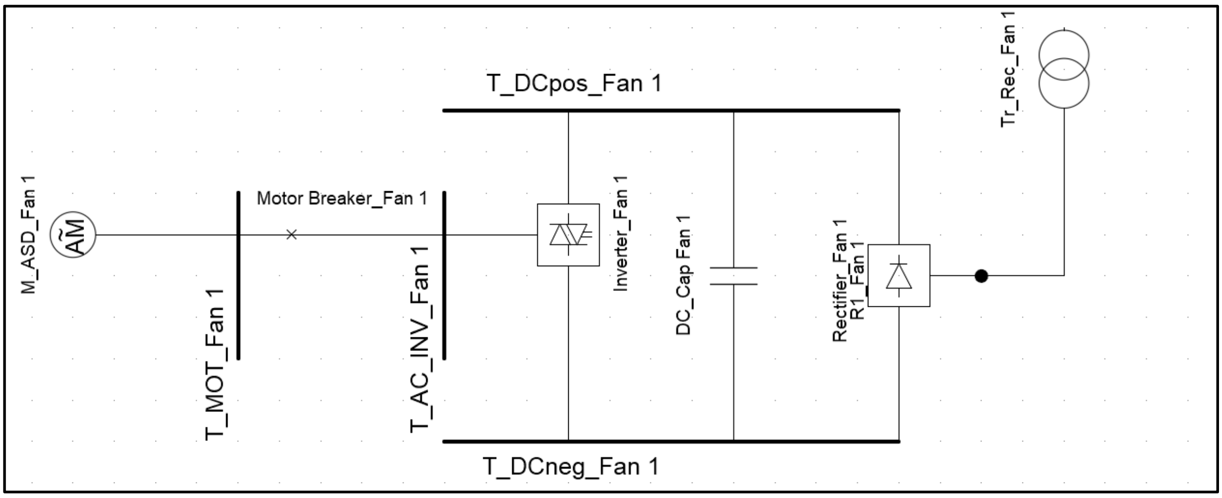


Figure 5.24: VSD model in DIgSILENT

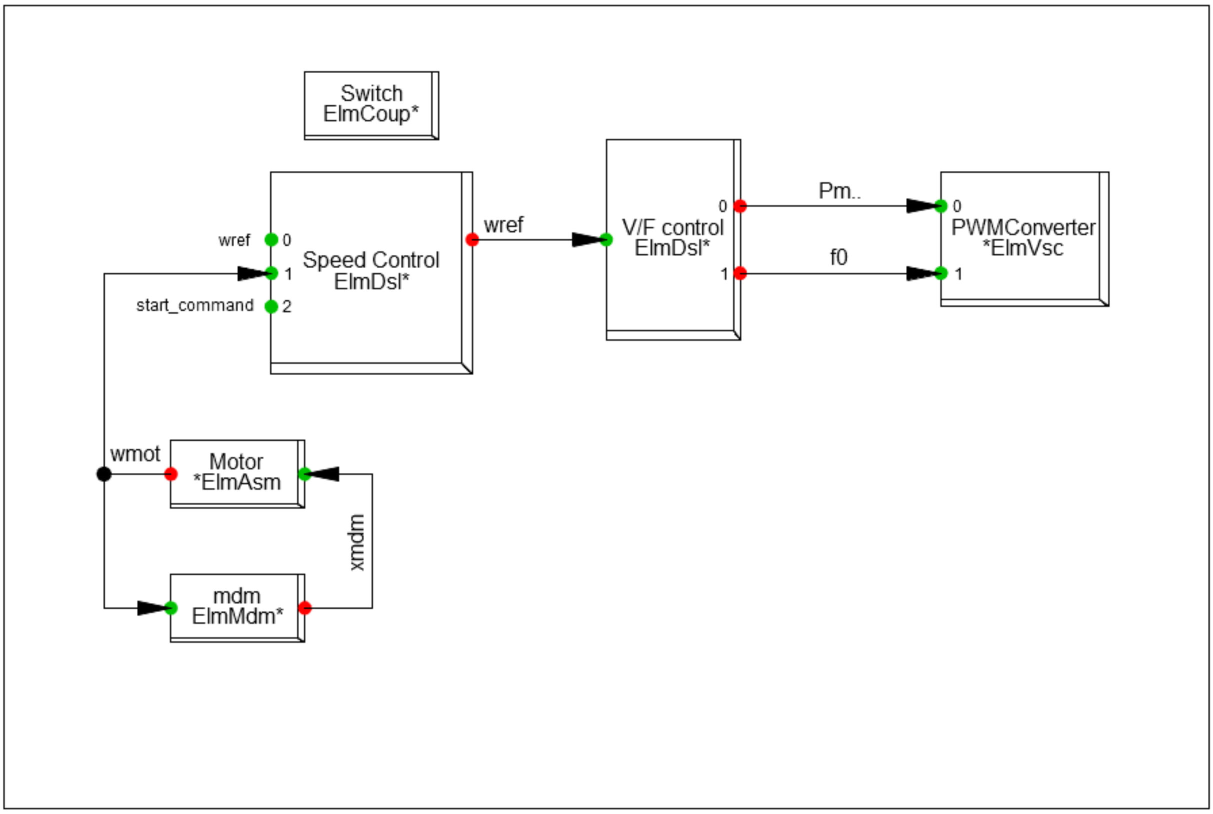


Figure 5.25: VSD control diagram

Figure B.7 and Figure B.8 gave the parameter on how the VSD controls the speed of the motor together with the use of model definition in terms of the program with all the equations and its variable descriptions. To obtain the graph for the start-up process of the induction motor the simulation for RMS/EMT was conducted. Although the focus of this research was a harmonic study, it was vital to understand and monitor how the induction motor starts and how its speed was controlled by the VSD. The simulation method to be used should be RMS values (electromechanical transients) for a balanced positive sequence network configuration. The integration step size for electromechanical transients was modified from 0.01 seconds to 0.0001 seconds to reduce the error of the “system matrix inversion failed”. Two events have to be set-up, the parameter and switch events. The parameter event was where the start command was defined as indicated in Figure 5.26. The switching event depends on the speed control parameters given in Figure B.9.

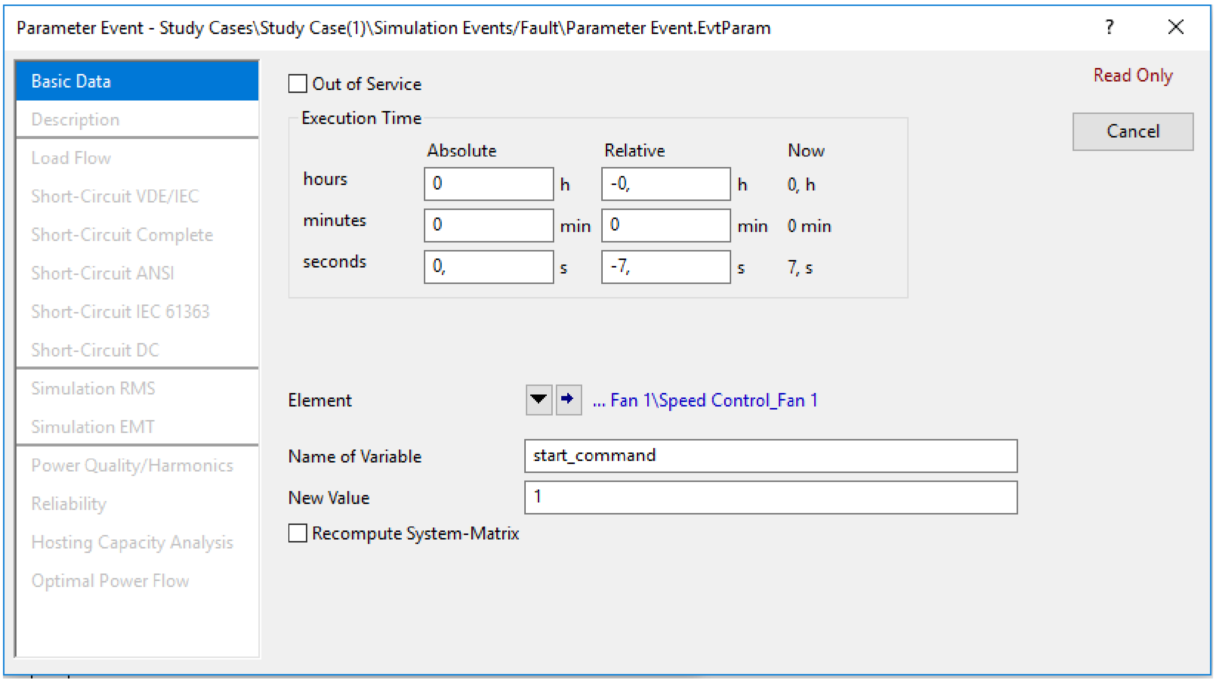


Figure 5.26: Parameter event block after simulation of RMS/EMT

5.3.3.8.1. RMS/EMT simulation with the motor breaker in an open position

The start-up procedure of the induction motor when the motor breaker opens is given in Figure 5.27. During the starting process, the transient current was shown in the positive sequence current magnitude waveform.

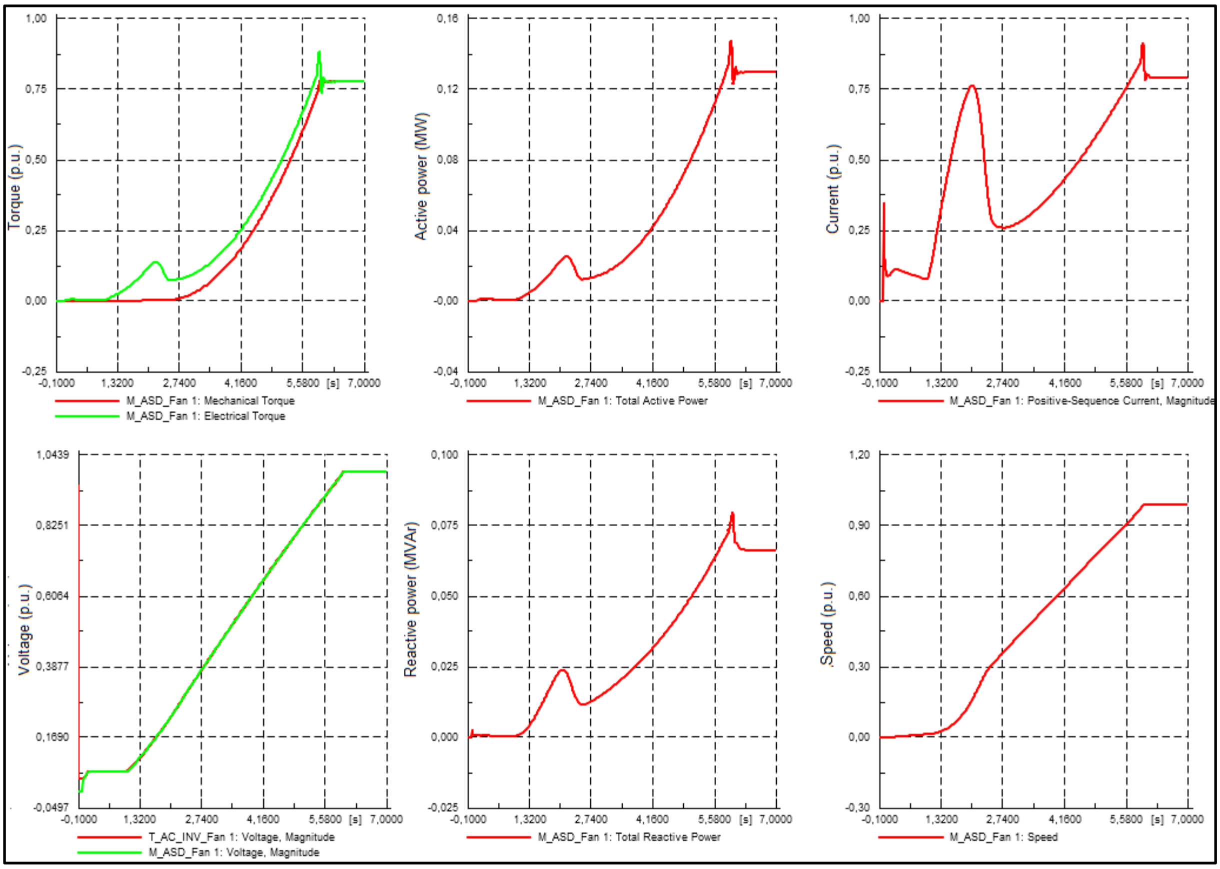


Figure 5.27: Motor start-up procedures with Motor Breaker_Fan 1 Open

It was shown in Figure 5.28 as the VSD model, the motor breaker _Fan 1 was highlighted with a red circle. The motor breaker _Fan 1 was open and the start-up process has to close it before the VSD starts to control the speed. Table 5.3 indicated the output results during the simulation.

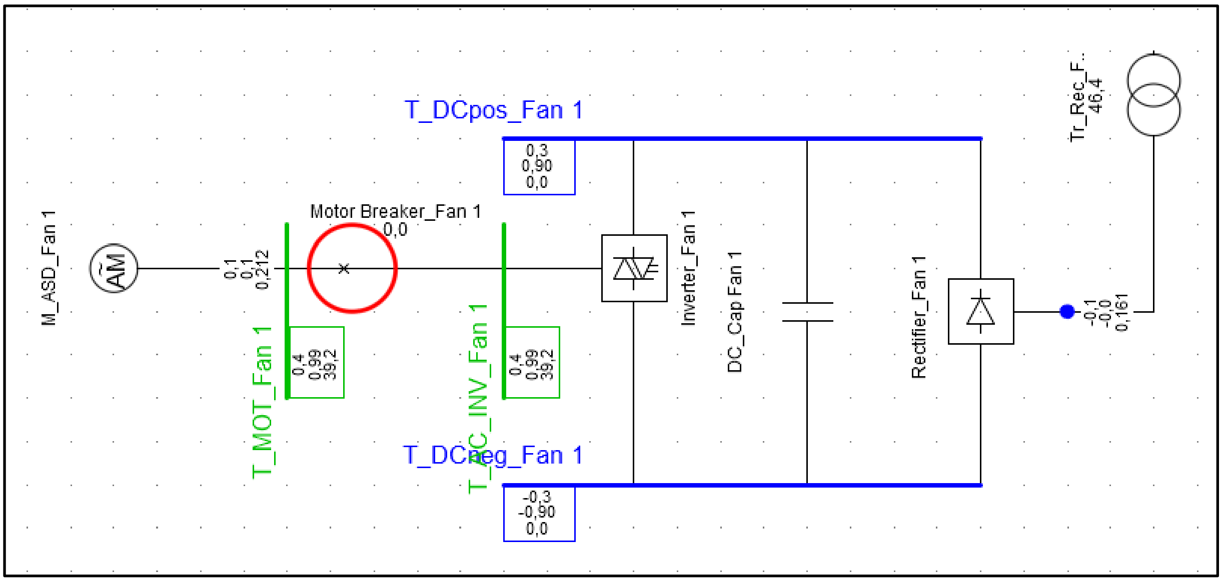


Figure 5.28: VSD model when Motor Breaker_Fan 1 open

Table 5.3: Result output of the motor starting procedures when Motor Breaker_Fan 1 open

```
(t=000:000 ms) ---------------------------------------------------------------
(t=000:000 ms) 'Grid\VSD_Model_Fan 1\Speed Control_Fan 1.ElmDsl':
(t=000:000 ms) Variable of calculation object: s:start_command set to  1,          0/1    (Motor Start Command OFF/ON)
(t=000:055 ms) ---------------------------------------------------------------
(t=000:055 ms) 'Grid\VSD_Model_Fan 1\Speed Control_Fan 1.ElmDsl':
(t=000:055 ms) Model triggered (t 000:027 ms, event 'ConnectMotor', trigger count 1)!
(t=000:027 ms) ---------------------------------------------------------------
(t=000:027 ms) 'Grid\Motor Breaker_Fan 1.ElmCoup':
(t=000:027 ms) Circuit-Breaker Action: 'Close' - 'All phases'.
```

5.3.3.8.2. RMS/EMT simulation with the motor breaker in a closed position

Additionally, there is an approach whereby the motor breaker was closed and the fan was off, then the operator decides to start the fan again the motor start-up procedure changes, as well as the resulting output during the simulation. The start-up procedure of the induction motor when the motor breaker is closed is given in Figure 5.29. This process only concentrates on the speed control of the induction motor. The VSD model in Figure 5.30 shows the flow of current to the induction motor as the motor breaker is in close position. The output results were given in Table 5.4.

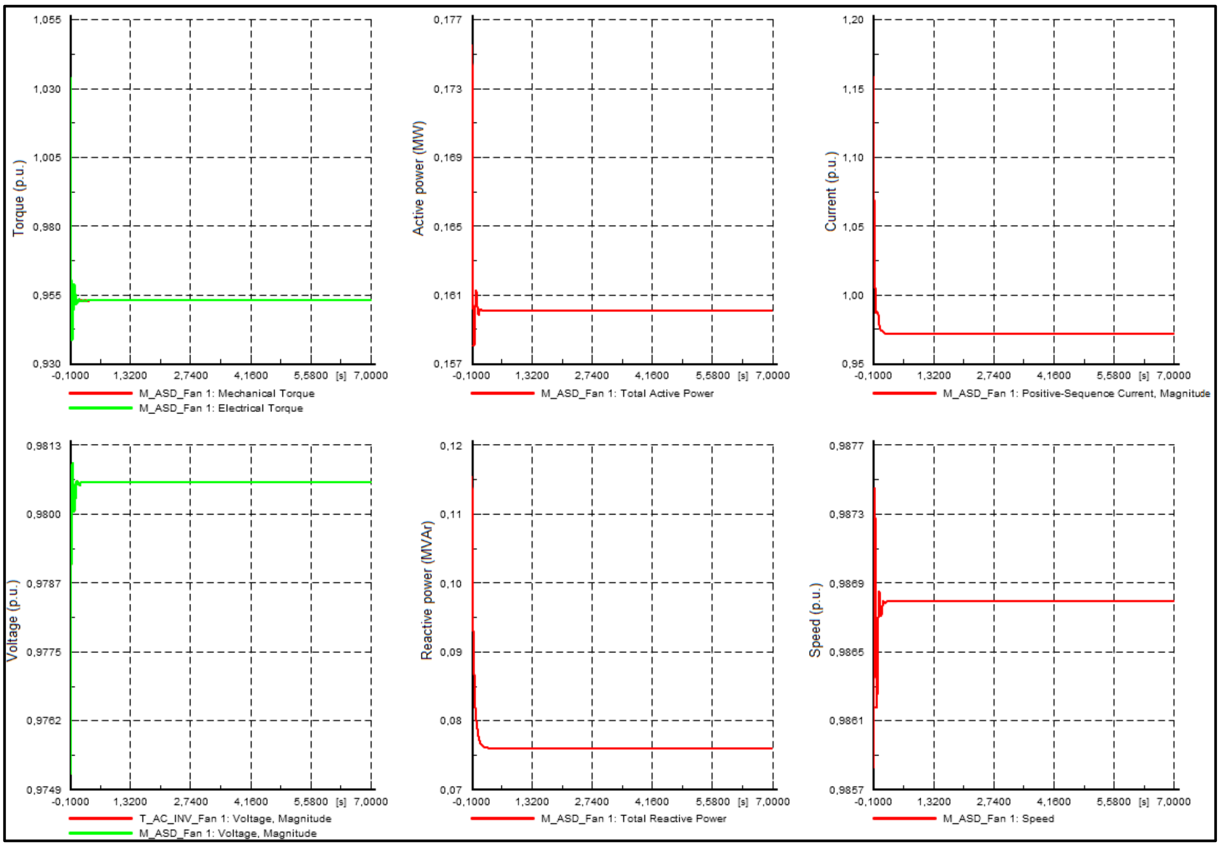


Figure 5.29: Motor start-up procedures with Motor Breaker_Fan 1 closed

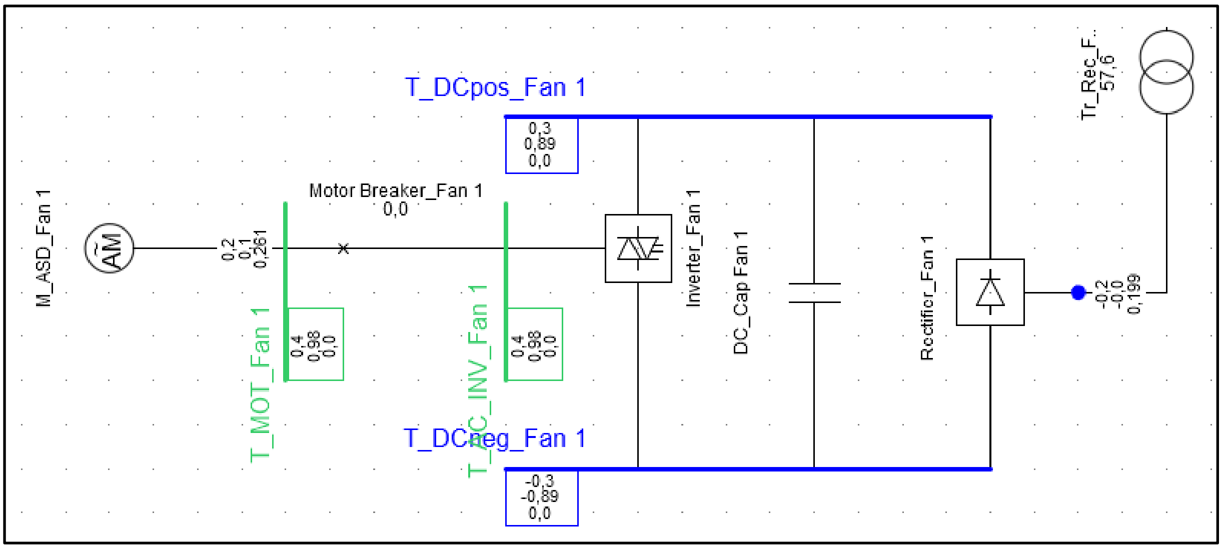


Figure 5.30: VSD model when Motor Breaker_Fan 1 is closed

Table 5.4: Result output of the motor starting procedures when Motor Breaker_Fan 1 closed

```
(t=000:000 ms) -------------------------------------------------------------
(t=000:000 ms) 'Grid\VSD_Model_Fan 1\Speed Control_Fan 1.ElmDsl':
(t=000:000 ms) Variable of calculation object: s:start_command set to  1,          0/1    (Motor Start Command OFF/ON)
(t=000:055 ms) -------------------------------------------------------------
(t=000:055 ms) 'Grid\VSD_Model_Fan 1\Speed Control_Fan 1.ElmDsl':
(t=000:055 ms) Model triggered (t 000:027 ms, event 'ConnectMotor', trigger count 1)!
(t=000:027 ms) Control Switch Event 'ConnectMotor' not possible. Breaker already closed.
```

5.3.3.9. Solar PV farm

The 5MW solar PV farm was modelled with its transformers, line, and cable as it formed part of the parameters indicated in Table B.5, Table B.6, and Table B.12. It consists of 36 parallel units each with a nominal power of 33kW, which gives a total power of 1188 kW. Thus, to obtain 5 MW five parallel units were needed, each with 1188 kW, which gave a total power of 5.94 MW. The model of a solar PV farm is given in Figure 5.31.

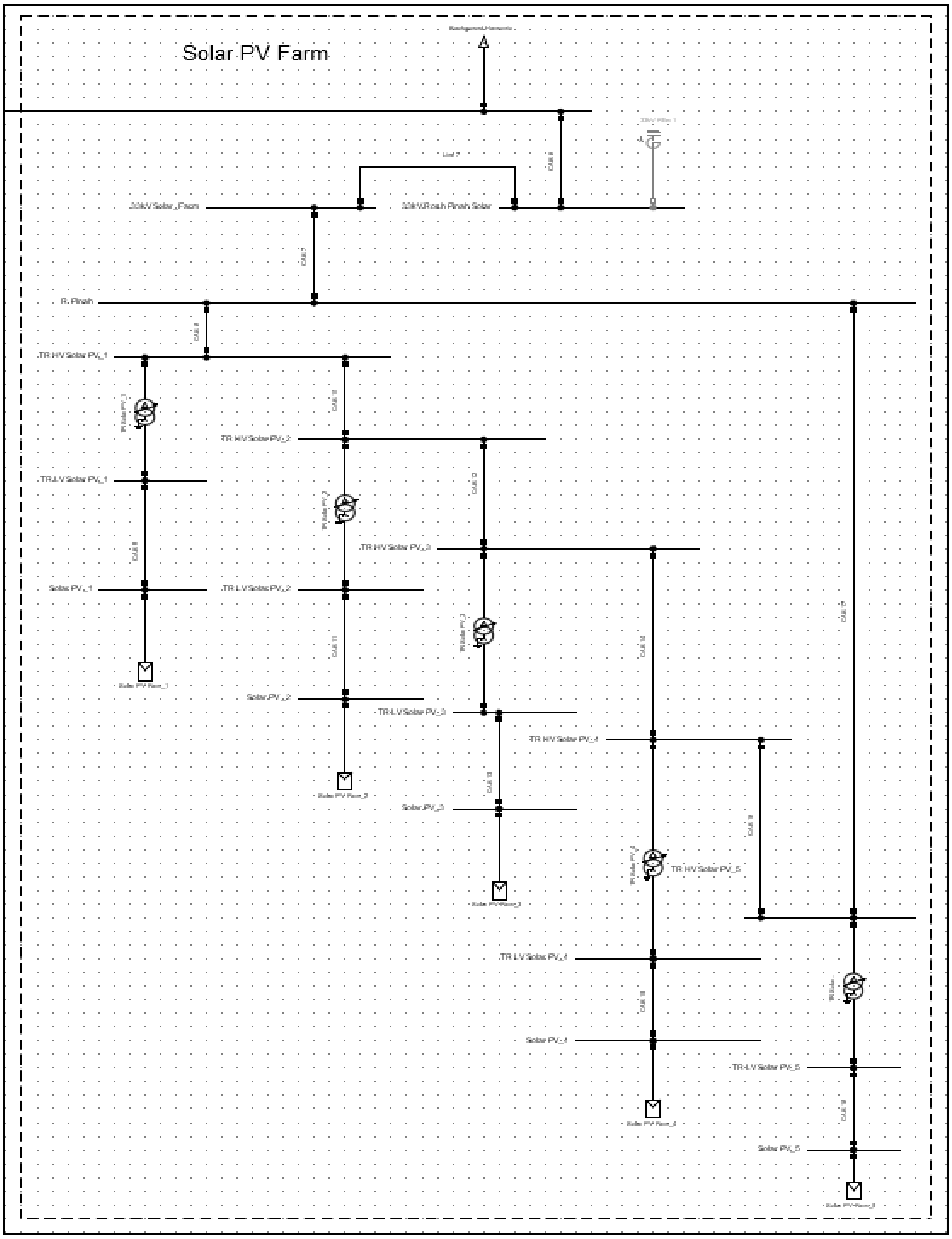


Figure 5.31: Solar PV farm model

The capability curve for the maximum and minimum reactive power (Qmax and Qmin) was part of the model at different voltage levels in each unit. Table B.13 gave the harmonic spectrum for the solar PV farm according to IEC 61000 where the harmonic current was referred to as the rated current. The inter-harmonic, even and triplen at different harmonic orders were part of the model, although this study only focused on the odd harmonic for analysis. The background harmonics as shown in Table B.8 was a current source and its harmonic spectrum is given in Table B.14. The installed harmonic filter was modelled and its parameter was added in Table B.10. This harmonic filter was used for harmonic mitigation mainly for the 25th harmonic order, which was found to be the dominant harmonics during harmonic analysis.

5.4. Summary

The chapter highlighted how different case studies and networks were modelled in the DIgSILENT software package. The equipment modelled and its controls were available within DIgSILENT. Most equipment were modelled according to the manufacturers' parameters as available at mining or solar PV farm sites respectively. Only a few parameters had to be calculated or were assumed to be ideal such as the harmonic spectrum for the rectifiers. Three different networks were used with different parameters and scenarios to validate a practical method for harmonic source detection at the point of common coupling. The VSDs were found to start according to the parameters given and accurately controlled the speed of the motor connected. The solar PV farm was modelled in detail.

CHAPTER 6: RESULTS AND DISCUSSIONS

6.1. Introduction

This chapter presents the results and analysis of three different networks, namely the IEEE PES Benchmark test system, the radial distribution network for new adapted equivalent circuits, and an industrial network. These three networks were simulated in the DIgSILENT software package. The simulated industrial network was validated with information from the practically measured data using Unipower PQ secure software. The model and configuration of the network have been covered in Chapter 5.

6.2. IEEE PES benchmark test system

The first three case studies (A-C) were conducted based on the parameters stated in Table 5.1. The fourth case study was mainly after the renewable energy source became part of the benchmark test system.

6.2.1. Case study A

Case study A, LOAD 1 was the only harmonic source customer connected, apart from the utility background harmonics. This customer 1 (LOAD 1) was connected via PCC 1 whereas LOAD 4 was connected at PCC 3. The harmonic load flow was conducted to identify the harmonic source and quantify its contributions per harmonic frequency.

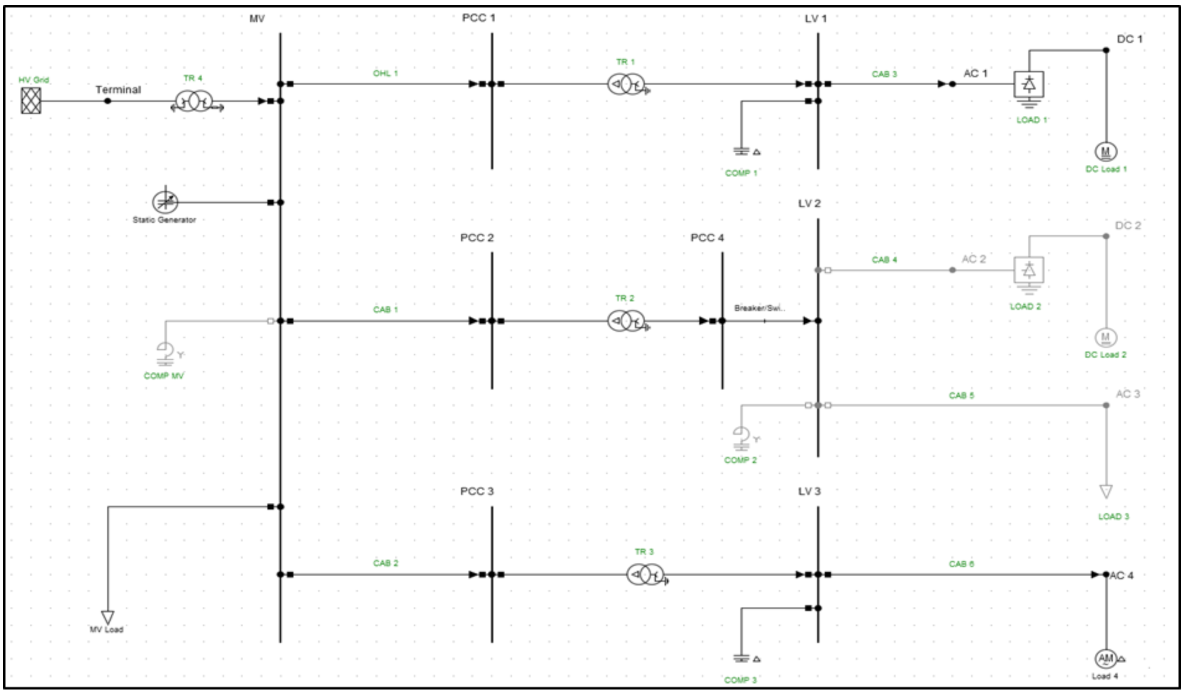


Figure 6.1: Case A_Active power flow for the 1st and 7th harmonic frequencies

This indicated that positive sequence harmonic frequencies could emanate from the utility through the background harmonics as per Figure 6.1, although in this case study the 13th harmonic frequency that is also a positive sequence component came from the customer side.

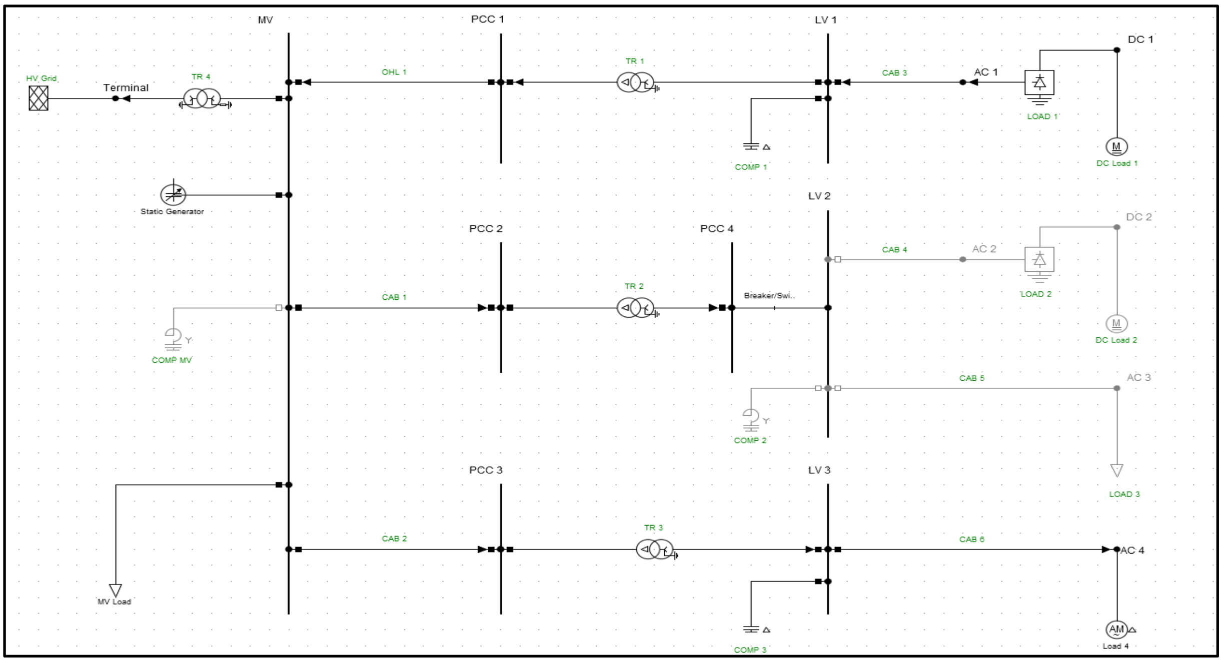


Figure 6.2: Case A_Active power flow for the 5th, 11th and 13th harmonic frequencies

Figure 6.2 indicated that negative sequence harmonic frequencies could be from the customer side, although in this case study the 13th harmonic frequency that was a positive sequence component came from the customer side as well.

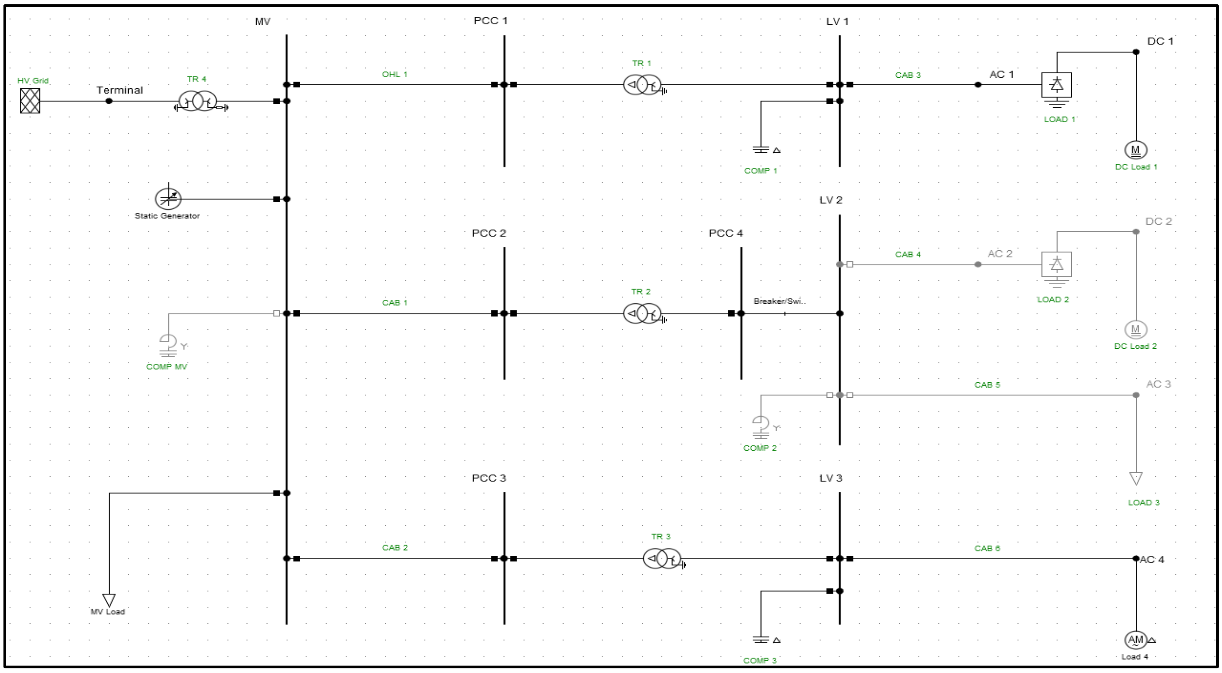


Figure 6.3: Case A_Active power flow for the 3rd, 6th and 9th harmonic frequencies

Figure 6.3 indicated that harmonic frequencies, which are zero sequence components, have been cancelled by the delta winding of the transformers within the network, thus this was not considered in this study.

Table 6.1 indicated the individual and total voltage harmonic distortion of different frequencies at the different points in the network. This indicated the point in the network that had the highest percentage of VTHD and gave its proximity of the customer connected at that point.

Table 6.1: Case A_HD and THD of voltage at different points within the network

HD%	LV 1	LV 2	LV 3	PCC 1	PCC 2	PCC 3	PCC 4	MV
5th	5.187	0.301	0.503	0.315	0.301	0.303	0.301	0.301
7th	6.864	0.234	0.046	0.246	0.234	0.232	0.234	0.324
11th	0.394	0.021	0.013	0.022	0.021	0.021	0.021	0.021
13th	0.260	0.036	0.026	0.035	0.036	0.035	0.036	0.035
THD (%)	8.617	0.384	0.507	0.402	0.384	0.384	0.384	0.383

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Table 6.2 indicated the responsible party of harmonic distortion within the network as it indicated the percentage harmonic distortion of each customer or utility at different frequencies, as well as the current total harmonic distortion (ITHD) of each party. The customer(s) or utility with the highest individual harmonic distortion percent per harmonic frequency was responsible for the harmonic source of that frequency. The main party responsible for the case study was the one with the highest ITHD percentage.

Table 6.2: Case A_HD and THD of current for the utility and customers

HD %	Utility	Customers	
		Customer 1 (LOAD 1)	Customer 3 (LOAD 4)
5th	1.286	5.479	2.266
7th	1.095	2.657	2.773
11th	0.041	1.010	0.090
13th	0.026	0.851	0.134
THD (%)	1.690	6.272	3.585

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

The power of the harmonic frequency also indicated the party responsible for the individual harmonic frequencies, which depended on the value of the highest power as shown in Table 6.3. The individual voltage harmonic distortion shown in Table 6.2 indicates that the 7th harmonics was from customer 3, but the power flow direction in Figure 6.1 and individual power at the harmonic frequency in Table 6.3 showed clearly that it was from the utility.

Table 6.3: Case A_Power at harmonic frequencies for the utility and customers

Power (kW)	Utility	Customers	
		Customer 1 (LOAD 1)	Customer 3 (LOAD 4)
5th	0	-0.057	0.001
7th	0.081	0.059	0
11th	0	-0.001	0
13th	0	-0.001	0

It was found that the main contributor to harmonic distortion for this case study was customer 1 (LOAD 1) with the current total harmonic distortion of 6.272% as indicated in Table 6.2. It was also possible to identify each harmonic frequency contributor. In this case study customer, 1 was the contributor of the 5th, 11th and 13th harmonic frequency whereas Customer 3 was a 7th harmonic contributor. Thus, the direction of active power flow and individual and total harmonic distortion of current gave the best option to identify the main harmonic contributor of the network as well as identify harmonic distribution according to the harmonic frequencies.

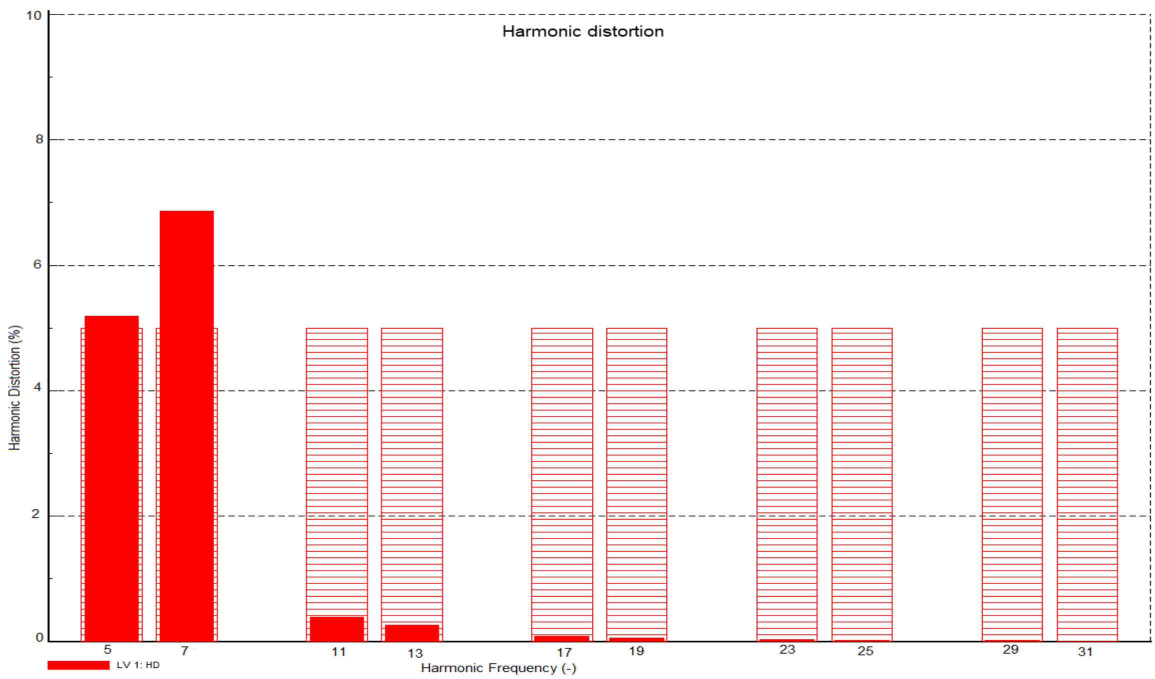


Figure 6.4: Case A_Comparison of voltage harmonic distortion with IEEE std. 519 (2014) for voltage (below 1kV)

6.2.2. Case study B

The 2nd case study was similar to the 1st case study as only customer 1 (LOAD 1) and customer 3 (LOAD 4) were part of the network; the only difference was parameters for customer 3, Comp 3, linear load, and HV/MV transformer. It was noticed that only a fundamental frequency that the active power flowed from the utility/grid to the load as per Figure 6.5. Figure 6.6 indicates that for the harmonic frequencies, the active power flowed from the load to the grid as the load was injecting the harmonic current into the network.

Table 6.4: Case B_ HD and THD of voltage at different points within the network

HD%	LV 1	LV 2	LV 3	PCC 1	PCC 2	PCC 3	PCC 4	MV
5th	5.151	0.287	0.362	0.301	0.287	0.288	0.287	0.287
7th	5.480	0.455	1.340	0.472	0.455	0.462	0.455	0.455
11th	0.395	0.020	0.002	0.021	0.020	0.020	0.020	0.020
13th	0.262	0.034	0.031	0.033	0.034	0.034	0.034	0.034
THD (%)	7.537	0.540	1.388	0.561	0.540	0.546	0.540	0.539

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Table 6.4 indicated that the dominant harmonics in this case study were the 5th and 7th harmonic orders because Customer 1 used a 6-pulse rectifier. LV 1 had the highest percentage of VTHD compared to other points within the network; this concluded that the customer connected at the proximity of LV 1 was a source of harmonics for the network.

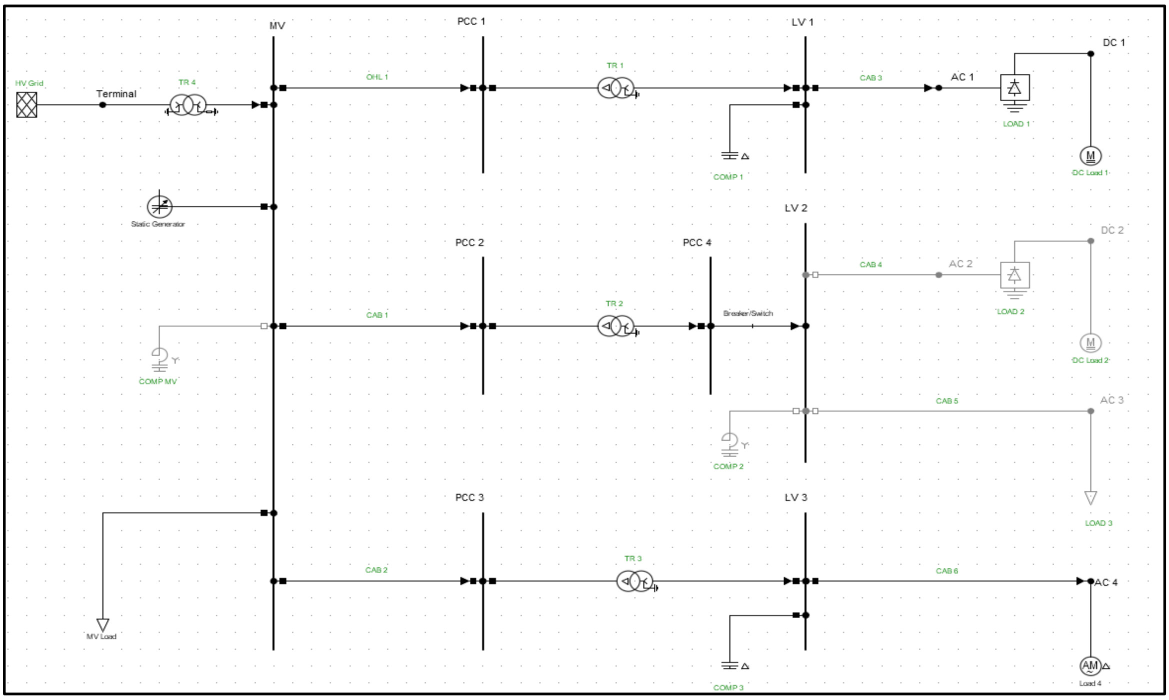


Figure 6.5: Case B_Active power flow for the 1st fundamental frequency

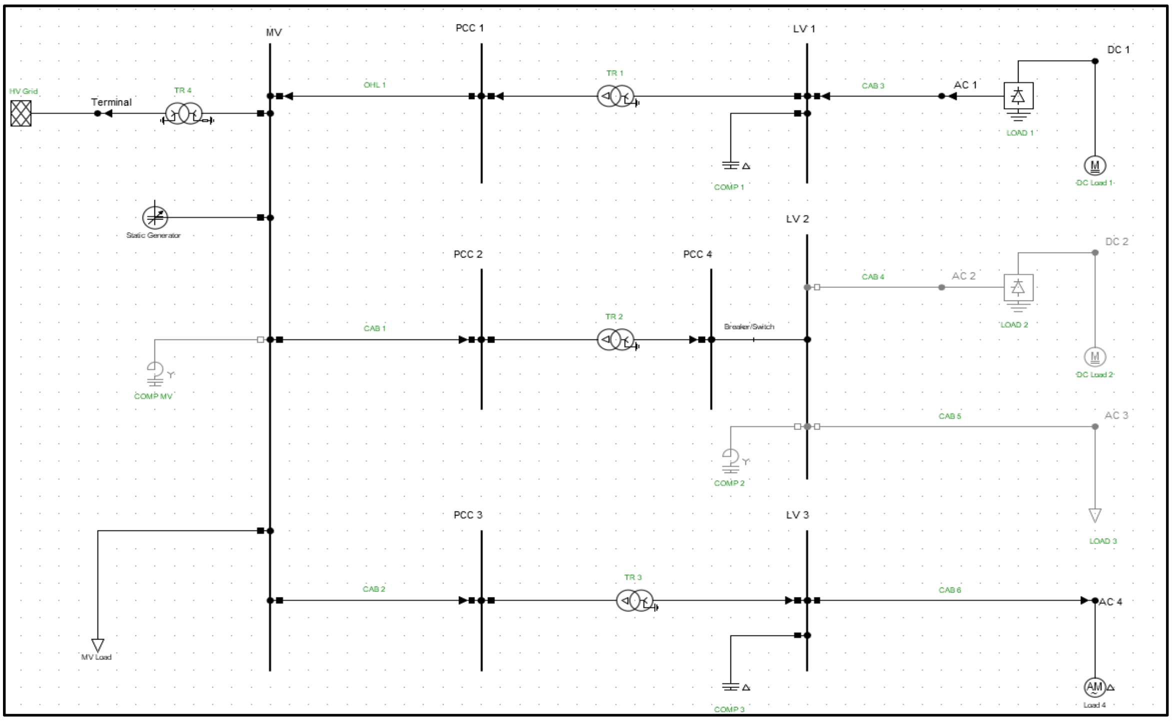


Figure 6.6: Case B_Active power flow for the 5th, 7th, 11th and 13th harmonic frequencies

Table 6.5: Case B_HD and THD of current for the utility and customers

HD %	Utility	Customers	
		Customer 1 (LOAD 1)	Customer 3 (LOAD 4)
5th	1.163	5.464	0.083
7th	1.068	2.657	0.750
11th	0.037	1.008	0.043
13th	0.025	0.850	0.095
THD (%)	1.580	6.259	0.762

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Table 6.6: Case B_Power at harmonic frequencies for the utility and customers

Power (kW)	Utility	Customers	
		Customer 1 (LOAD 1)	Customer 3 (LOAD 4)
5th	0	-0.056	0
7th	-0.146	-0.166	0.002
11th	0	-0.002	0
13th	0	-0.001	0

The results of Table 6.5 and Table 6.6 indicated clearly that Customer 1 (LOAD 1) was a source of harmonics in case study B. This was also validated by the active power flow shown in Figure 6.6. Figure 6.7 indicated the comparison between case study B and the IEEE std.519 (2014) for the voltage below 1kV, and only the dominant harmonic exceeded the limits set on the standard.

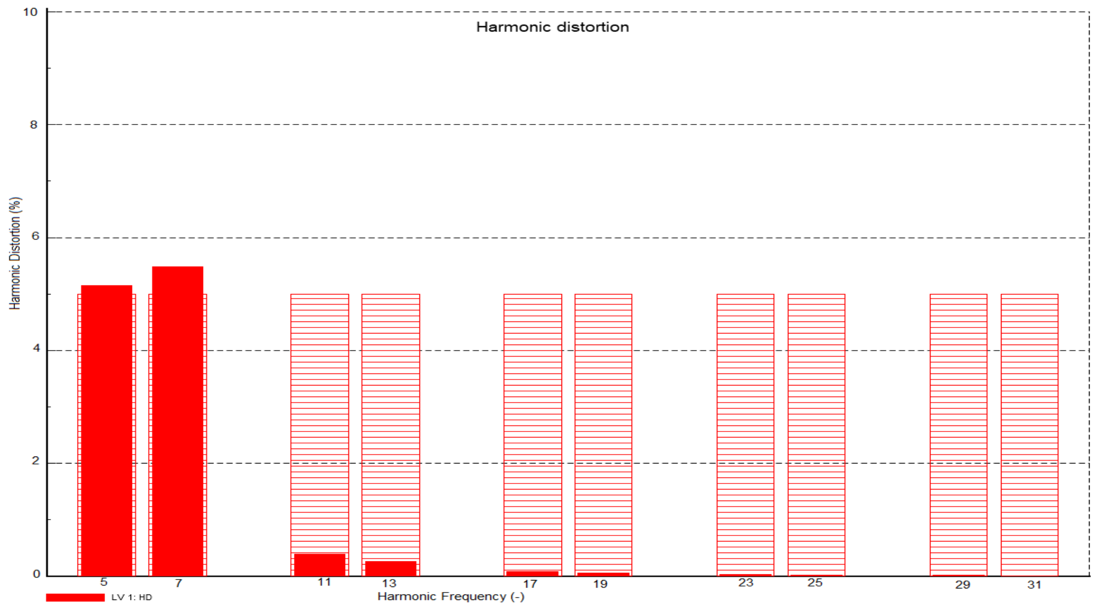


Figure 6.7: Case B_Comparison of voltage harmonic distortion with IEEE std. 519 (2014) for voltage (below 1kV)

6.2.3. Case study C

In the 3rd case study, all three customers were part of the network. This gave an overview of what happens when multiple customers are part of the network and are sources of harmonics.

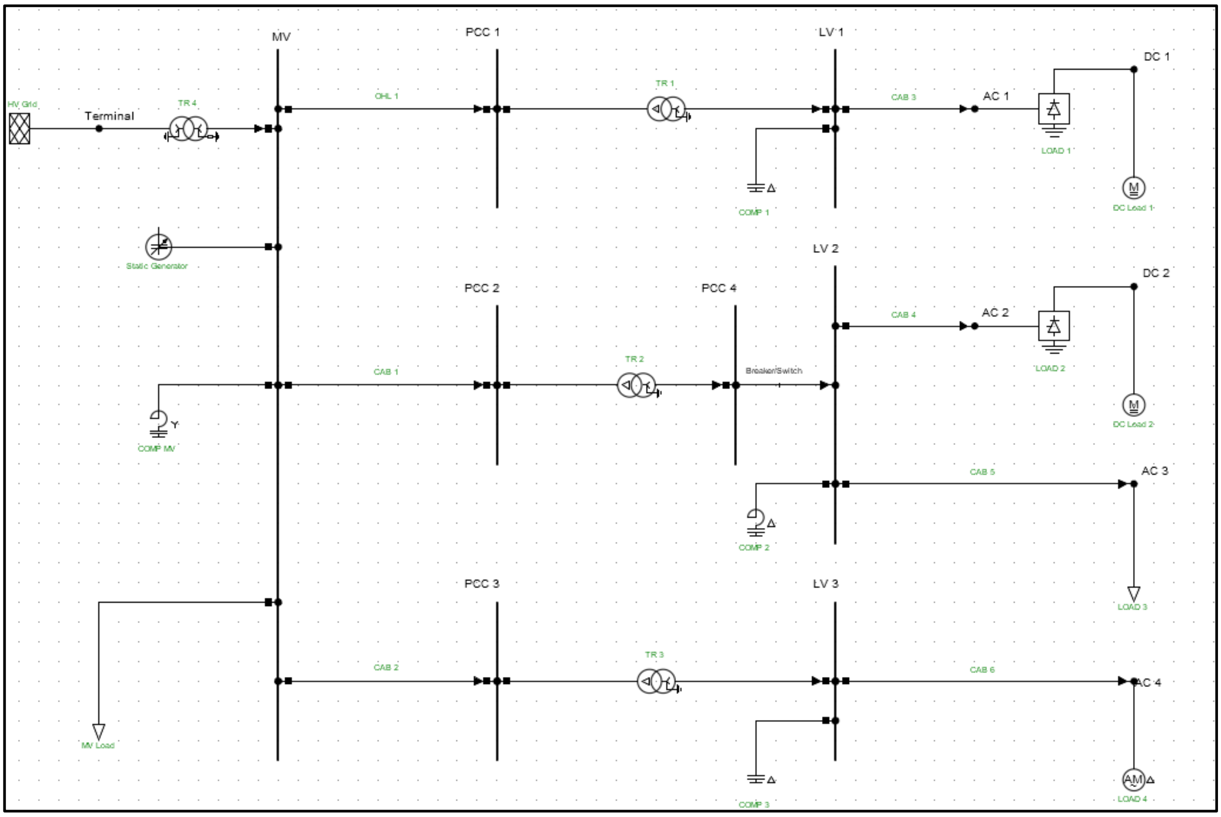


Figure 6.8: Case C_Active power flow for the 1st fundamental frequency

The active power flow of the fundamental frequency in Figure 6.8 always comes from the utility/grid except there were renewable energy sources connected to the network. This was validated by case study D. Table 6.7 showed that LV 3 had the highest percentage of VTHD.

Table 6.7: Case C_HD and THD of voltage at different points within the network

HD%	LV 1	LV 2	LV 3	PCC 1	PCC 2	PCC 3	PCC 4	MV
5th	5.650	1.333	0.629	0.457	0.459	0.447	1.333	0.446
7th	5.336	2.722	0.233	0.521	0.512	0.501	2.722	0.507
11th	0.483	3.829	0.761	1.292	1.326	1.292	3.829	1.296
13th	0.621	1.880	0.849	1.151	1.126	1.153	1.880	1.155
THD (%)	7.813	8.664	10.777	1.896	1.899	1.881	8.664	1.894

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

The harmonic frequency indicated in Figure 6.9 – Figure 6.12 showed the flow of active power at different frequencies. Figure 6.9 showed that the main source of harmonic at the 5th harmonic frequency was from the Customer 2 (LOAD 2), this was also validated by the individual current harmonic distortion and power as per Table 6.8 and Table 6.9 respectively.

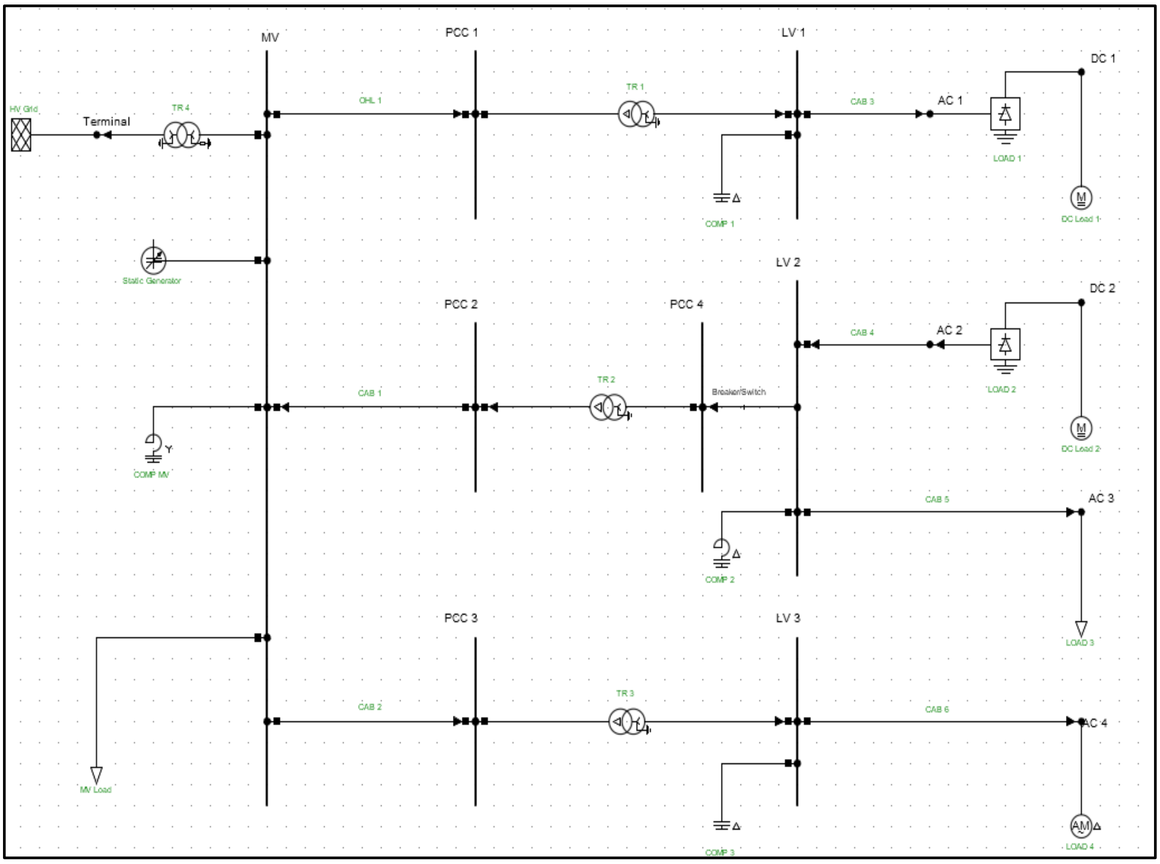


Figure 6.9: Case C_Active power flow for the 5th harmonic frequency

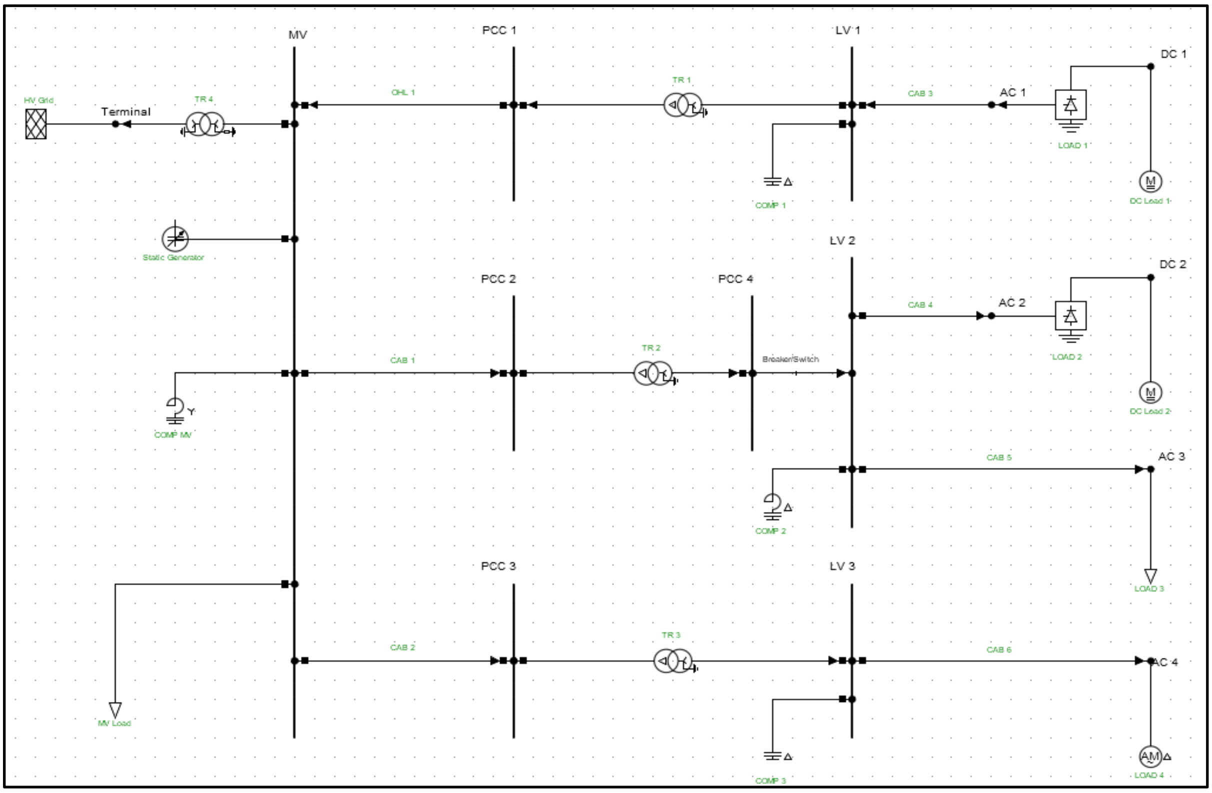


Figure 6.10: Case C_Active power flow for the 7th harmonic frequency

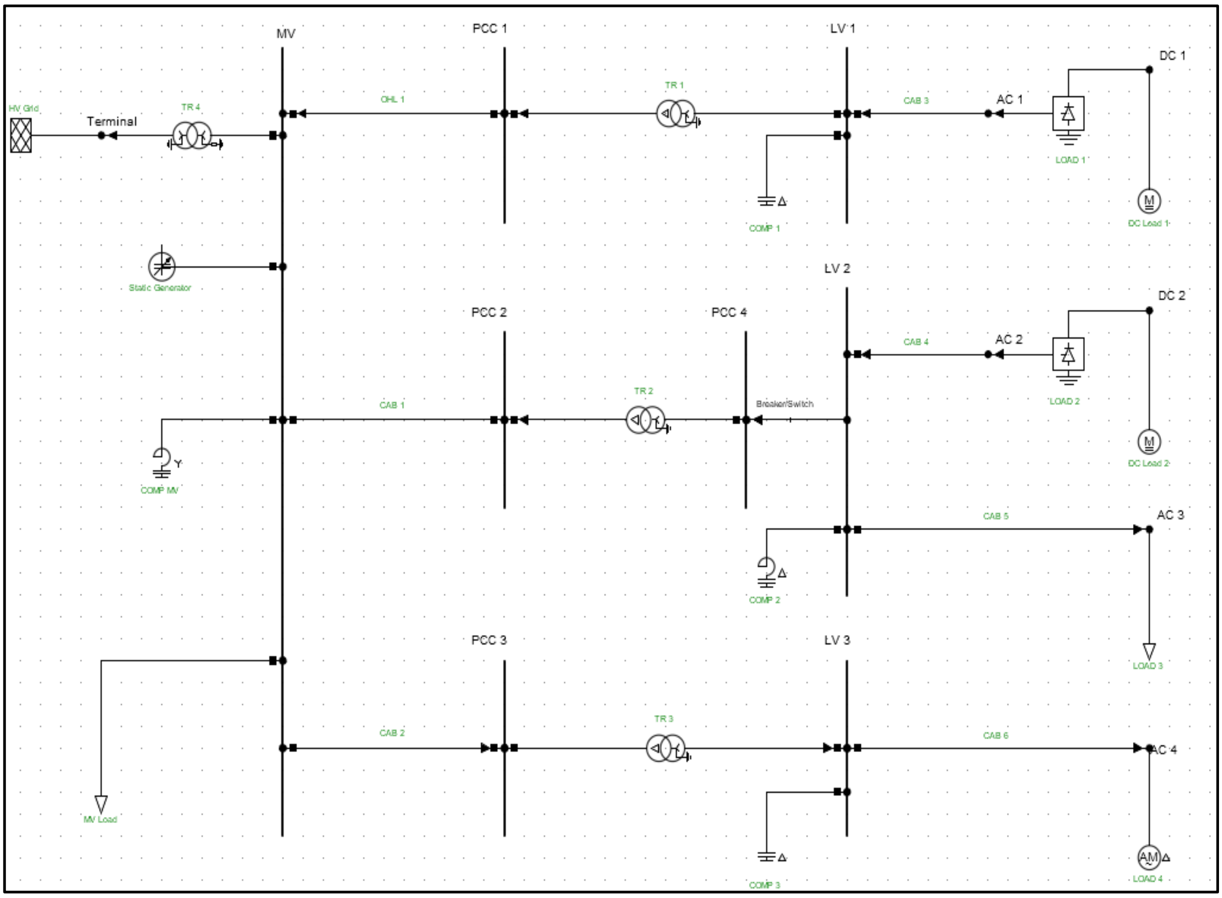


Figure 6.11: Case C_Active power flow for the 11th harmonic frequency

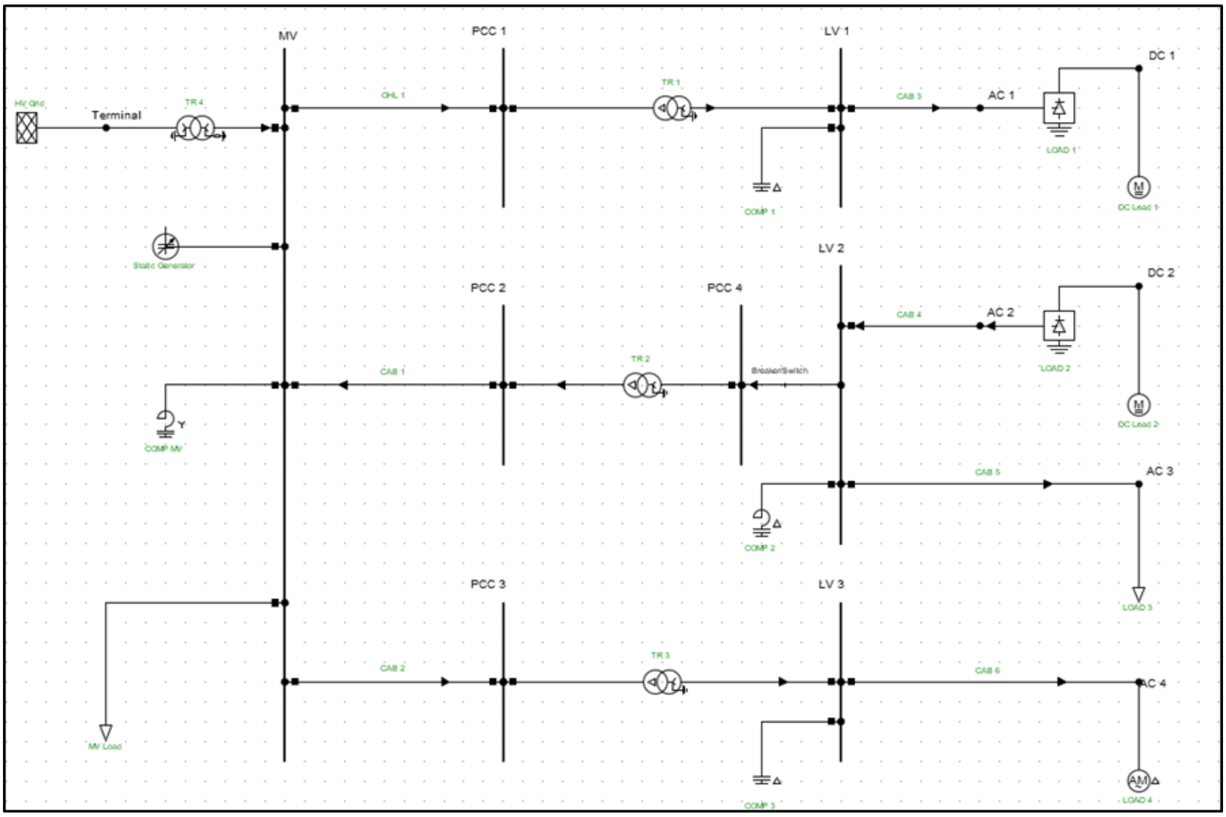


Figure 6.12: Case C_Active power flow for the 13th harmonic frequency

Table 6.8: Case C_HD and THD of current for the utility and customers

HD %	Utility	Customers		
		Customer 1 (LOAD 1)	Customer 2 (LOAD 2)	Customer 3 (LOAD 4)
5th	1.857	5.580	20.00	1.875
7th	1.077	2.657	14.286	7.246
11th	2.453	1.019	9.091	5.556
13th	1.774	0.855	7.692	4.378
THD (%)	3.729	6.364	29.418	26.876

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Table 6.9: Case C_Power at harmonic frequencies for the utility and customers

Power (kW)	Utility	Customers		
		Customer 1 (LOAD 1)	Customer 2 (LOAD 2)	Customer 3 (LOAD 4)
5th	-0.001	0.058	-0.365	0.001
7th	-0.097	-0.357	-0.121	0.001
11th	-0.001	-0.032	-0.038	0
13th	0.020	0.004	-0.048	0

From Table 6.9 and Figure 6.9 – Figure 6.12 one could conclude that with the active power sign, the harmonic contributors are summarised in Table 6.10. The main contributor depended on the highest power recorded at that certain frequency. The main harmonic source contributor for case study C was customer 2 (LOAD 2).

Table 6.10: Harmonic contributor per harmonic frequency

Harmonic frequency	Harmonic contributor	Main contributor
5^{th}	Customer 2	Customer 2
7^{th}	Customer 1	Customer 1
11^{th}	Customer 1 and Customer 2	Customer 2
13^{th}	Utility and Customer 2	Customer 2

Figure 6:13 presents the individual voltage harmonic distortion at four different points in the network. LV 1, LV 2, and LV 3 were the points in the network where the customers were connected whereas the MV was the PCC of this network. The point of connection where Customer 1 was connected is beyond the limit for the 5^{th} and 7^{th} harmonic orders set by the IEEE std. 519 (2014). The voltage harmonic distortion of the 23^{rd} harmonic frequency at the LV 3 is where Customer 3 has exceeded the harmonic limit set by the international standard.

Table 6.11 showed the comparison between the conclusion made in Papic et al. (2019) and the conclusion was drawn in this study using the same network modelled in different software packages to determine the harmonic source contributor. Papic et al. (2019) demonstrated this using the voltage harmonic vector method, the IEC voltage phase method, and illustrative results from simulations using the PSCAD software package. For this study, the direction of the active power flow method was used using simulation using the DIgSILENT software package and individual and total harmonic distortion of the current and voltage of different customers and points within the network.

Table 6.11: Comparison of harmonic contributor/responsibility per case study

Case studies	Papic et al. (2019) conclusion	This study conclusion
Case study A	Customer 1	Customer 1
Case study B	Customer 1	Customer 1
Case study C	Customer 1 and Customer 2	Customer 2

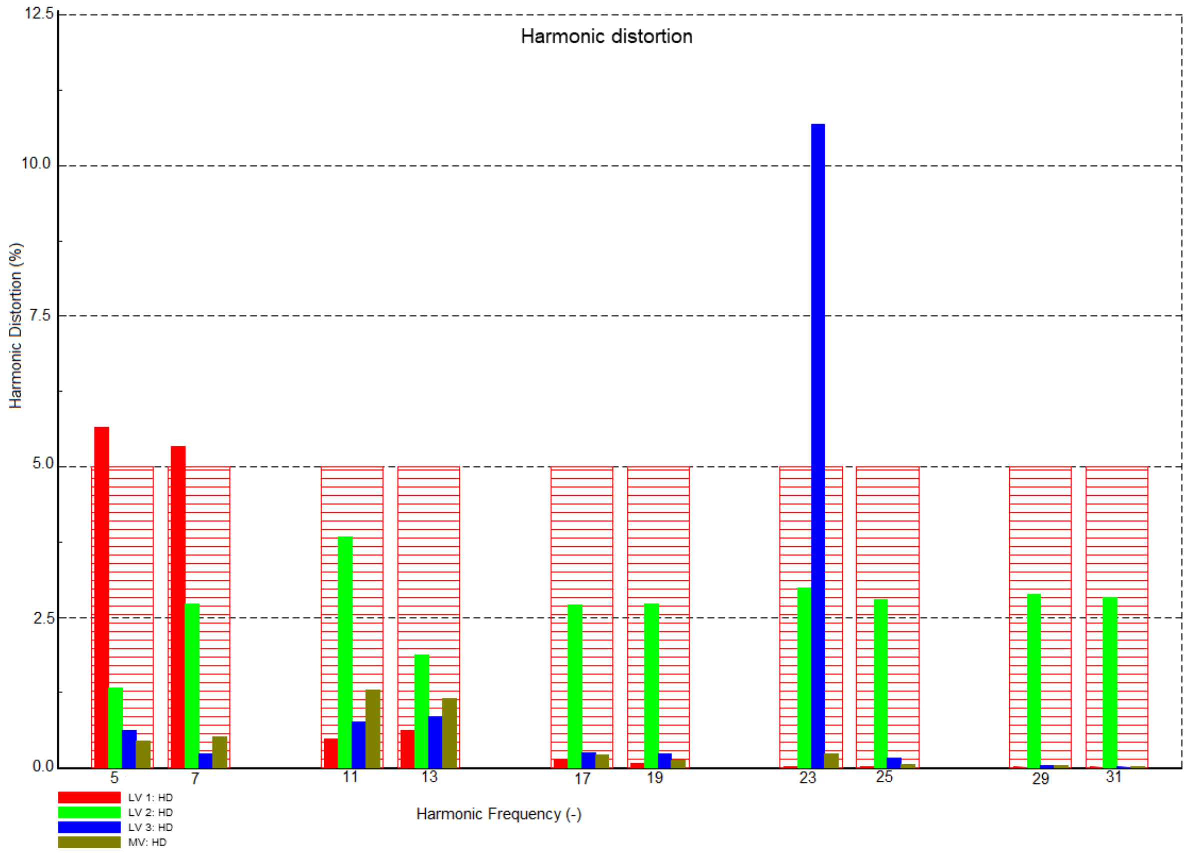


Figure 6.13: Case C_Comparison of voltage harmonic distortion with IEEE std. 519 (2014) for voltage (below 1kV)

6.2.4. Case study D

Case study C with the addition of renewable energy sources of 1 MW solar PV connected at the LV 3 and 5 MW wind turbine generator (WTG) connected at MV made up Case study D. This gave an understanding of how the active power flowed at the fundamental frequency as well as at harmonic frequency.

Figure 6.14 presented the direction of active power flow from the grid, WTG 5 MW, and 1 MW solar PV at the fundamental frequency. It is known that at the fundamental frequency the active power flows from the grid, although with a penetration of the RES the new phenomenon of the direction of active power was represented in Figure 6.14. Figure 6.15 – Figure 6.18 gave the direction of active power flow at the harmonic frequency.

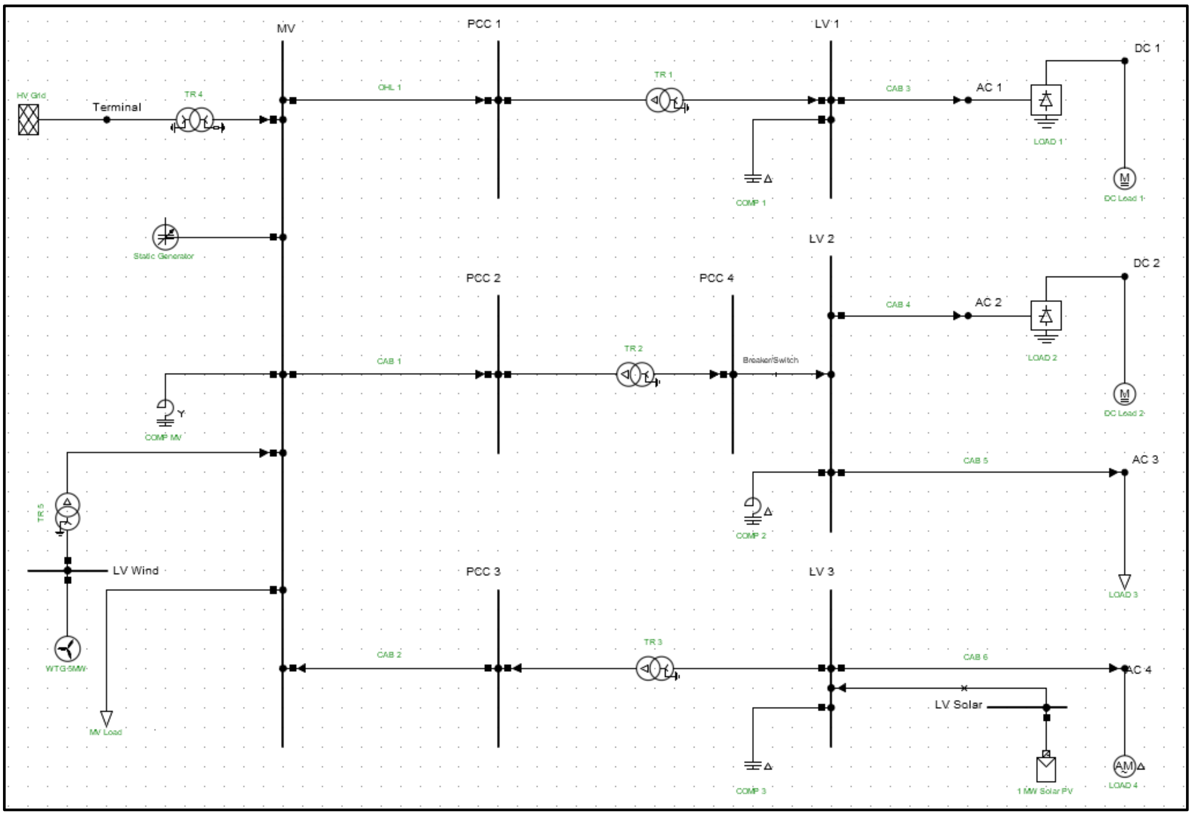


Figure 6.14: Case D_Active power flow for the 1st fundamental frequency

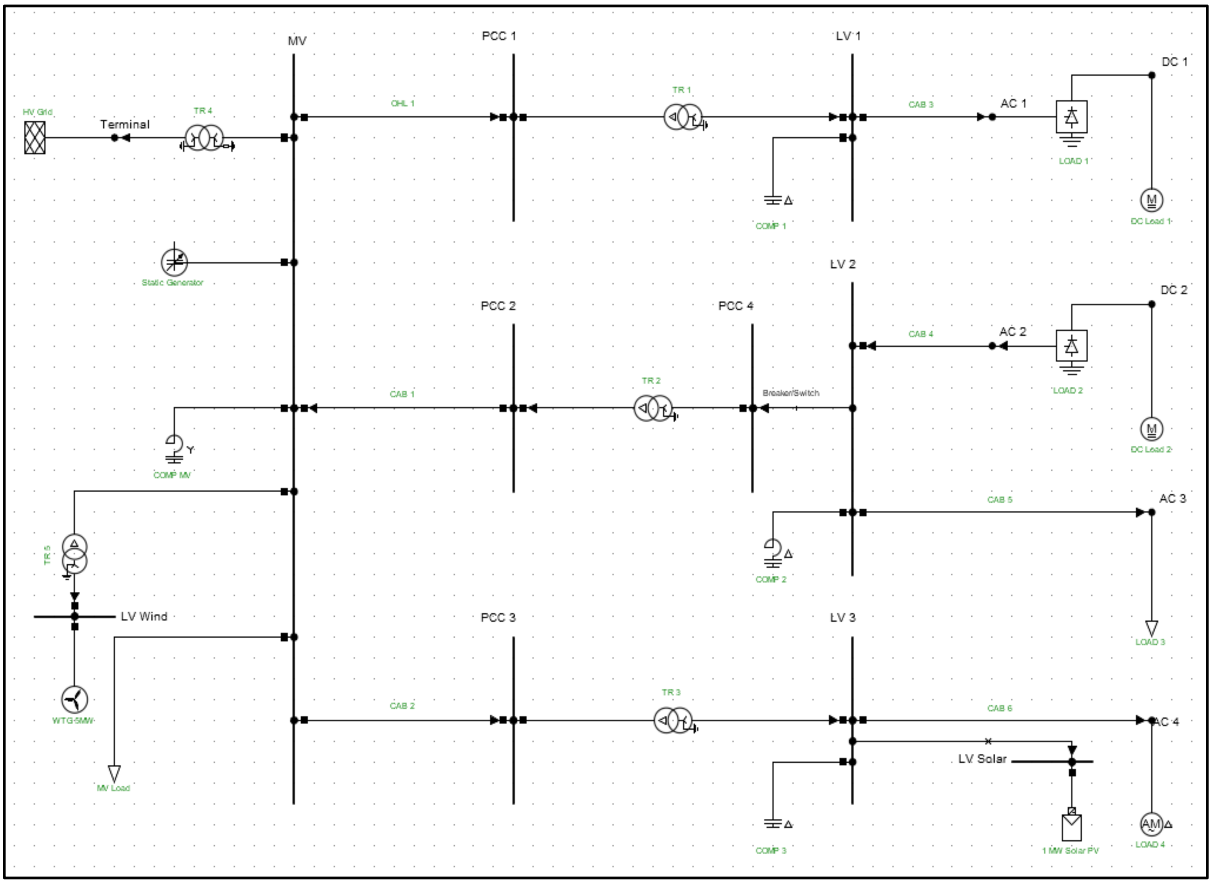


Figure 6.15: Case D_Active power flow for the 5th harmonic frequency

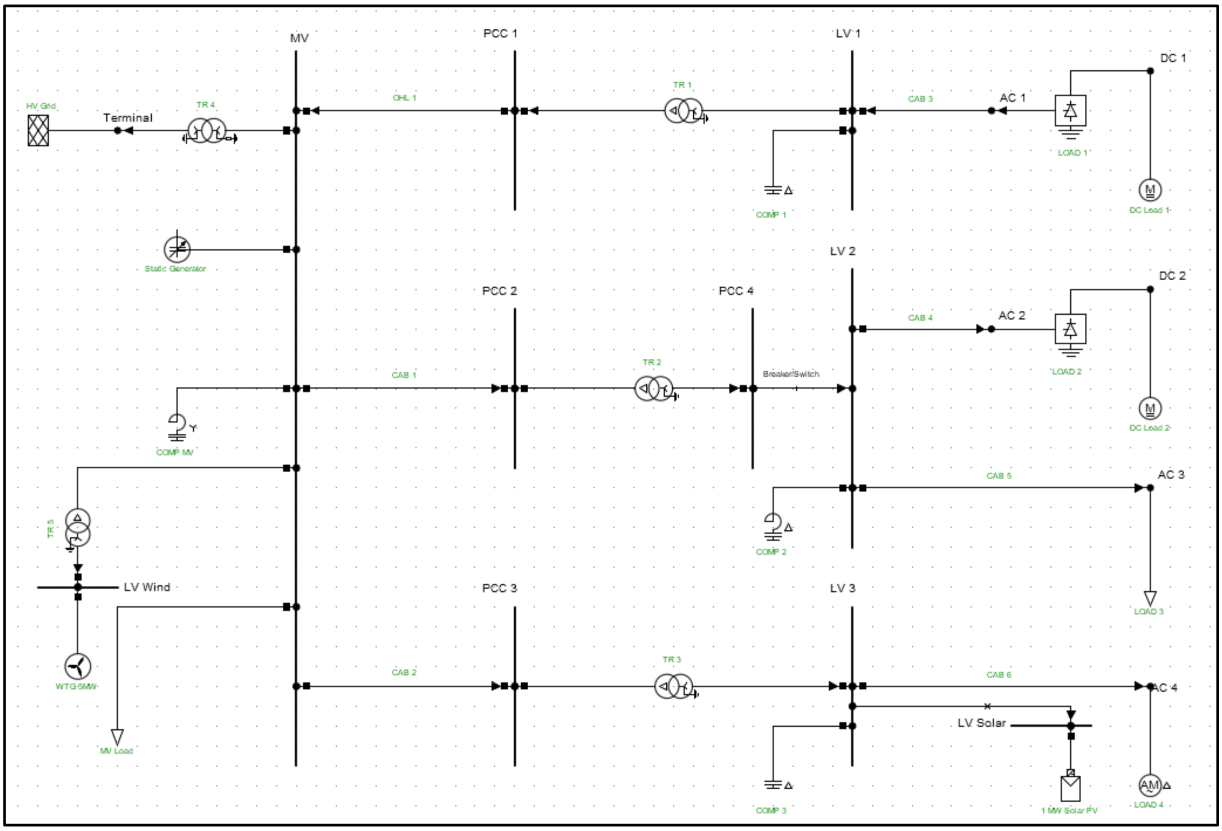


Figure 6.16: Case D_Active power flow for the 7th harmonic frequency

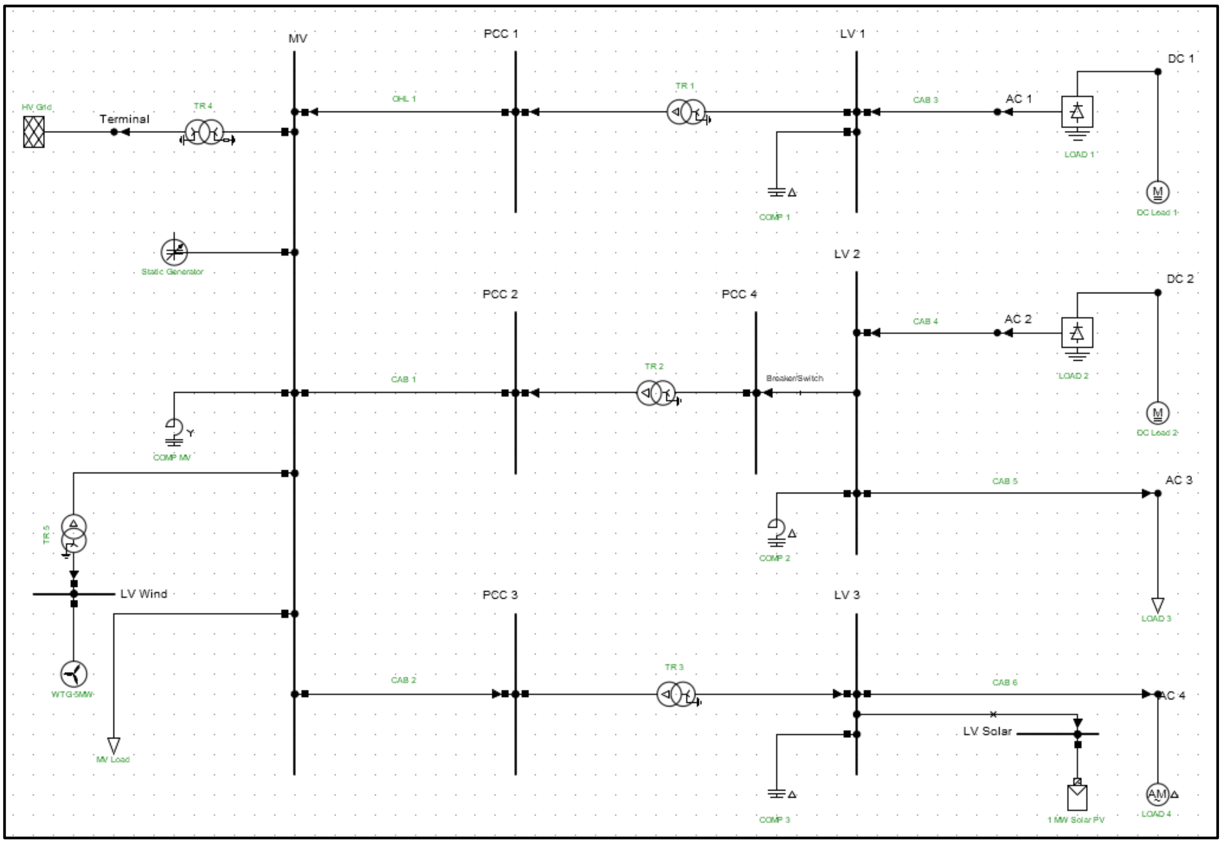


Figure 6.17: Case D_Active power flow for the 11th harmonic frequency

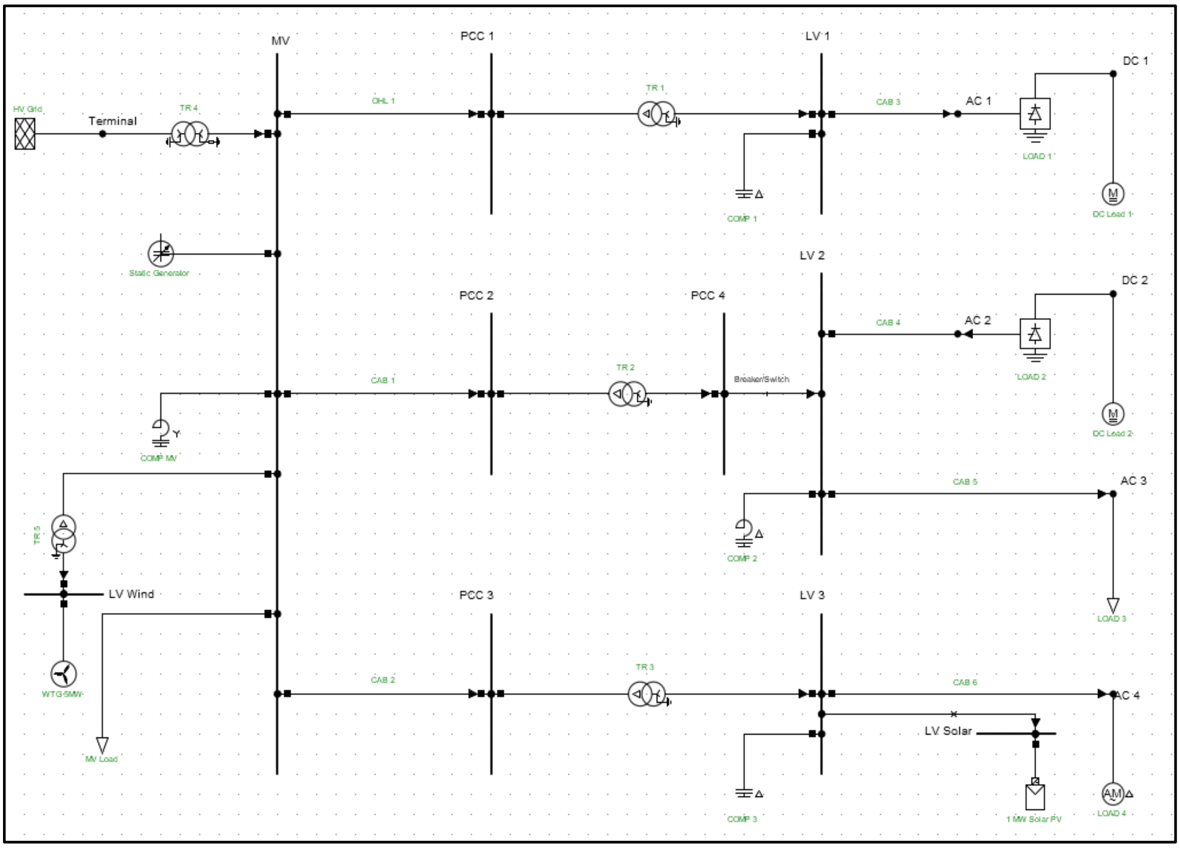


Figure 6.18: Case D_Active power flow for the 13th harmonic frequency

According to the direction of active power flow indicated in Figure 6.14 – Figure 6.18 and Table 6.15, the harmonic contributor per harmonic frequency was summarised in Table 6.12. When RES was part of the network it was identified that its power was mostly used because of lack of availability for the storage system. The main source of harmonic for case study D was Customer 2 (LOAD 2) with an ITHD of 29.418% indicated in Figure 6.14, and with the highest total power as indicated in Table 6.15. Customer 3 (LOAD 4) was negatively affected by the harmonic from LOAD 2; at LV 3 the VTHD was higher than LV 1 and LV 2, as presented in Figure 6.13.

Table 6.12: Case D_Summary of the harmonic contributor at different harmonic frequencies

Harmonic frequency	**Harmonic contributor**	**Main contributor**
1st	Utility, 1 MW Solar PV and 5 MW WTG	5 MW WTG
5th	Customer 2	Customer 2
7th	Customer 1	Customer 1
11th	Customer 1 and Customer 2	Customer 2
13th	Utility and Customer 1	Utility

Table 6.13: Case D_HD and THD of voltage at different points within the network

HD%	LV 1	LV 2	LV 3	PCC 1	PCC 2	PCC 3	PCC 4	MV	LV solar	LV Wind
5th	5.648	1.334	0.629	0.456	0.459	0.447	1.334	0.446	0.629	0.446
7th	4.987	2.705	0.242	0.541	0.530	0.520	2.705	0.527	0.242	0.527
11th	0.483	3.834	0.761	1.294	1.327	1.292	3.834	1.297	0.761	1.298
13th	0.664	1.773	0.954	1.293	1.269	1.292	1.773	1.298	0.954	1.298
THD%	7.581	8.646	10.790	1.992	1.993	1.975	8.646	1.991	10.790	1.992

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Table 6.14: Case D_HD and THD of current for the utility and customers

HD %	Utility	Customers		
		Customer 1 (LOAD 1)	Customer 2 (LOAD 2)	Customer 3 (LOAD 4)
5th	6.124	5.570	20.00	1.873
7th	3.512	2.657	14.286	7.536
11th	8.102	1.018	9.091	5.562
13th	6.762	0.855	7.692	4.919
THD (%)	12.754	6.355	29.418	27.055

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Table 6.15: Case D_Power at harmonic frequencies for the utility and customers

Power (kW)	Utility	Solar PV	WTG	Customers		
				Customer 1 (LOAD 1)	Customer 2 (LOAD 2)	Customer 3 (LOAD 4)
1st	2095	1000	5000	550	550	200
5th	-0.001	0	0	0.058	-0.365	0.001
7th	-0.034	0	0	-0.317	0.149	0.001
11th	-0.001	0	0	-0.032	-0.038	0
13th	0.076	0	0	0.007	-0.003	0
P_T	2094.04	1000	5000	499.716	549.743	200.002

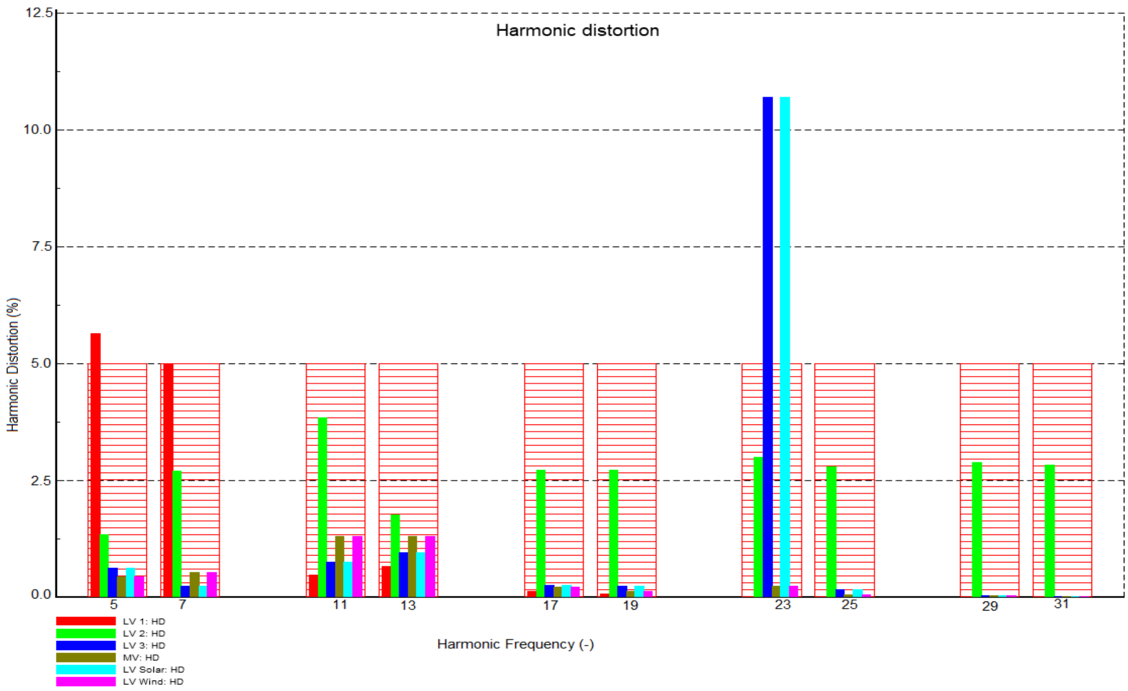


Figure 6.19: Case D_Comparison of voltage harmonic distortion with IEEE std. 519 (2014) for voltage (below 1kV)

When RES was part of the network, it was only the 5th harmonic order for LV1 and 23rd harmonic order for LV 3 and LV solar that exceeded the harmonic limit specified by the standard.

Case study D had two renewable energy sources with three customers all connected at different PCCs; the point of common coupling for all these three customers is MV (busbar). The network had harmonic distortion and the source of it was identified. Table 6.16 interpreted the active power sign at the harmonic frequency and highlights the meaning of the total power for each customer connected at the PCC. The total power (TP) was obtained from DIgSILENT; the software used the same formulae to calculate the total power.

Table 6.16: Active power at harmonic frequencies for the customers at MV busbar

Active Power (kW)	**Customer 1**	**Customer 2**	**Customer 3**
P_1	564.762	715.788	-798.453
P_5	0.116	-0.119	0.001
P_7	-0.301	0.260	0.004
P_{11}	-0.030	0	0.002
P_{13}	0.009	0.026	0.001
P_T calculated	564.556	715.955	-798.445
TP from DIgSILENT (MW)	0.565	0.716	-0,798

The positive sign of active power of the load means the load was absorbing power while the negative sign means that the load was generating power, this validated the equation in Table 4.5 in Chapter 4. For instance, at the fundamental frequency, customer 1 and customer 2 were absorbing power from the grid or the RES while customer 3 was generating power. Customer 3 was connected at the LV 3 busbar where a 1MW Solar PV was also connected. Solar PV is a RES that is generating power. At the 13th harmonic frequency, all three customers were absorbing power; this means that the generation of this harmonic was from the utility side. For 11th harmonic frequency, it was noticed that Customer 2 had zero power at the PCC; this meant that it generates low harmonic power and with the network losses, it cannot reach the PCC. The total active power highlighted that the main source of harmonic was from customer B with the highest value. It also highlighted that Customer 3 always absorbed the harmonics. Although this customer was not a source of harmonic, the awareness needs to be in place as the harmonic from the other customers could have negative effects and damage the equipment.

Table 6.17 highlighted the total and individual active power at the PCC, which in this case was MV. This validated the equation in Table 4.2 and Table 4.3 in Chapter 4. The value of the voltage and its angle at the MV was obtained from DIgSILENT at different harmonic frequencies (1st, 5th, 7th, 11th and 13th). The value of current and its angle were obtained from the MV side of the TR 4 at different harmonic frequencies. The formulae used were:

$$P_{pcc(h)} = V\angle\theta \times I^{*}\angle\varphi \tag{6.1}$$

$$P_{T\_pcc} = P_1 + \sum P_h \tag{6.2}$$

Table 6.17: Case D_Harmonic source determination of individual harmonic frequency and total power at the PCC

	Power (kW)	Sign	Harmonic source
Power of individual harmonic frequency	$P_{Pcc(1)} = -3052.727$	Negative	utility
	$P_{Pcc(5)} = 0.255$	Positive	customer
	$P_{Pcc(7)} = 0.055$	Positive	customer
	$P_{Pcc(11)} = 0.0007$	Positive	customer
	$P_{Pcc(13)} = -0.044$	Negative	utility
Total active power	$P_{T\_Pcc} = -3052.461$	Negative	customer

6.3. Comparison of the case studies within Benchmark IEEE PES test system

Description of case studies is summarised as follow:

i. Case study A – 2 customers in the operation

Different operation configuration as per Table 5.1

ii. Case study B – 2 customers in the operation

iii. Case study C – 3 customers in the operation

iv. Case study D – similar to Case study C with RES $\begin{cases} 1\text{ MW Solar} - \text{connected at LV 3} \\ 5\text{ MW Wind} - \text{connected at MV} \end{cases}$

Based on the case studies the different comparisons indicated in Table 6.18 – Table 6.20 were made for a better understanding of the results tabulated per case study.

Table 6.18: Comparison of the direction of active power flow

Harmonic Order	**Case studies**			
	Case study A	**Case study B**	**Case study C**	**Case study D**
1st	HV Grid (utility)	utility	utility	utility and RES
5th	customer 1	customer 1	customer 2	customer 2
7th	utility	customer 1	customer 1	customer 1
11th	customer 1	customer 1	customer 1 and 2	customer 1 and 2
13th	customer 1	customer 1	utility and customer 2	utility and customer 2

The direction of active power flow as indicated by DIgSILENT was summarised in Table 6.18, thus it gives the harmonic source per harmonic frequencies. This indicated that the direction of active flow is directly proportional to the network operation configuration.

Table 6.19 gave the comparison of the different busbars with the total harmonic distortion of the voltage in each case study. The percentage of the VTHD indicated that for case studies A and B the point which was affected most was LV 1 where customer 1 was connected. In case studies C and D, the network point affected more by the VTHD was LV where Customer 3 was connected. This showed the harmonic content injected by another load connected at a different point in the network could affect the nearest point in the network.

Table 6.19: Comparison of the percentage for VTHD at different points in the network

	Busbars	**Case studies**			
		Case study A	**Case study B**	**Case study C**	**Case study D**
VTHD (%)	LV 1	**8.617**	**7.537**	7.813	7.581
	LV 2	0.384	0.540	8.664	8.646
	LV 3	0.507	1.388	**10.777**	**10.790**
	PCC 1	0.402	0.561	1.896	1.992
	PCC 2	0.384	0.540	1.899	1.993
	PCC 3	0.384	0.546	1.881	1.975
	PCC 4	0.384	0.540	8.664	8.646
	MV	0.383	0.539	1.894	1.991

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Table 6.20 gave a comparison for the percentage of the ITHD of different customers within the network.

Table 6.20: Comparison of the percentage for ITHD of different customers

	Customers	Case studies			
		Case study A	Case study B	Case study C	Case study D
ITHD (%)	Customer 1	**6.272**	**6.259**	6.364	6.355
	Customer 2	N/A	N/A	**29.418**	**29.418**
	Customer 3	3.585	0.762	26.876	27.055

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

For case studies A and B, customer 1 injects the highest harmonic current. Hence, in case studies C and D, Customer 2 injects the highest harmonic current. Therefore, the customer who injects the highest harmonic current was the source of harmonic for that specific case study. To validate the harmonic source, the total power was calculated in case study D, which concluded that Customer 2 was a dominant harmonic source. The individual harmonic distortion was also analysed to ensure which harmonic order was dominant. These were applicable in case the test system requires a harmonic mitigation method. Therefore, the direction of active power flow was a good indication of the source of harmonic of the network.

6.4. The radial distribution network for new adapted equivalent circuits

6.4.1. Simulation case study

It has been the practice to represent multiple customers as one at the point of common coupling and complete the mathematical model using the Thevenin and Norton equivalent circuits. However, this mathematical model no longer holds as customers have the different operation and load conditions. To represent multiple customers as one gives inaccurate information. This network was therefore simulated to give an overview of the differences in voltage and current at the PCC when multiple customers are represented as one and when the multiple customers are represented as individually.

The supply power at the fundamental frequency was from the utility and solar PV plant as a RES, thus to obtain the total current at the PCC the following equation (6.3) should be used taking into consideration the angle. When two sources of supply were part of the network, they form a parallel circuit.

$$I_{Pcc} = I_{solar} + I_{voltage\ source} \tag{6.3}$$

The value of current obtained by using this equation (6.4) is tested using the current flowing into the circuit, which should be equal to the current flowing out of the circuit.

$$I_{supply} = I_{load} \tag{6.4}$$

The direction of active power flow was used to determine the source to calculate the total current at the PCC as given in Table 6.21. For this case study, it was done only at the fundamental frequency, where there were two sources. To obtain the value of current and voltage at the PCC with multiple customers connected at the PCC were combined and represented as one, the sum of the power of the three customers was calculated including the power losses of cable 1 (CAB 1) and represented in Customer A. This does not take into consideration each customer's operating condition during fundamental and harmonic frequency. In this case study, only the magnitude value of current and voltage is given in Table 6.23.

Table 6.21: Voltage and current at the PCC at different harmonic frequencies

Harmonic frequencies	**Combined customers**		**Individual customers**	
	$\mathbf{V_{pcc}\ (kV)}$	$\mathbf{I_{pcc}\ (kA)}$	$\mathbf{V_{pcc}\ (kV)}$	$\mathbf{I_{pcc}\ (kA)}$
1^{st}	0.383	13.439	0.386	10.349
5^{th}	0.072	0.815	0.090	1.475
7^{th}	0.051	0.422	0.048	1.054
11^{th}	0	0	0.014	0.670
13^{th}	0	0	0.014	0.567

Table 6.21 indicated clearly that when the multiple customers were represented as one it does not represent the true scenario of a power system as the voltage and current at the PCC differ. The differences were discussed in Chapter 4 as part of the mathematical model and this was validated in the simulation case study. It was observed that when multiple customers were combined as one, the was zero value for the 11^{th} and 13^{th} harmonic frequencies as the background harmonic only consists of the 5^{th} and 7^{th} harmonic orders. Table 6.22 and Figure 6.21 – Figure 6.22 presented the differences in voltage harmonic distortion and total harmonic distortion at the PCC when multiple customers were represented differently within the network. Thus, it was concluded that combining the customers connected at the PCC as one could give inaccurate information about the case study or power system harmonic distortion.

Table 6.22: HD and THD of the voltage at bus 2 (PCC)

HD (%) of harmonic frequency	Combined customers	Individual customers
5^{th}	18.829	23.245
7^{th}	13.421	12.457
11^{th}	0	3.718
13^{th}	0	3.722
THD (%)	23.123	28.431

6.4.2. Hand calculation using mathematical model formulae

Three customers were used to conduct two case studies in each equivalent circuit. Firstly, the three customers' impedance were represented as a single customer, and secondly, three customers were represented separately. The input data used for the case studies is given in Table 6.23. The current and voltage were obtained from the simulation case study, whereas the impedance and admittance were calculated.

Table 6.23: Input data used for case studies

V_u	$11000\angle 0\ V$
V_c	$386\angle 28.727\ V$
I_u	$307\angle -58.356\ A$
I_c	$8448\angle -28.358\ A$
I_{cA}	$2994\angle -8.143\ kA$
I_{cB}	$7375\angle -16.001\ kA$
I_{cC}	$3046\angle -149.290\ kA$
Z_u	$35.831\angle 58.358\ \Omega$
Z_{cA}	$0.129\angle 36.87\ \Omega$
Z_{cB}	$0.052\angle 44.728\ \Omega$
Z_{cC}	$0.127\angle 178.017\ \Omega$
$Z_T\ or\ Z_c$	$0.046\angle 57.085\ \Omega$
Y_u	$0.028\angle -58.356\ \mho$
Y_{cA}	$7.752\angle -36.87\ \mho$
Y_{cB}	$19.231\angle -44.728\ \mho$
Y_{cC}	$7.874\angle -178.017\ \mho$
Y_c	$21.740\angle -57.085\ \mho$

6.4.2.1. Norton equivalent circuit

i. Single customer

$$V_{u-pcc} = \frac{I_u}{Y_u+Y_c} = \frac{307\angle-58.356}{0.028\angle-58.356+21.740\angle-57.085} = 14.103\angle-1.269\,V$$

$$V_{c-pcc} = \frac{-I_c}{Y_u+Y_c} = \frac{-(8448\angle-28.358)}{0.028\angle-58.356+21.740\angle-57.085} = 388.093\angle-151.271\,V$$

$$V_{pcc} = V_{u-pcc} + V_{c-pcc} = 14.103\angle-1.269 + 388.093\angle-151.271 = \mathbf{375.945\angle-150.197}$$

$$I_{u-pcc} = I_u - (V_{u-pcc} \times Y_u) = 307\angle-58.356 - (14.103\angle-1.269 \times 0.028\angle-58.356) = 306.605\angle-58.354\,A$$
$$I_{c-pcc} = -I_c - (V_{c-pcc} \times Y_c) = -(8448\angle-28.358) - (388.093\angle-151.271 \times 21.740\angle-57.085) = 10.862\angle150.088\,A$$
$$I_{pcc} = I_{u-pcc} - I_{c-pcc} = 306.605\angle-58.354 - 10.862\angle150.088 = \mathbf{316.198\angle-57.417\,A}$$

ii. Multiple customers

$$V_{u-pcc} = \frac{I_u}{(Y_u+Y_{cA})+(Y_u+Y_{cB})+(Y_u+Y_{cC})}$$
$$= \frac{307\angle-58.356}{(0.028\angle-58.356+7.752\angle-36.87)+(0.028\angle-58.356+19.231\angle-44.728)+(0.028\angle-58.356+7.874\angle-178.017)}$$
$$= 13.894\angle--1.370\,V$$

$$V_{c-pcc} = \frac{-(I_{cC}+I_{cB}+I_{cA})}{(Y_u+Y_{cA})+(Y_u+Y_{cB})+(Y_u+Y_{cC})}$$
$$= \frac{-(2994\angle-8.143+7375\angle-16.001+3046\angle-149.290)}{(0.028\angle-58.356+7.752\angle-36.87)+(0.028\angle-58.356+19.231\angle-44.728)+(0.028\angle-58.356+7.874\angle-178.017)}$$
$$= 382.315\angle-151.372\,V$$

$$V_{pcc} = V_{u-pcc} + V_{c-pcc} = 13.894\angle-1.370 + 382.315\angle-151.372 = \mathbf{370.347\angle-150.297\,V}$$

$$I_{u-pcc} = I_u - (V_{u-pcc} \times Y_u) = 307\angle-58.356 - (13.894\angle-1.370 \times 0.028\angle-58.356) = 306.611\angle-58.354\,A$$

$$I_{c-pcc} = \left(-I_{cC} - (V_{c-pcc} \times Y_{cC})\right) + \left(-I_{cB} - (V_{c-pcc} \times Y_{cB})\right) + \left(-I_{cA} - (V_{c-pcc} \times Y_{cA})\right)$$
$$= \left(-(3046\angle-149.290) - (382.315\angle-151.372 \times 7.874\angle-178.017)\right) +$$
$$\left(-(7375\angle-16.001) - (382.315\angle-151.372 \times 19.231\angle-44.728)\right) +$$
$$\left(-(2994\angle-8.143) - (382.315\angle-151.372 \times 7.752\angle-36.87)\right)$$
$$= 32.271\angle150.373\,A$$

$$I_{pcc} = I_{u-pcc} - I_{c-pcc} = 306.611\angle-58.354 - 32.271\angle150.373 = \mathbf{335.269\angle-55.702\,A}$$

In Table 6.24, the voltage and current at the PCC were compared to determine the difference in modelling.

Table 6.24: Comparison of the voltage and current at the PCC using Norton equivalent circuit

	Multiple customers represented as Single customer	**Multiple customers represented individual**
V_{pcc}	$375.945\angle-150.197\,V$	$370.347\angle-150.297\,V$
I_{pcc}	$316.198\angle-57.417\,A$	$335.269\angle-55.702\,A$

The multiple customers were connected at the PCC and represented as a single customer; this does not give a true meaning when it comes to the voltage and current at the PCC using the Norton equivalent circuit. Thus, the customers need to be modelled individually as it is in the practical power system.

6.4.2.2. Thevenin equivalent circuit

i. Single customer

$$I_{u-pcc} = \frac{V_u}{Z_u+Z_c} = \frac{11000\angle 0}{35.831\angle 58.356+0.046\angle 57.085} = 306.603\angle -58.354\ A$$

$$I_{c-pcc} = \frac{V_c}{Z_u+Z_c} = \frac{386\angle 28.727}{35.831\angle 58.356+0.046\angle 57.085} = 10.759\angle -29.627\ A$$

$$I_{pcc} = -I_{c-pcc} + I_{u-pcc} = -(10.759\angle -29.627) + 306.603\angle -58.354 = \mathbf{297.213\angle -59.351\ A}$$

$$V_{u-pcc} = V_u - (I_{u-pcc} \times Z_u) = 11000\angle 0 - (306.603\angle -58.354 \times 35.831\angle 58.356) = 14.113\angle -1.557\ V$$
$$V_{c-pcc} = V_c - (I_{c-pcc} \times Z_c) = 386\angle 28.727 - (10.759\angle -29.627 \times 0.046\angle 57.085) = 385.505\angle 28.729\ V$$
$$V_{pcc} = V_{u-pcc} + V_{c-pcc} = 14.113\angle -1.557 + 385.505\angle 28.729 = \mathbf{397.756\angle 27.703\ V}$$

ii. Multiple customers

$$I_{u-pcc} = \frac{V_u}{(Z_u+Z_{cA})+(Z_u+Z_{cB})+(Z_u+Z_{cC})}$$
$$= \frac{11000\angle 0}{(35.831\angle 58.356 + 0.129\angle 36.87) + (35.831\angle 58.356 + 0.052\angle 44.728) + (35.831\angle 58.356 + 0.127\angle 178.017)}$$
$$= 102.230\angle -58.383\ A$$

$$I_{c-pcc} = \frac{V_{cA} = V_{cB} = V_{cC}}{(Z_u + Z_{cA}) + (Z_u + Z_{cB}) + (Z_u + Z_{cC})}$$

$$= \frac{386\angle 28.727}{(35.831\angle 58.356 + 0.129\angle 36.87) + (35.831\angle 58.356 + 0.052\angle 44.728) + (35.831\angle 58.356 + 0.127\angle 178.017)}$$
$$= 3.587\angle -29.656\ A$$

$$I_{pcc} = -I_{c-pcc} + I_{u-pcc} = -(3.587\angle -29.656) + 102.230\angle -58.383 = \mathbf{99.099\angle -59.380\ A}$$

$$V_{u-pcc} = V_u - (I_{u-pcc} \times Z_u) = 11000\angle 0 - (102.230\angle -58.383 \times 35.831\angle 58.356) = 7339.997\angle 0.013\ V$$

$$V_{c-pcc} = (V_{cC} = V_{cB} = V_{cA}) - \begin{pmatrix} (I_{c-pcc} \times Z_{cC}) + \\ (I_{c-pcc} \times Z_{cB}) + (I_{c-pcc} \times Z_{cA}) \end{pmatrix}$$
$$= 386\angle 28.727 - \begin{pmatrix} (3.587\angle -29.656 \times 0.127\angle 178.017) + \\ (3.587\angle -29.656 \times 0.052\angle 44.728) + (3.587\angle -29.656 \times 0.129\angle 36.87) \end{pmatrix}$$
$$= 385.614\angle 28.700\ V$$

$$V_{pcc} = V_{u-pcc} + V_{c-pcc} = 7339.997\angle 0.013 + 385.614\angle 28.700 = \mathbf{7680.510\angle 1.394\ V}$$

Table 6.25 showed the voltage and current at the PCC using the Thevenin equivalent circuit, which was compared to determine the difference in modelling.

Table 6.25: Comparison of the voltage and current at the PCC using Thevenin equivalent circuit

	Multiple customers represented as a single customer	**Multiple customers represented individually**
V_{pcc}	$\mathbf{397.756\angle 27.703\ V}$	$\mathbf{7680.510\angle 1.394\ V}$
I_{pcc}	$\mathbf{297.213\angle -59.351\ A}$	$\mathbf{99.099\angle -59.380\ A}$

There was a difference in voltage and current when multiple customers were connected at the PCC and represented as a single customer, compared to when multiple customers were modelled separately using the Thevenin equivalent circuit. The modelling of the power system has an effect on the value of current and voltage at the PCC as well as the percentage of the individual harmonic distortion and total harmonic distortion of the voltage.

For any circuit analysis, the Norton and Thevenin equivalent circuits should be represented with the number of customers as they are in the practical power system to obtain the correct overview of the network. The challenge is that to analyse a power system using the impedance is critical as the impedance varies depending on the load and operation of the network. During switching, the impedance differs compared to the normal operation. The impedance when the power system is operating at full load differs compared to when it operates at half load. The power system is not stable as switching at the utility can affect the utility impedance and may affect the impedance of the customers. Using Thevenin and Norton equivalent circuits for harmonic source is not possible as the impedance of the utility and customers varies.

6.4.3. Comparison between hand calculation and simulation results

Both hand calculation and simulation results showed that there is a difference between representing customers as one and modelling individually, reflecting a practical power system. Thus to conclude, the existing equivalent Norton and Thevenin's circuits do not represent a practical power system. A power system has a different number of customers connected at the point of common coupling. The number of customers connected at the point of common coupling must be mathematically modelled and be part of the equivalent circuits to give the correct circuit analysis. Most researchers use the equivalent circuit for harmonic source detection, which is incorrect due to the fact that the impedance used in the circuit varies because of the load and operation conditions of the network. Apart from the impedance that varies, the circuit does not represent a true power system. The mathematical model for adapted equivalent circuits gave a state of the art model of the circuit that can be used in the modern era. Researchers who use existing equivalent circuits for harmonic source detection can re-model case studies using adapted equivalent circuits to verify the difference in the results. Using the existing equivalent circuit cannot quantify the contributions of harmonics as the diverse customers are represented as a single customer. It was found that the adapted equivalent circuits can be used for circuit analysis and academic purposes but not for harmonic source analysis.

6.5. Industrial network

The industrial network represents a Namibian network where two zinc mines are connected at the same point. One of the zinc mines is an underground mine whereas the other is an open-pit mine. These mines have different operating and load conditions with various equipment and machinery. For a certain period, the THD at 66kV Obib (PCC) was observed to have exceeded the limit. Four different case studies were analysed.

6.5.1. Case study 1 - Normal condition

6.5.1.1. Network with double busbars for Skorpion Zinc mine – Case study 1A

The Skorpion Zinc mine has three-phase, 12-pulse rectifiers that are sources of harmonic with the 11th and 13th as dominant harmonics. The Rosh Pinah zinc mine has many three-phase, 6-pulse VSDs that drive the induction motor. These VSDs are sources of harmonic with 5th and 7th as dominant harmonics. The solar PV farm is a renewable energy source known to be a harmonic source as well. This case study was analysed based on the direction of active power flow, THD, and HD and total active power to determine the source of harmonics at the PCC and quantify the contributions. These scenarios were validated by the practical measurements done at the site and obtained using PQ Secure software for UP-2210.

At normal conditions, the active power flows were from the grid (utility) as well as from the RES, in this case, a solar PV farm. Due to the complexity of the network, it was a challenge to graphically represent both network 1 – Benchmark IEEE PES test system, and network 2 – Radial distribution network. These networks were only analysed until the 25th harmonic order. The main harmonic source is according to the direction of active power flow, depending on the power at that harmonic frequency. The party with the highest power determined the main harmonic source.

Table 6.26: Determination of harmonic source based on active power direction flow_ Case study 1A

Harmonic Frequency	**Source of harmonic with Power (kW)**	**Main harmonic source**
1st	Utility – 303152.090 kW Solar PV farm – - 5785.609 kW	Utility
5th	Rosh Pinah Zinc mine – -0.00011 kW Solar PV farm – 0 kW	Rosh Pinah Mine
7th	Rosh Pinah Zinc mine – -0.00066 kW Solar PV farm – 0 kW	Rosh Pinah Mine
11th	Skorpion Zinc mine – -2.93826 kW Rosh Pinah Mine – -0.56741 kW	Skorpion Zinc mine
13th	Skorpion Zinc mine – -1.91228 kW Rosh Pinah Mine – -0.34593 kW	Skorpion Zinc mine
17th	Rosh Pinah Mine – -0.00256 kW	Rosh Pinah Zinc mine
19th	Rosh Pinah Zinc mine – -0.00004 kW Solar PV farm – 0 kW	Rosh Pinah Zinc mine
23rd	Skorpion Zinc mine – -0.644875 kW	Skorpion Zinc mine
25th	Skorpion Zinc mine – -0.510115 kW	Skorpion Zinc mine

Observations were made according to Table 6.26 that the direction of active power flow at the 5^{th}, 7^{th}, and 19^{th} harmonic frequencies of the solar PV farm flowed from the solar plant to the rest of the network. The measured power indicated zero, which meant that the percentage of the harmonic current was minimal. The results obtained from the case study agreed about the dominant harmonic each mine had as a theoretical measure. The Rosh Pinah zinc mine used 6-pulse VSDs whereas the Skorpion Zinc mine had 12-pulse rectifiers. The active power flow direction indicated that customers were responsible for the harmonic observed in this network. The identification of harmonic source per harmonic order is defined as in Table 6.26. Table 6.27 indicated that the total power at the PCC was negative which meant the harmonic source was from customers. Some power at harmonic frequencies were measured at zero, which meant that the harmonic power was too small to reach the PCC. This indicated which customer was the main harmonic source measured at the PCC.

Table 6.27: Determination of harmonic source by total power at the PCC_ Case study 1A

	Power (kW)	**Sign**	**Harmonic source**
Power of individual harmonic frequency	$P_{Pcc(1)} = -303152.290$	Negative - upstream	utility
	$P_{Pcc(5)} = -0.00001$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(7)} = -0.00007$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(11)} = -0.18609$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(13)} = -0.02068$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(17)} = -0.00093$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(19)} = 0$	-	Customer – Rosh Pinah
	$P_{Pcc(23)} = -0.18831$	Negative	Customer – Skorpion Zinc
	$P_{Pcc(25)} = -0.18167$	Negative	Customer – Skorpion Zinc
Total active power	$P_{T\_Pcc} = -303152.868$	Negative	Customer

Table 6.28 gave the active power of each customer to quantify the harmonic contribution per harmonic order as well as the total active power to identify the contributor of harmonic at the PCC. There were six customers as part of the network, but at the PCC only Skorpion Zinc mine and Customer B. Customer B included the solar PV farm, Orange River 1, Spitskop 1, Namdeb Sendelingsdrif 1, and Rosh Pinah zinc mine. The first approach was to determine the harmonic source between Skorpion Zinc and Customer B and its quantification, as indicated in Table 6.28. The second was to quantify the customer contribution within the categories of Customer B as shown in Table 6.29.

Table 6.28: Active power at harmonic frequencies for the customers at the PCC (66kV Obib)_Case study 1A

Active Power (kW)	**Skorpion Zinc mine**	**Customer B**
P_1	293638.1107	9513.97903
P_5	0.00002	-0.00001
P_7	0.00006	-0.00007
P_{11}	0.28089	-0.18609
P_{13}	0.24534	-0.02068
P_{17}	0.00093	-0.00093
P_{19}	0	0
P_{23}	-0.08192	0.06819
P_{25}	-0.0918	0.09179
P_T calculated	293638.4642	9513.93123
TP from DIgSILENT (MW)	293.637	9.515

According to the results obtained in Table 6.28, the harmonic contributor was the Skorpion Zinc mine with the highest total power at the PCC. Skorpion Zinc mine was the one absorbing more power than Customer B at the fundamental frequency.

Table 6.29: Total active power of customers grouped in Customer B_Case study 1A

Active Power (kW)	**Orange River 1**	**Spitskop 1**	**Solar PV farm**	**Namdeb Sendelingsdrif 1**	**Rosh Pinah Mine**
P_1	4170.000	960.000	-5785.609	1000.000	9115.704
P_5	0	0	0	0	-0.00011
P_7	0	0	0	0	-0.00066
P_{11}	0.10518	0.01896	0.00283	0.01677	-0.56741
P_{13}	0.03225	0.00578	0.00094	0.00808	-0.34593
P_{17}	0.00004	0.00001	0	0	-0.00256
P_{19}	0	0	0	0	0
P_{23}	0.00121	0.00021	0.00140	0.00192	0.06144
P_{25}	0	0	0.00047	0.00143	0.08846
P_T calculated	4170.139	960.025	-5785.603	1000.028	9108.863
TP from DIgSILENT (MW)	4.170	0.960	-5.786	1.000	9.115

It was observed that solar PV farm generated power at the fundamental frequency while the other loads absorbed power. The main contributor of harmonic within Customer B was Rosh

Pinah zinc mine with the highest total power as well as generating harmonic power as in Table 6.29.

The harmonic aggregation according to the IEC 61000 – 3 - 6 is stipulated in Table 6.30.

Table 6.30: IEC 61000-3-6 harmonic aggregation method
Adapted from IEC Std. 61000-3-6 (2013)

α	Harmonic order
1	$h < 5$
1.4	$5 < h < 10$
2	$h > 10$

Where α is an exponent representing diversity for harmonic summation for the individual harmonic order given by IEC 61000-3-6. Thus the following formulae were used to calculate the total individual harmonic of voltage and current when multiple harmonic sources were connected at one point, as in Equation 6.5 and Equation 6.6:

$$V_{HD\ total} = \sqrt[\alpha]{\sum V_{HD}^{\alpha}} \quad (6.5)$$

$$I_{HD\ total} = \sqrt[\alpha]{\sum I_{HD}^{\alpha}} \quad (6.6)$$

To calculate the total harmonic distortion of voltage and current, the formula used in Equation 6.7 and Equation 6.8 were given as follows:

$$V_{THD\ total} = \sqrt[\beta]{\sum V_{THD}^{\beta}} \quad (6.7)$$

$$I_{THD\ total} = \sqrt[\beta]{\sum I_{THD}^{\beta}} \quad (6.8)$$

where β is the exponent representing diversity for harmonic summation for THD of voltage and current. The value of β used in the calculation was based on the assumption made by Gosbell & Barr (2014). The harmonic summation law was used to determine the total individual HD and total THD of current for Skorpion Zinc mine as the mine has four rectifiers as a harmonic source connected at different busbars. It was also used to calculate the total individual HD and total THD of voltage as Skorpion Zinc mine has double busbars for operational redundancy purposes due to the critical nature of its operation. It was not possible to calculate the summation of HD and THD by straight addition due to phase, time, and spectral diversity as three factors. The combined THD can only possibly be the sum of the individual THDs when each contribution has the same relative spectrum. Table 6.31 gave the harmonic contribution of each party within a network using the percentage of harmonic distortion as well as defining and quantifying the contribution of each harmonic order. This determined the main contributor of harmonic source based on the THD percentages.

Table 6.31: HD and THD of current for the utility and customers_ Case study 1A

HD %	Utility	Customers					
		Skorpion Zinc mine	Orange River 1	Spitskop 1	Solar PV farm	Namdeb Sendelingsdrif 1	Rosh Pinah Zinc mine
5th	0.008	0.022	0.056	0.051	0.367	0.010	0.306
7th	0.014	0.034	0.086	0.077	0.522	0.019	0.600
11th	1.020	2.944	0.594	0.526	0.987	0.417	1.197
13th	0.933	2.619	0.520	0.459	1.258	0.311	0.950
17th	0.005	0.018	0.036	0.031	0.173	0.010	0.287
19th	0.002	0.006	0.045	0.040	0.313	0.004	0.269
23rd	0.338	1.055	0.059	0.052	1.325	0.139	0.543
25th	0.347	1.019	0.002	0.002	0.778	0.119	0.477
THD (%)	1.496	4.26	0.859	0.758	2.872	0.588	1.931

Harmonic Source Contributor (red)

Exceed the harmonic limits (blue)

Harmonic Source Contributor & Exceed the harmonic limit (green)

It was found that according to the current total harmonic distortion the harmonic source of this network was the Skorpion Zinc mine. The individual current harmonic distortion varied depending on the customer's dominant harmonic order. The harmonic source of the individual current harmonic distortion were as highlighted in Table 6.31. With the network range where the I_{sc}/I_L is < 20 as per Table 2.5 in Chapter 2, the TDD should not exceed 5%. All customers' ITHDs were within the limit. The Solar PV individual current HD% of the 23rd and 25th harmonic exceeded the limit. The Skorpion Zinc mine's HD% of the 11th, 13th, 23rd and 25th exceeded the limit as well.

Table 6.32 gave the individual and total harmonic distortion of the voltage at different points within the network. These results were compared to the measured results obtained on-site. It was observed that according to the voltage total harmonic distortion the Skorpion - Obib Mine was a harmonic source in the network. The other busbars with the highest individual harmonic distortion were the Aloe PV Plant 33kV and Lorelei 33kV.

Table 6.32: HD and THD of voltage at different busbars_Case study 1A

Busbar name	Individual Harmonic Distortion (%)								THD (%)
	5th	7th	11th	13th	17th	19th	23rd	25th	
Aloe PV Plant 33kV	0.10	0.20	2.02	2.07	0.18	0.26	0.43	0	4.53
Lorelei 33kV	0.10	0.20	2.02	2.06	0.18	0.26	0.40	0.01	4.51
Obib – Lorelei 66kV	0.02	0.05	1.73	1.50	0.06	0.02	1.11	1.02	3.55
Skorpion - Obib 1 66kV	0.01	0.01	2.18	1.95	0.01	0	1.52	1.40	4.10
Skorpion – Obib 2 66kV	0.01	0.01	2.18	1.95	0.01	0	1.51	1.39	4.07
Skorpion - Obib 1 and 2 Summation	0.02	0.02	3.08	2.76	0.01	0	2.14	1.97	5.78
Rosh Pinah Mine 66kV	0.02	0.05	1.72	1.49	0.06	0.03	1.11	1.02	3.62
Zincum 66kV	0.02	0.05	1.72	1.49	0.06	0.03	1.11	1.03	3.65
Obib 66kV PCC	0.01	0.01	1.74	1.48	0.01	0	1.21	1.06	3.25

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

The individual and total harmonic distortion of the voltage were within the prescribed limit set by IEEE Std. 519 – 2014. This network range was between 1kV < V ≤ 69 kV as in Table 2.6 in Chapter 2. Thus, the recorded VTHD % and 11th individual voltage HD % which exceeded the summation of the Skorpion – Obib 66 kV only. For the Obib 66kV busbar which was a PCC the VTHD % was still within the prescribed limit, thus for this network, the harmonic filters were working accordingly.

6.5.1.2. Network with single busbar for Skorpion Zinc mine – Case study 1B

To validate the results, the case study was repeated using one busbar only, as the 2nd busbar was only for operational purposes as well as for redundancy because of the critical nature of the Skorpion mine industry. Table 6.33 indicated that the Rosh Pinah mine was a harmonic dominant for 5th, 7th, 17th and 19th, whereas the Skorpion mine was a harmonic dominant for 11th, 13th, 23rd and 25th. Table 6:34 indicated that the harmonic source was from downstream of the network.

Table 6.33: Determination of harmonic source based on active power direction flow_ Case study 1B

Harmonic Frequency	Source of harmonic with Power (kW)	Main harmonic source
1st	Utility – 303152.152 kW Solar PV farm – - 5785.609 kW	Utility
5th	Rosh Pinah Zinc mine – -0.00011 kW Solar PV farm – 0 kW	Rosh Pinah Mine
7th	Rosh Pinah Zinc mine – -0.00066 kW Solar PV farm – 0 kW	Rosh Pinah Mine
11th	Skorpion Zinc mine – -2.93850 kW Rosh Pinah Mine – -0.56741 kW	Skorpion Zinc mine
13th	Skorpion Zinc mine – -1.91251 kW Rosh Pinah Mine – -0.34593 kW	Skorpion Zinc mine
17th	Rosh Pinah Mine – -0.00256 kW	Rosh Pinah Zinc mine
19th	Rosh Pinah Zinc mine – -0.00004 kW Solar PV farm – 0 kW	Rosh Pinah Zinc mine
23rd	Skorpion Zinc mine – -0.64503kW	Skorpion Zinc mine
25th	Skorpion Zinc mine – -0.51024 kW	Skorpion Zinc mine

Table 6.34: Determination of harmonic source by Total Power at the PCC_ Case study 1B

	Power (kW)	Sign	Harmonic source
Power of individual harmonic frequency	$P_{Pcc(1)} = -303152.152$	Negative - upstream	utility
	$P_{Pcc(5)} = -0.00001$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(7)} = -0.00007$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(11)} = -0.18609$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(13)} = -0.02068$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(17)} = -0.00093$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(19)} = 0$	-	Customer – Rosh Pinah
	$P_{Pcc(23)} = -0.08194$	Negative	Customer – Skorpion Zinc
	$P_{Pcc(25)} = -0.0918$	Negative	Customer – Skorpion Zinc
Total active power	$P_{T\_Pcc} = -303152.534$	Negative	Customer

According to Table 6.35, the harmonic source for this case study was Skorpion mine as a customer connected downstream of the network. Table 6.29 under Case study 1A gave similar results for Case study 1B. Thus, the harmonic contributor based on the active power for customers grouped under Customer B was Rosh Pinah Mine.

Table 6.35: Active power at harmonic frequencies for the customers at the PCC (66kV Obib)_Case study 1B

Active Power (kW)	Skorpion Zinc mine	Customer B
P_1	293638.17352	9513.97829
P_5	0.00002	-0.00001
P_7	0.00006	-0.00007
P_{11}	0.28088	-0.18609
P_{13}	0.2453	-0.02068
P_{17}	0.00094	-0.00093
P_{19}	0	0
P_{23}	-0.08194	0.06820
P_{25}	-0.09118	0.09181
P_T calculated	293638.5276	9513.93052
TP from DIgSILENT (MW)	293.638	9.515

Table 6.36 gave the results of individual and total harmonic distortion of current for different loads within the network.

Table 6.36: HD and THD of current for the utility and customers_ Case study 1B

HD %	Utility	Customers					
		Skorpion Zinc mine	Orange River 1	Spitskop 1	Solar PV farm	Namdeb Sendelingsdrif 1	Rosh Pinah Zinc mine
5th	0.008	0.022	0.056	0.051	0.367	0.010	0.306
7th	0.014	0.034	0.086	0.077	0.522	0.019	0.600
11th	1.020	2.944	0.594	0.526	0.987	0.417	1.197
13th	0.933	2.620	0.520	0.459	1.258	0.311	0.950
17th	0.005	0.018	0.036	0.031	0.173	0.010	0.287
19th	0.002	0.006	0.045	0.040	0.313	0.004	0.269
23rd	0.338	1.054	0.059	0.052	1.325	0.139	0.543
25th	0.347	1.018	0.002	0.002	0.778	0.119	0.477
THD (%)	1.496	4.26	0.859	0.758	2.872	0.588	1.931

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Case study 1 B results as given in Table 6.36 for the individual and total harmonic distortion corresponding with the results obtained in Case study 1A. The summation law formulae of the current as Equation 6.6 and Equation 6.8 were used.

Table 6.37: HD and THD of voltage at different busbars_Case study 1B

Busbar name	Individual Harmonic Distortion (%)								THD
	5th	7th	11th	13th	17th	19th	23rd	25th	(%)
Aloe PV Plant 33kV	0.10	0.20	2.02	2.07	0.18	0.26	0.43	0	4.53
Lorelei 33kV	0.10	0.20	2.02	2.06	0.18	0.26	0.40	0.01	4.51
Obib – Lorelei 66kV	0.02	0.05	1.73	1.50	0.06	0.02	1.11	1.02	3.55
Skorpion - Obib 1 66kV	0.01	0.01	2.18	1.95	0.01	0	1.52	1.40	4.10
Skorpion – Obib 2 66kV	0.01	0.01	2.18	1.95	0.01	0	1.51	1.39	4.07
Skorpion - Obib 1 and 2 Summation	0.01	0.01	2.18	1.95	0.01	0	1.52	1.40	4.09
Rosh Pinah Mine 66kV	0.02	0.05	1.72	1.49	0.06	0.03	1.11	1.02	3.62
Zincum 66kV	0.02	0.05	1.72	1.49	0.06	0.03	1.11	1.03	3.65
Obib 66kV PCC	0.01	0.01	1.74	1.48	0.01	0	1.21	1.06	3.25

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

The individual and total harmonic distortion of the voltage were within the prescribed limit set by IEEE Std. 519 – 2014. This network range was between 1kV < V ≤ 69 kV as in Table 2.6 in Chapter 2. The loads connected at Skorpion – Obib 2 66 kV were transferred to Skorpion – Obib 1 66 kV. Skorpion Zinc mine loads were connected at one busbar. This busbar is called respectively called Skorpion – Obib 1 and 2 Summation. If the network was represented in DIgSILENT with one busbar, this does not give the true scenario of the practical network. The result obtained for the busbar Skorpion – Obib 1 and 2 Summation for Case study 1B does not correspond to the results obtained for Case study 1A. According to Table 6.37, the harmonic source of the network was solar PV and this does not correspond to the direction of active power flow as well as the active harmonic power flow. Thus, it was recommended to use the configuration of the network as per the practical network to give accurate results.

6.5.2. Case study 2 – two 66kV harmonic filters at Skorpion mine out of service

This case study was conducted when 66 kV Filter 1 and 66 kV Filter 2 were out of service, for example for maintenance or any other operation that fits the mining area at that specific period. The effect of out of service filters on power transformers was discussed. Table 6.38 gave an overview of the source of harmonic based on active power direction flow at different harmonic orders within the network. Observations made according to Table 6.38 were as per Table 6.26 of case study 1A. The active power at the fundamental frequency was flowing from upstream (grid) and downstream (Solar PV). The 5th, 7th, 17th and 19th are from Rosh Pinah mine. The 11th, 13th, 23rd and 25th were from Skorpion Zinc mine.

Table 6.38: Determination of harmonic source based on active power direction flow_ Case study 2

Harmonic Frequency	Source of harmonic with Power (kW)	Main harmonic source
1st	Utility – 216157.119 kW Solar PV farm – - 5786.627 kW	Utility
5th	Rosh Pinah Zinc mine – -0.00010 kW Solar PV farm – 0 kW	Rosh Pinah Mine
7th	Rosh Pinah Zinc mine – -0.00065 kW Solar PV farm – 0 kW	Rosh Pinah Mine
11th	Skorpion Zinc mine – -6.24098 kW Rosh Pinah Mine – -0.78182 kW	Skorpion Zinc mine
13th	Skorpion Zinc mine – -4.08912 kW Rosh Pinah Mine – -0.52003 kW	Skorpion Zinc mine
17th	Rosh Pinah Mine – -0.00321 kW	Rosh Pinah Zinc mine
19th	Rosh Pinah Zinc mine – -0.00004 kW Solar PV farm – 0 kW	Rosh Pinah Zinc mine
23rd	Skorpion Zinc mine – -1.5883 kW Rosh Pinah Mine - -0.05368 kW	Skorpion Zinc mine
25th	Skorpion Zinc mine – -1.20635 kW Rosh Pinah Mine - -0.00598 kW	Skorpion Zinc mine

Table 6.39 determined whether the harmonic source was from upstream or downstream of the PCC. In this case, it was noticed that the harmonic source was from downstream of the PCC.

Table 6.39: Determination of harmonic source by total power at the PCC_ Case study 2

	Power (kW)	Sign	Harmonic source
Power of individual harmonic frequency	$P_{Pcc(1)} = -216157.119$	Negative - upstream	utility
	$P_{Pcc(5)} = -0.00001$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(7)} = -0.00007$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(11)} = -0.13344$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(13)} = -0.06657$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(17)} = -0.00123$	Negative - downstream	Customer – Rosh Pinah
	$P_{Pcc(19)} = 0$	-	Customer – Rosh Pinah
	$P_{Pcc(23)} = -0.29472$	Negative	Customer – Skorpion Zinc
	$P_{Pcc(25)} = -0.24915$	Negative	Customer – Skorpion Zinc
Total active power	$P_{T\_Pcc} = -216157.864$	Negative	Customer

Table 6.40 demonstrated that Skorpion Zinc mine was a harmonic contributor at the PCC based on the active per harmonic order as well as the total active power. The harmonic contribution of customers who were part of Customer B was quantified in Table 6.41.

Table 6.40: Active power at harmonic frequencies for the customers at the PCC (66kV Obib)_Case study 2

Active Power (kW)	**Skorpion Zinc mine**	**Customer B**
P_1	206642.7291	9514.39025
P_5	0.00002	-0.00001
P_7	0.00006	-0.00007
P_{11}	0.16168	-0.13344
P_{13}	0.27271	-0.05472
P_{17}	0.00123	-0.00123
P_{19}	0	0
P_{23}	0.00294	-0.03144
P_{25}	-0.00196	0.00196
P_T calculated	206643.1658	9514.1713
TP from DIgSILENT (MW)	206.642	9.516

According to the results obtained in Table 6.28, the harmonic contributor was the Skorpion Zinc mine with the highest total power at the PCC. Skorpion Zinc mine was the one absorbing more power than Customer B at the fundamental frequency.

Table 6.41: Total active power of customers grouped in Customer B_Case study 2

Active Power (kW)	**Orange River 1**	**Spitskop 1**	**Solar PV farm**	**Namdeb Sendelingsdrif 1**	**Rosh Pinah Mine**
P_1	4170.000	960.000	-5786.627	1000.000	9116.174
P_5	0	0	0	0	-0.00010
P_7	0	0	0	0	-0.00065
P_{11}	0.24966	0.04502	0.00758	0.03629	-0.78182
P_{13}	0.09444	0.01693	0.00327	0.01765	-0.52003
P_{17}	0.00006	0.00001	0.00001	0.00001	-0.00321
P_{19}	0	0	0	0	-0.00004
P_{23}	0.00343	0.00061	0.00392	0.00515	-0.05368
P_{25}	0	0	0.00124	0.00372	-0.00598
P_T calculated	4170.348	960.022	-5786.611	1000.063	9114.808
TP from DIgSILENT (MW)	4.170	0.960	-5.787	1.000	9.116

It was observed that the solar PV farm was generating power at the fundamental frequency while the other loads were absorbing power. The main contributor of harmonic within Customer B was Rosh Pinah zinc mine with the highest total power; it was also the only one generating harmonic power.

Table 6.42 gave the harmonic contribution of each party within a network using the percentage of harmonic distortion as well as defining and quantifying the contribution of each harmonic order. This determined the main harmonic source contribution based on the THD percentages

Table 6.42: HD and THD of current for the utility and customers_ Case study 2

HD %	**Utility**	**Customers**					
		Skorpion Zinc mine	**Orange River 1**	**Spitskop 1**	**Solar PV farm**	**Namdeb Sendelingsdrif 1**	**Rosh Pinah Zinc mine**
5th	0.014	0.016	0.056	0.051	0.368	0.011	0.304
7th	0.024	0.028	0.087	0.078	0.525	0.020	0.602
11th	2.054	13.020	0.870	0.770	1.457	0.611	1.446
13th	1.848	10.993	0.751	0.663	1.831	0.450	1.090
17th	0.010	0.020	0.041	0.036	0.201	0.012	0.287
19th	0.003	0.006	0.046	0.040	0.322	0.004	0.270
23rd	0.755	6.065	0.096	0.061	2.176	0.227	0.699
25th	0.767	5.556	0.003	0.003	1.263	0.193	0.616
THD (%)	3.060	20.054	1.279	1.130	4.552	0.891	2.357

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

It was found that according to the current total harmonic distortion the harmonic source of this network was Skorpion Zinc mine. The individual current harmonic distortions which exceeded the limit prescribed by IEEE 519-2014 were:

v. Utility – 11th, 23rd and 25th harmonic order

vi. Skorpion Zinc mine – 11th, 13th, 23rd and 25th harmonic order

vii. Solar PV farm – 23rd and 25th harmonic order

viii. Rosh Pinah mine – 23rd and 25th harmonic order

The ITHD that exceeded the limit was only for Skorpion Zinc mine, therefore the harmonic filter should be in operation all the time.

Table 6.43 compared the harmonic distortion for the NamPower power transformers. The IEEE Standard C57.12.00^{TM}-2015 (2015) imposed the following limits on transformers operating in a harmonic environment: the ITHD should not exceed 5%. The Lorelei TR 1 exceeded the prescribed limit even when the Skorpion Zinc harmonic filter was in operation, thus NamPower needs to install the harmonic filter at the Lorelei 33kV busbar to mitigate the harmonic distortion. Transformers were not designed to operate at higher levels of distortion, which increases losses and degradation of the insulation, and lastly, its lifetime was minimized. The ITHDs of the other power transformers were within the limit.

Table 6.43: THD of current for the power transformers

Power Transformers	**ITHD (%)**	
	Filter in operation	**2 x 66kV Filter out of Service**
Obib TR 1/Obib TR 2	1.496	3.060
Skorpion TR 1	3.031	4.449
Skorpion TR 2	2.523	3.692
Rosh Pinah TR 1/Rosh Pinah TR 2	1.928	2.357
Lorelei TR 1	8.045	12.965

Table 6.44 gave the individual and total harmonic distortion of the voltage at different points within the network. It was observed that according to the total harmonic distortion of the voltage, the Skorpion - Obib 1 and 2 summations were harmonic sources in the network. In another term, the Skorpion Zinc mine was a harmonic contributor to the network. The other busbars with high individual harmonic distortion were Aloe PV Plant 33kV and Lorelei 33kV.

Table 6.44: HD and THD of voltage at different busbars_Case study 2

Busbar name	Individual Harmonic Distortion (%)								THD
	5th	7th	11th	13th	17th	19th	23rd	25th	(%)
Aloe PV Plant 33kV	0.10	0.20	2.96	2.99	0.21	0.27	0.69	0	7.41
Lorelei 33kV	0.10	0.20	2.95	2.98	0.21	0.26	0.66	0.02	7.37
Obib – Lorelei 66kV	0.02	0.05	2.52	2.17	0.06	0.02	1.81	1.64	5.75
Skorpion - Obib 1 66kV	0.01	0.01	3.18	2.79	0.02	0	2.46	2.24	6.47
Skorpion – Obib 2 66kV	0.01	0.01	3.17	2.79	0.02	0	2.44	2.22	6.43
Skorpion - Obib 1 and 2 Summation	0.02	0.02	4.49	3.95	0.03	0	3.46	3.15	9.12
Rosh Pinah Mine 66kV	0.02	0.05	2.51	2.16	0.07	0.03	1.82	1.65	5.89
Zincum 66kV	0.02	0.05	2.51	2.16	0.07	0.03	1.82	1.66	5.94
Obib 66kV PCC	0.01	0.01	2.53	2.12	0.02	0.01	1.95	1.69	5.15

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

The 11th individual harmonic distortion of the voltage for Skorpion – Obib 66 kV 1 and 2 exceeded the limit as prescribed by IEEE Std. 519 (2014). In Skorpion – Obib 1 and 2 Summation, the 11th, 13th, 23rd and 25th harmonic order exceeded the limit. For this case study, the VTHD of all busbars exceeded the prescribed limit. The VTHD at the PCC which was Obib 66kV exceeded the limit as well. For NamPower to mitigate the harmonic at the PCC, it was advised to budget for a new harmonic filter to be installed at the PCC. NamPower has no control over Skorpion Zinc mine filters, which made it difficult to make sure that the harmonic filters were all in operation. Harmonic distortion had effects on power equipment thus, NamPower needs to protect its assets, for instance, the transformers.

6.5.3. Case study 3 – all four 66kV harmonic filters at Skorpion mine out of service

This case study was conducted when all four 66 kV filters were out of service, which can be for maintenance or any other operation that fits the mining area at a specific period. The effect of out of service filters on power transformers was discussed. Three case studies confirmed the source of harmonic distortion for this network, thus these case studies only concentrated on the individual and total harmonic distortion of current and voltage without the 66kV filters as part of the network.

Table 6.45 gave the harmonic contribution of each party within a network using the percentage of harmonic distortion as well as defining and quantifying the contribution of each harmonic order. This determined the main contributor of harmonic sources based on the THD percentages.

Table 6.45: HD and THD of current for the utility and customers_ Case study 3

HD %	Utility	Customers					
		Skorpion Zinc mine	Orange River 1	Spitskop 1	Solar PV farm	Namdeb Sendelingsdrif 1	Rosh Pinah Zinc mine
5th	0.025	0	0.057	0.052	0.369	0.012	0.302
7th	0.046	0	0.088	0.079	0.527	0.021	0.598
11th	4.816	17.98	1.320	1.168	2.220	0.927	1.934
13th	4.184	15.15	1.103	0.974	2.699	0.661	1.338
17th	0.025	0	0.052	0.045	0.253	0.015	0.280
19th	0.007	0	0.048	0.042	0.334	0.004	0.270
23rd	2.077	8.331	0.172	0.151	3.926	0.410	0.951
25th	2.024	7.618	0.005	0.005	2.190	0.334	0.803
THD (%)	7.666	27.612	2.198	1.937	9.974	1.586	3.539

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

It was found that according to the current total harmonic distortion the harmonic source of this network was the Skorpion Zinc mine. The individual current harmonic distortion which exceeded the limit prescribed by IEEE 519-2014 were:

ix. Utility – 11th, 13th, 23rd and 25th harmonic order

x. Skorpion Zinc mine – 11th, 13th, 23rd and 25th harmonic order

xi. Solar PV farm – 11th, 13th, 23rd and 25th harmonic order

xii. Rosh Pinah mine – 23rd and 25th harmonic order

The ITHD that exceeded the limit was for Skorpion Zinc mine, utility (NamPower), and the solar PV farm, therefore the harmonic filter should be in operation all the time.

Table 6.46 indicated ITHD % of power transformers as NamPower assets. Rosh Pinah TR 1 and 2 were still operating within the prescribed limit in the harmonic environment. The Lorelei TR 1, Obib TR 1 and 2, Skorpion TR 1, and Skorpion TR 2 exceeded the prescribed limit, thus NamPower needs to install the harmonic filter at Lorelei 33kV Busbar and at Obib 66kV to mitigate the harmonic distortion. The utility harmonic filter design was part of case study 4.

Table 6.46: THD of current for the power transformers

Power Transformers	**ITHD (%)**
	Filters out of service
Obib TR 1/Obib TR 2	7.666
Skorpion TR 1	7.387
Skorpion TR 2	6.118
Rosh Pinah TR 1/Rosh Pinah TR 2	3.539
Lorelei TR 1	29.537

Table 6.47 gave the individual and total harmonic distortion of the voltage at different points within the network. The VTHDs for all the busbars exceeded the prescribed limit. The individual voltage harmonic that exceeded the limits were as summarised below:

- Aloe PV Plant 33kV – 11th, and 13th harmonic order
- Lorelei 33kV - 11th, and 13th harmonic order
- Obib – Lorelei 66kV – 11th, 13th, and 23rd harmonic order
- Skorpion – Obib 1 66kV - 11th, 13th, 23rd, and 25th harmonic order
- Skorpion – Obib 2 66kV - 11th, 13th, 23rd, and 25th harmonic order
- Skorpion – Obib 1 and 2 summation - 11th, 13th, 23rd, and 25th harmonic order
- Rosh Pinah 66kV - 11th, 13th, and 23rd harmonic order
- Zincum 66kV - 11th, 13th, and 23rd harmonic order
- Obib 66kV PCC – 11th, 13th, and 23rd harmonic order

Table 6.47: HD and THD of voltage at different busbars_Case study 3

Busbar name	Individual Harmonic Distortion (%)								THD (%)
	5th	7th	11th	13th	17th	19th	23rd	25th	
Aloe PV Plant 33kV	0.10	0.20	4.49	4.39	0.27	0.27	1.25	0	16.76
Lorelei 33kV	0.10	0.20	4.48	4.37	0.26	0.27	1.18	0.04	16.65
Obib–Lorelei 66kV	0.02	0.05	3.83	3.18	0.08	0.02	3.25	2.83	12.81
Skorpion - Obib 1 66kV	0.01	0.02	4.77	4.05	0.03	0.01	4.32	3.77	12.98
Skorpion–Obib 2 66kV	0.01	0.02	4.78	4.05	0.03	0.01	4.32	3.76	12.97
Skorpion - Obib 1 and 2 Summation	0.02	0.03	6.75	5.73	0.04	0.01	6.11	5.32	18.35
Rosh Pinah Mine 66kV	0.02	0.06	3.81	3.17	0.09	0.03	3.27	2.86	13.33
Zincum 66kV	0.02	0.06	3.81	3.17	0.09	0.03	3.29	2.87	13.50
Obib 66kV PCC	0.01	0.02	3.82	3.09	0.03	0.01	3.45	2.88	10.59

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

6.5.4. Case study 4 – harmonic mitigation for the utility

Two harmonic filters were designed to mitigate the harmonic distortion at Obib 66 kV and Lorelei 66 kV. The main purpose of these filters was to protect the long lead equipment transformers that were the main assets for the distribution network. These harmonic filters protect the transformers from harmonic distortion in cases when the customer's harmonic filters were out of service for any reason known only by the customer's operation section. NamPower had no control over the customer's plant equipment, thus it was advisable to have their protection measures in place.

These protection measures to install harmonic filters at those points in the network is crucial for the NamPower. The transformers operate in a harsh harmonic environment that is not according to their design criteria. Once these transformers work in such an environment, it can develop challenging conditions that affect their life expectancy. Replacing transformers is a time-consuming process as they are long-lead equipment. It takes a long time to manufacture transformers. Once the transformers starting experiencing problems, it is not advisable to replace them without a comprehensive investigation of the causes of failure. A risk assessment report needs to be provided; if the causes are not known, there is no guarantee that the replacement transformer will not suffer the same problem, resulting again in transformer failure. In most cases, the transformer failure investigation report excludes harmonic distortion. Harmonic distortion is an important power quality issue that utilities should not ignore when investigating the power system failure of any equipment. Power systems are not designed to accommodate harmonic distortion, thus mitigation needs to be considered until a power system is compatible in design and well managed to accommodate harmonic distortion.

6.5.4.1. Design of the harmonic filter

The harmonic filters were designed according to the following formulae: the reactive power for the capacitor was determined based on the power factor correction.

Step 1: $Q_c = P(\tan\delta_1 - \tan\delta_2)$ (6.9)

Step 2: $X_c = \frac{kV^2}{Q_c}$ (6.10)

Step 3: $X_L = \frac{X_c}{hr^2}$ (6.11)

Step 4: $X_n = \sqrt{X_c \times X_L}$ (6.12)

Step 5: $Q = \ 30 < Q < 100,\ Q = 100$ (6.13)

Step 6: $R = \frac{X_n}{Q}$ (6.14)

Step 7: $L = \frac{X_L}{2\pi f_1}$ (6.15)

Step 8: $C = \frac{1}{2\pi f_1 X_c}$ (6.16)

Step 9: $Q_{Filter} = \frac{kV^2}{X_c - X_L}$ (6.17)

The parameters of the following two filters were summarised in Table 6.48 as modelled in DIgSILENT software.

Table 6.48: Utility harmonic filters design parameters

Design parameters	Obib Filter	Lorelei Filter
Nominal voltage(kV)	66	
Filter type	Shunt type R-L-C	
$Reactive\ power\ for\ capacitor\ Q_c\ (MVAr)$	13.972	1.437
$Resistance\ R\ (\Omega)$	0.2986106	1.317983
$Inductance\ L\ (mH)$	9.095762	18.2403
$Capacitance\ C\ (\mu F)$	10.20067	1.050056
$Reactive\ power\ for\ Filter\ Q_{Filter}\ (MVAr)$	14.0884	1.4397
$Resonant\ frequency\ hr\ (HZ)$	522.5	1150
$Quality\ Factor\ (at\ fr)$	100	

This case study was conducted when all four 66 kV filters were out of service, but the utility filters at Obib 66 kV and Lorelei 66 kV were in operation. This is a corrective measure to protect the transformers from working in a harmonic environment. The case study only concentrates on the individual and total harmonic distortion of current and voltage with 66kV utility filters as part of the network. Table 6.49 gave the harmonic contribution of each party within a network using the percentage of harmonic distortion as well as defining and quantifying the contribution of each harmonic order. This determined the main harmonic source based on the THD percentages.

Table 6.49: HD and THD of current for the utility and customers_ Case study 4

HD %	Utility	Customers					
		Skorpion Zinc mine	Orange River 1	Spitskop 1	Solar PV farm	Namdeb Sendelingsdrif 1	Rosh Pinah Zinc mine
5th	0.034	0	0.058	0.053	0.368	0.013	0.297
7th	0.097	0	0.098	0.086	0.528	0.029	0.581
11th	0.615	17.98	0.202	0.179	0.337	0.143	0.342
13th	1.763	15.15	0.611	0.539	1.482	0.367	0.709
17th	0.062	0	0.203	0.179	0.988	0.052	0.389
19th	0.010	0	0.099	0.087	0.699	0.008	0.264
23rd	0.883	8.334	0.001	0.001	0.031	0.002	0.232
25th	1.002	7.62	0.001	0.001	0.233	0.036	0.232
THD (%)	2.655	27.617	0.740	0.653	2.687	0.444	1.347

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

It was found that according to the current total harmonic distortion the harmonic source of this network was Skorpion Zinc mine. The individual current harmonic distortion, which exceeded the limit prescribed by IEEE 519-2014, is:

xiii. Utility – 23rd, and 25th harmonic order

xiv. Skorpion Zinc mine – 11th, 13th, 23rd, and 25th harmonic order

The ITHD that exceeded the limit was only for Skorpion Zinc mine, once the utility takes part in mitigating harmonic distortion. Thus in this case the harmonic contributor was the only customer who will have the harmonic distortion exceeded the prescribed harmonic limits.

Table 6.50 indicated the ITHD % of power transformers as NamPower assets when the four Skorpion Zinc mine 66kV Filters were out of service and NamPower installed their harmonic filters to mitigate and exert control over the harmonic distortion. Only Lorelei TR 1 still exceeds the prescribed limit, although its ITHD % was significantly reduced.

Table 6.50: THD of current for the power transformers

Power Transformers	ITHD (%)		
	Skorpion Zinc 66kV Filters out of service and utility Filters in operation	**Skorpion Zinc 66kV Filter 1 and 2 out of service**	**All 66kV filters in operation**
Obib TR 1/Obib TR 2	2.655	1.253	0.703
Skorpion TR 1	3.568	2.707	2.112
Skorpion TR 2	2.962	2.252	1.757
Rosh Pinah TR 1/Rosh Pinah TR 2	1.347	1.305	1.278
Lorelei TR 1	7.351	5.515	4.722

It is observed that once all the 66kV filters were in operation, transformers within the network operate within the prescribed limit. The initiative that was proposed for NamPower was to assist the transformer not to work under the stress of harmonic distortion.

Table 6.51 gave the individual and total harmonic distortion of the voltage at different points within the network.

Table 6.51: HD and THD of voltage at different busbars_Case study 4

Busbar name	Individual Harmonic Distortion (%)								THD (%)
	5^{th}	7^{th}	11^{th}	13^{th}	17^{th}	19^{th}	23^{rd}	25^{th}	
Aloe PV Plant 33kV	0.10	0.22	0.69	2.43	1.05	0.57	0.01	0	4.11
Lorelei 33kV	0.10	0.22	0.69	2.42	1.04	0.56	0.01	0	4.08
Obib – Lorelei 66kV	0.03	0.07	0.59	1.76	0.32	0.05	0.03	0.30	2.91
Skorpion - Obib 1 66kV	0.01	0.04	1.52	2.27	0.07	0.01	2.37	2.32	6.73
Skorpion – Obib 2 66kV	0.01	0.04	1.52	2.27	0.07	0.01	2.37	2.32	6.72
Skorpion - Obib 1 and 2 Summation	0.02	0.07	2.15	3.21	0.10	0.01	3.35	3.28	9.51
Rosh Pinah Mine 66kV	0.03	0.08	0.59	1.76	0.32	0.05	0.02	0.31	3.00
Zincum 66kV	0.03	0.08	0.59	1.76	0.32	0.05	0.02	0.31	3.03
Obib 66kV PCC	0.01	0.04	0.47	1.26	0.07	0.01	1.42	1.38	4.16

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

The VTHDs for Skorpion - Obib 1 66 kV, Skorpion - Obib 2 66 kV, and Obib-Skorpion 1 and 2 summation exceeded the prescribed limit. The individual voltage harmonic that exceeded the limit was only Skorpion – Obib 1 and 2 summation - 13th, 23rd, and 25th harmonic orders.

6.6. Comparison of the case studies within the industrial network

Active power direction flow was compared for the three case studies as in Table 6.52 to determine the harmonic source per harmonic frequency.

This comparison indicated that for the three case studies the outcome of the harmonic source was the same per harmonic frequency. This validated the theoretical aspects of the loads that were connected to the PCC. For example, the Rosh Pinah mine had 6-pulse VSDs, and theoretically, the dominant harmonics were the 5th, 7th, 17th, and 19th and this was exactly what the outcome of these cases studies proves.

Table 6.52: Harmonic source determination based on active power direction flow

Harmonic frequency	Main harmonic source		
	Case study 1A	**Case study 1B**	**Case study 2**
1st	Utility	Utility	Utility
5th	Rosh Pinah	Rosh Pinah	Rosh Pinah
7th	Rosh Pinah	Rosh Pinah	Rosh Pinah
11th	Skorpion Zinc	Skorpion Zinc	Skorpion Zinc
13th	Skorpion Zinc	Skorpion Zinc	Skorpion Zinc
17th	Rosh Pinah	Rosh Pinah	Rosh Pinah
19th	Rosh Pinah	Rosh Pinah	Rosh Pinah
23rd	Skorpion Zinc	Skorpion Zinc	Skorpion Zinc
25th	Skorpion Zinc	Skorpion Zinc	Skorpion Zinc

The percentage of the ITHD of the utility and customers were compared for the different case studies to determine the side as well as the main contributor, summarised in Table 6.53. It indicates that Skorpion Zinc Mine was the main contributor to all case studies conducted. Hence, in Case study 3 the ITHD percentage of the utility and the solar PV farm exceeded the harmonic limits.

Table 6.53: Comparison of the percentage for ITHD for the utility and customers

Case studies	ITHD (%)						
	utility	Customers					
		Skorpion Zinc mine	Orange River 1	Spitskop 1	Solar PV farm	Namdeb Sendelingsdrif 1	Rosh Pinah Zinc mine
Case study 1A	1.496	**4.26**	0.859	0.758	2.872	0.588	1.931
Case study 1B	1.496	**4.26**	0.859	0.758	2.872	0.588	1.931
Case study 2	3.060	**20.054**	1.279	1.130	4.552	0.891	2.357
Case study 3	7.666	**27.612**	2.198	1.937	9.974	1.586	3.539
Case study 4	2.655	**27.617**	0.740	0.653	2.687	0.444	1.347

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

The percentage of the VTHD at different busbars within the industrial network was compared for the case studies conducted as in Table 6.54. The main focus was the PCC, which in this case was Obib 66kV busbar. Case studies 2 and 3 have to be avoided although the operation of the harmonic filters depends on the Skorpion Zinc mine load capacity. For these two case studies, all the busbars exceeded the limit of 5% based on the IEEE 519 standard. As the main focus was the PCC, once the utility installed the harmonic filters which they have control over, then the total harmonic distortion was reduced to 4.16% which is within the harmonic limits.

Table 6.54: Comparison of the percentage for VTHD at different busbars

Case studies	VTHD (%)								
	Busbar Name								
	Aloe PV plant 33kV	**Lorelei 33kV**	**Obib-Lorelei 66kV**	**Skorpion – Obib 1 66kV**	**Skorpion – Obib 2 66kV**	**Skorpion – Obib 1 and 2 summation**	**Rosh Pinah 66kV**	**Zincum 66kV**	**Obib 66kV PCC**
Case study 1A	4.53	4.51	3.55	4.10	4.07	**5.78**	3.62	3.65	3.25
Case study 1B	4.53	4.51	3.55	N/A	N/A	4.09	3.62	3.65	3.25
Case study 2	**7.41**	**7.37**	**5.75**	**6.47**	**6.43**	**9.12**	**5.89**	**5.94**	**5.15**
Case study 3	**16.76**	**16.65**	**12.81**	**12.98**	**12.97**	**18.35**	**13.33**	**13.50**	**10.59**
Case study 4	4.11	4.08	2.91	**6.73**	**6.51**	**9.51**	3.00	3.03	**4.16**

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

The comparison was conducted for the transformers within the network to determine the scenario where they were working within a harsh harmonic environment as indicated in Table 6.55. In this scenario the two case studies were added as follows:

- Case study 4A – utility filter in operation and Skorpion Zinc harmonic filter 1 and 2 are out of service
- Case study 4B – all harmonic filters are in operation

Table 6.55: Comparison of the percentage for ITHD for the power transformers

Power transformers	ITHD (%)					
	Case study 1A	**Case study 2**	**Case study 3**	**Case study 4**	**Case study 4A**	**Case study 4B**
Obib TR 1/TR 2	1.496	3.060	**7.666**	2.655	1.253	0.703
Skorpion TR 1	3.031	4.449	**7.387**	3.568	2.707	2.112
Skorpion TR 2	2.523	3.692	**6.118**	2.962	2.252	1.757
Rosh Pinah TR 1/TR 2	1.928	2.357	3.539	1.347	1.305	1.278
Lorelei TR 1	**8.045**	**12.965**	**29.537**	**7.351**	**5.515**	4.722

Harmonic Source Contributor

Exceed the harmonic limits

Harmonic Source Contributor & Exceed the harmonic limit

Case study 3 needs to be avoided as most of the transformers were exposed to harmonic distortion. The PCC transformers were Obib 1 and 2, once the utility invested in and installed the harmonic filter which reduced the percentage of harmonic content at the PCC.

6.7. Waveforms comparison for the four-case study

6.7.1. Individual harmonic distortion

Figure 6.20 – Figure 6.23 gave the individual voltage harmonic spectrum for the four-case study conducted. The individual voltage harmonic distortion should not exceed 3%. The individual voltage harmonic distortion for case study 1 showed that all the harmonic orders are within the limit prescribed by IEEE 519-2014.

Case study 2 - When the two 66 kV Filter 1 and 2 were out of service, it was noticed that the 11th harmonic order exceeded the limit for No. 1 and No. 2 Skorpion – Obib 66kV busbar. The harmonic order which forms part of this study was only the odd harmonics excluding the triplen from the 5th – 25th harmonic order. Other harmonic orders exceeded the limit but were not part of this study, for instance, the 37th harmonic order.

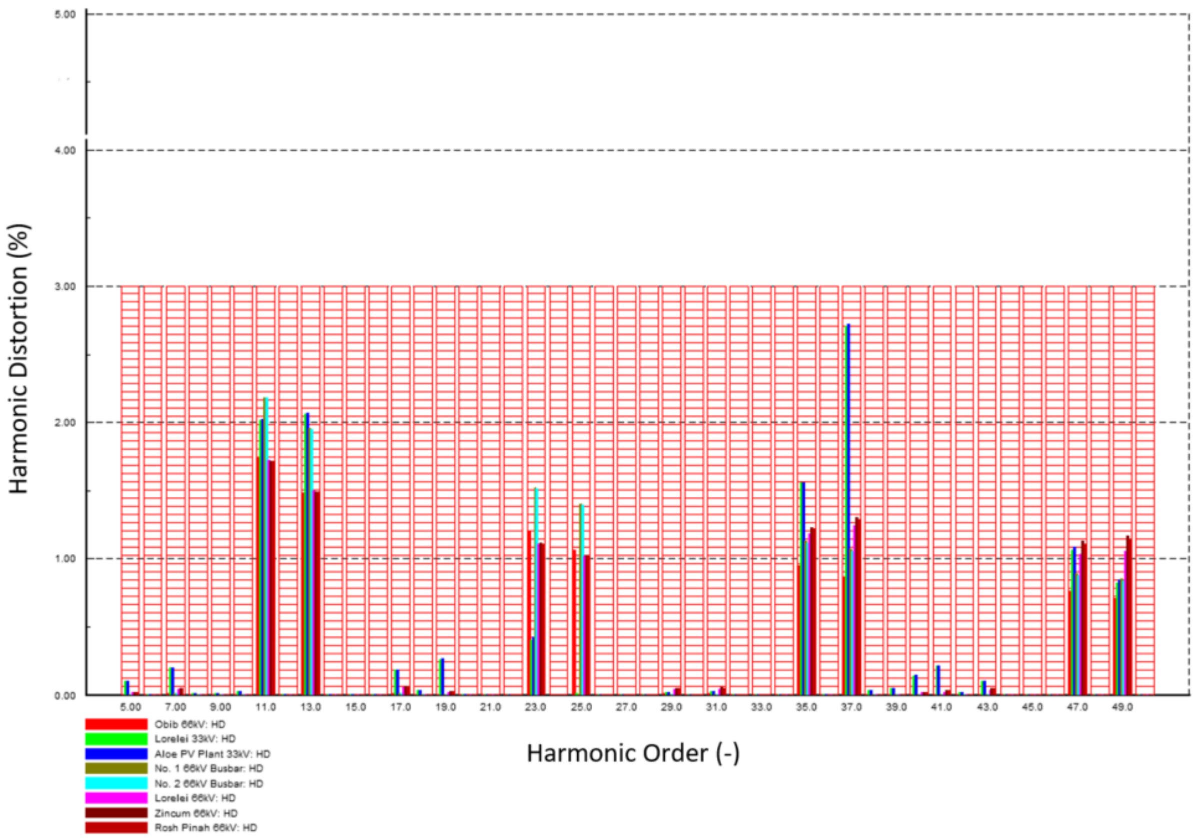


Figure 6.20: Individual voltage harmonic spectrum for case study 1

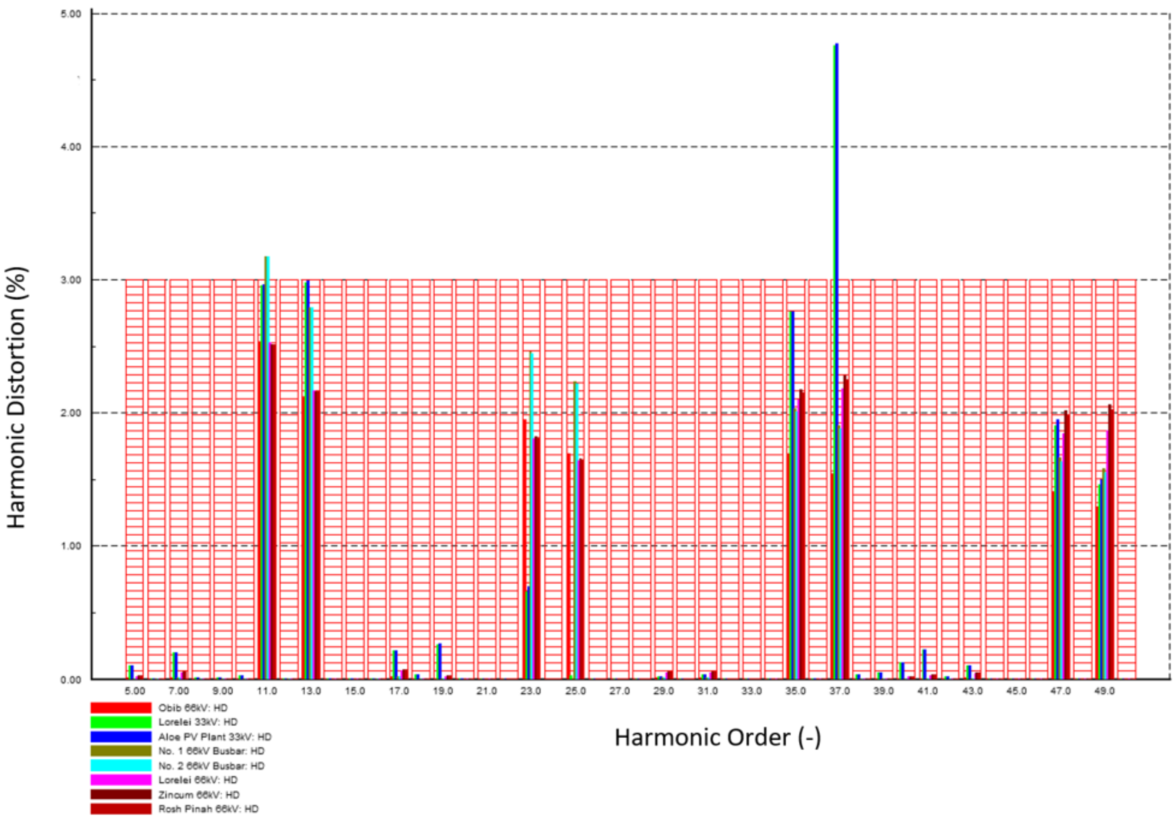


Figure 6.21: Individual voltage harmonic spectrum for Case study 2

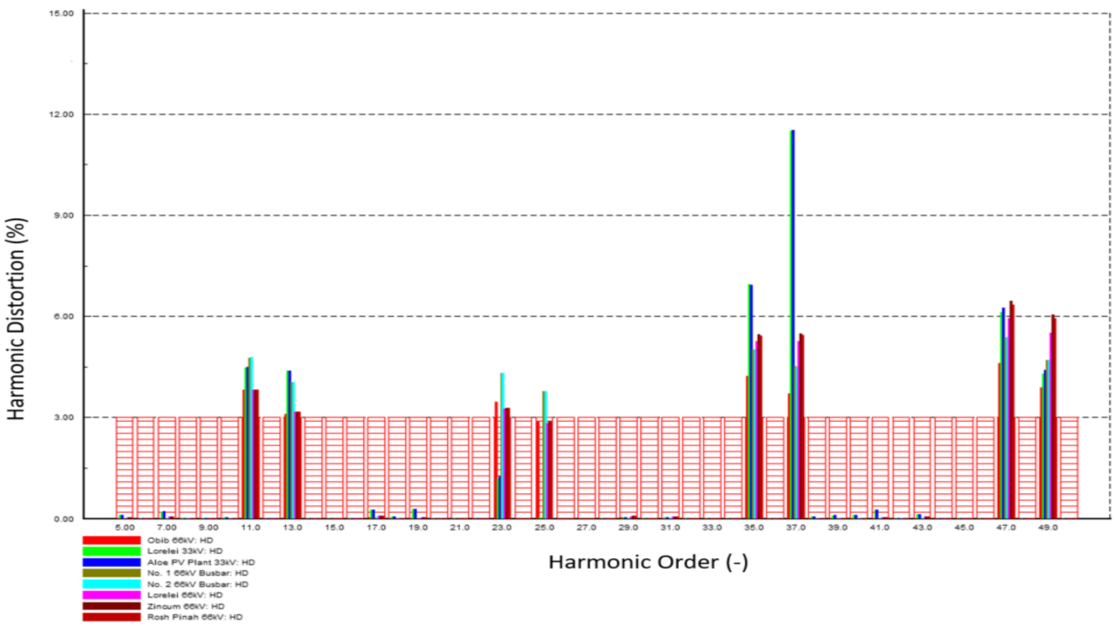


Figure 6.22: Individual voltage harmonic spectrum for case study 3

Case study 3 - When all four filters were out of service, this was when most busbars' harmonic distortion exceeded the limit. The network was modelled with the harmonic spectrum of the even, odd, and triplen until the 50th harmonic order. The most exceeded harmonic orders were the 11th, 13th, 23rd, and 25th as indicated in Figure 6.22.

With the proposed installation of two 66kV filters by the utility for harmonic mitigation of the transformers as per case study 4, the individual voltage harmonic distortion for all busbars at different harmonic orders was within the prescribed limit. Figure 6.23 describes it clearly.

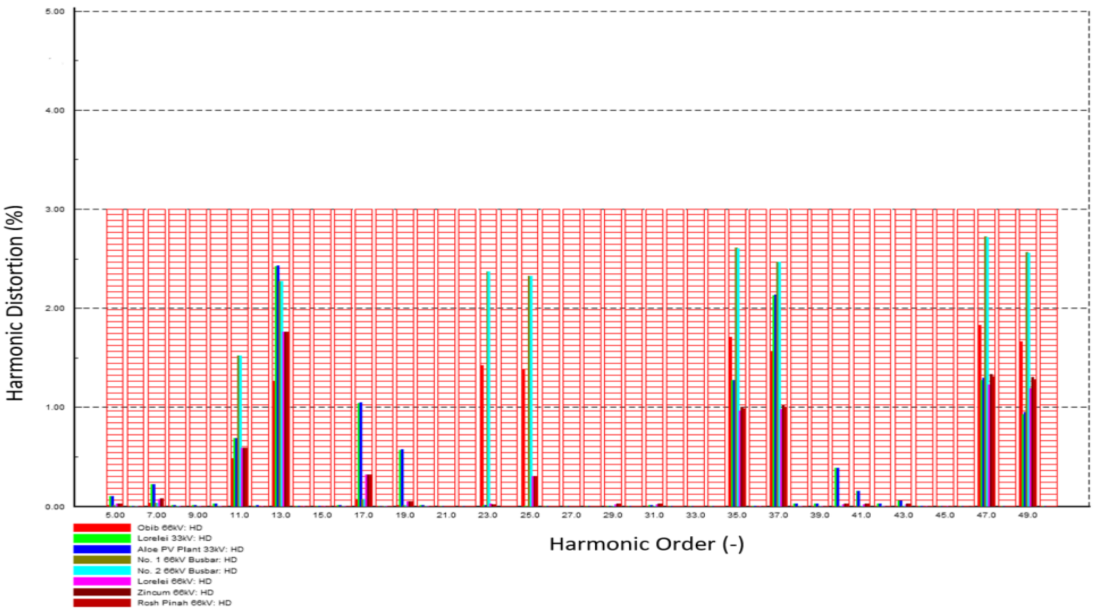


Figure 6.23: Individual voltage harmonic spectrum for case study 4

6.7.2. Voltage waveform at the PCC

The comparison of the voltage waveforms for four case studies was discussed by pointing out the issues causing the waveform shapes. The known waveform of voltage should be sinusoidal; however, in today's network, the voltage waveforms were distorted because of harmonic distortion. Figure 6.24 gave the voltage waveform for case study 1. The waveform was distorted; the shape of a sinusoidal waveform still exists. The network experiences harmonic distortion, which was still within the limit as the harmonic mitigation method was in place and operation.

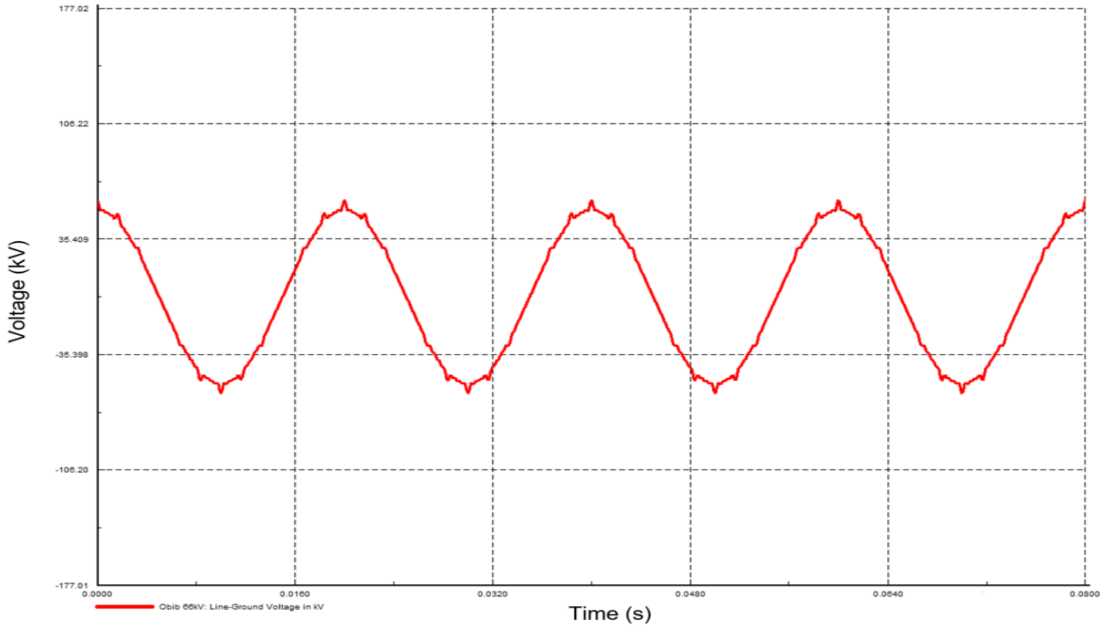


Figure 6.24: Voltage distortion waveform at the Obib 66 kV (PCC) for case study 1

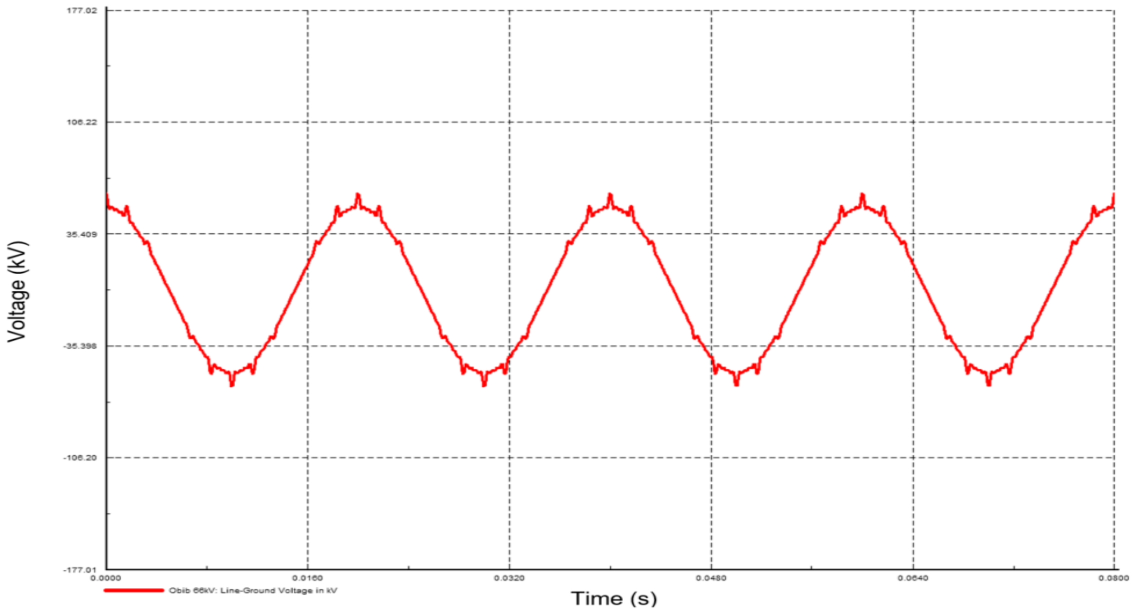


Figure 6.25: Voltage distortion waveform at the Obib 66 kV (PCC) for case study 2

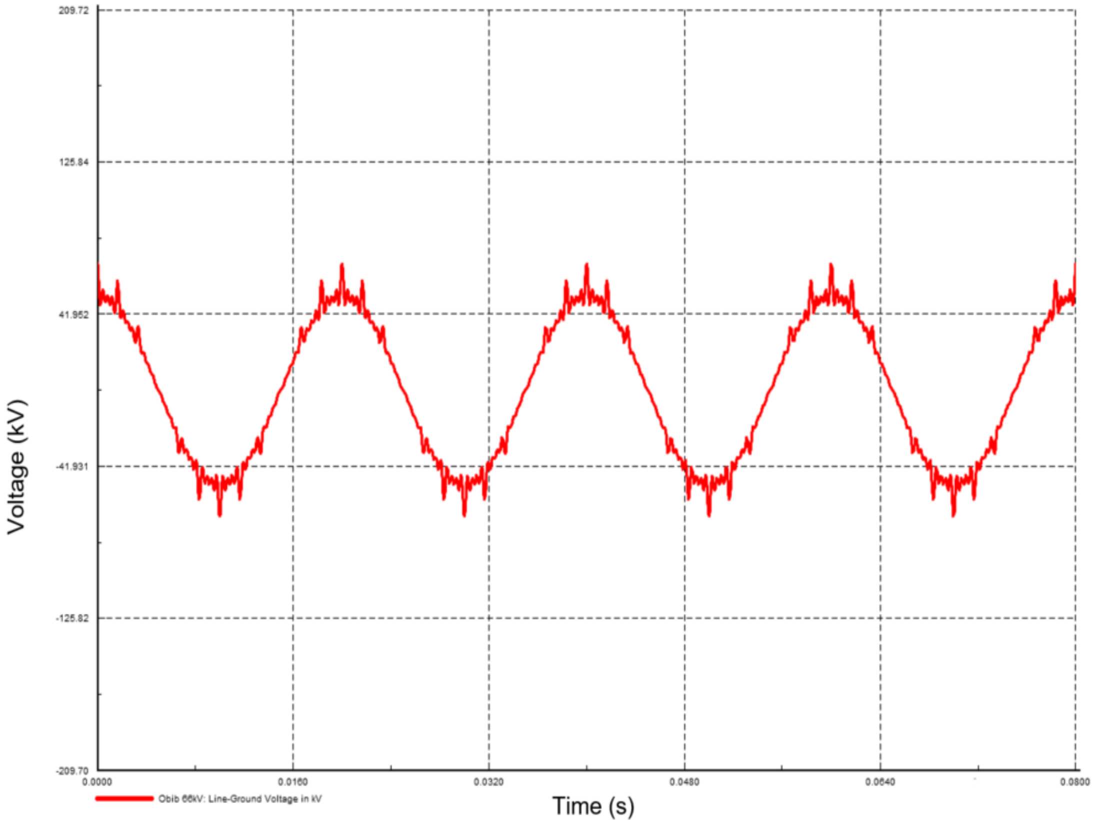


Figure 6.26: Voltage distortion waveform at the Obib 66 kV (PCC) for case study 3

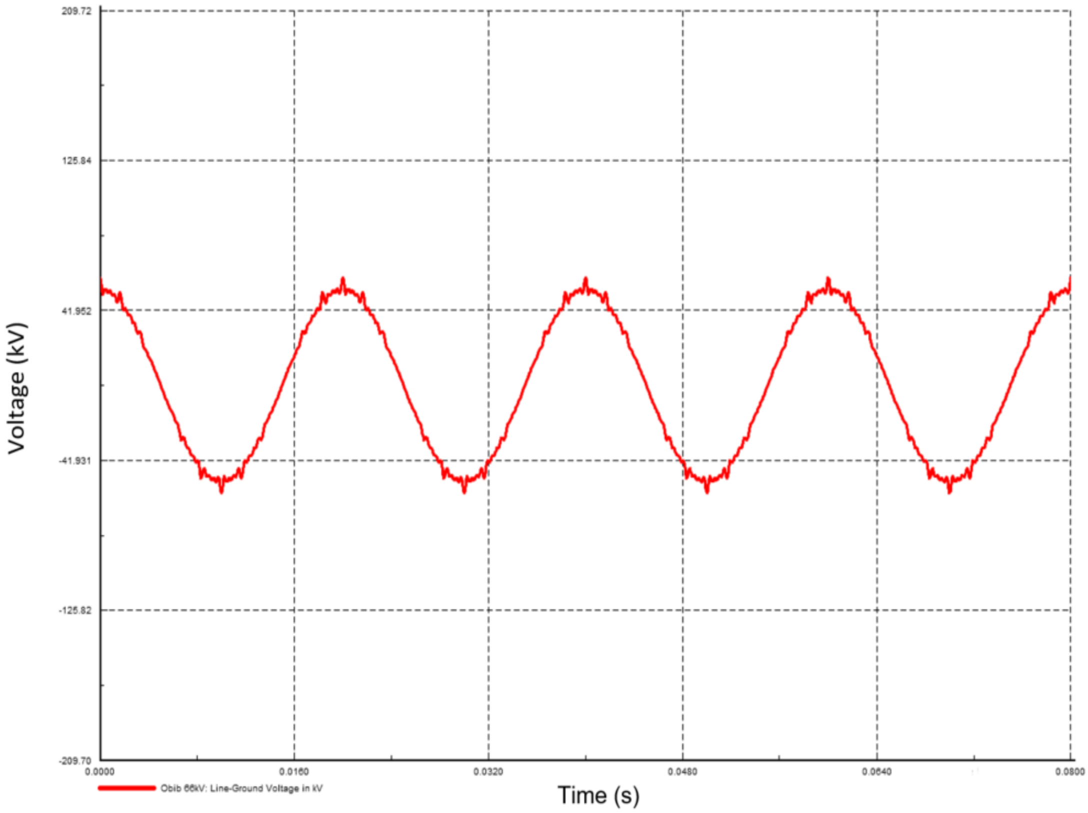


Figure 6.27: Voltage distortion waveform at the Obib 66 kV (PCC) for case study 4

The voltage waveform for case study 3 as indicated in Figure 6.26 was more distorted than the other case studies' waveforms. The waveform shapes in Figure 6.24, Figure 6.25, and Figure 6.27 were similar to each other with different distorted voltages that fall in the same range.

6.7.3. Transformers' current waveforms

Four sets of transformers that belong to NamPower were to be protected from harmonic distortion. The current waveforms of these transformers were compared in case studies. Figure 6.28 – Figure 6.31 showed the current waveforms of transformers for the four case studies conducted. The comparison of the shapes for the current waveforms was discussed.

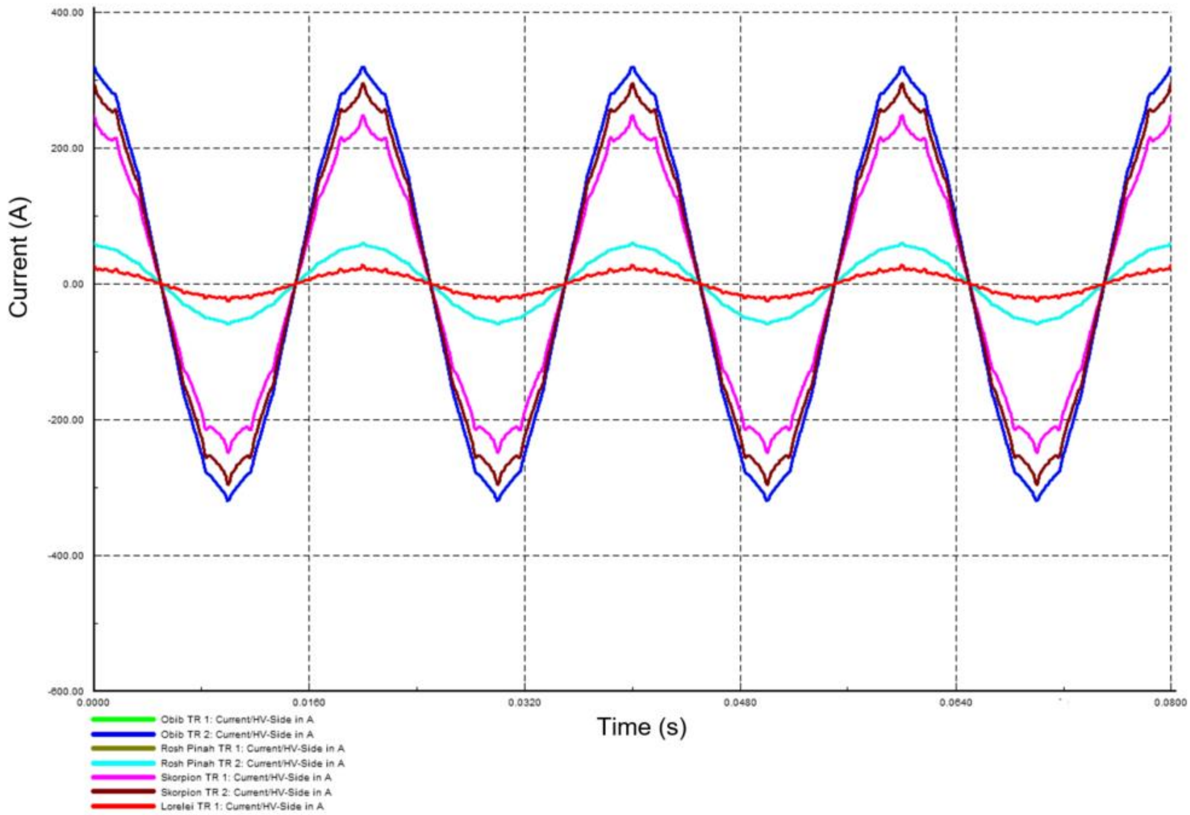


Figure 6.28: Case study 1 - Transformers current waveforms

The Lorelei TR 1 was one of the transformers that operate in a higher harmonic environment for all the case studies than the rest of the transformers that were part of the network. Case study 3 was when the transformers were operating in a harsh environment with higher percentages of total harmonic distortion for the current. This is not a desirable environment, thus it is not recommended to operate the transformers unless corrective measures are in place. Figure 6.28 gave the highest harmonic current for Obib TR 1 and 2 whereas the highest harmonic current for the other three case studies is Skorpion TR 2.

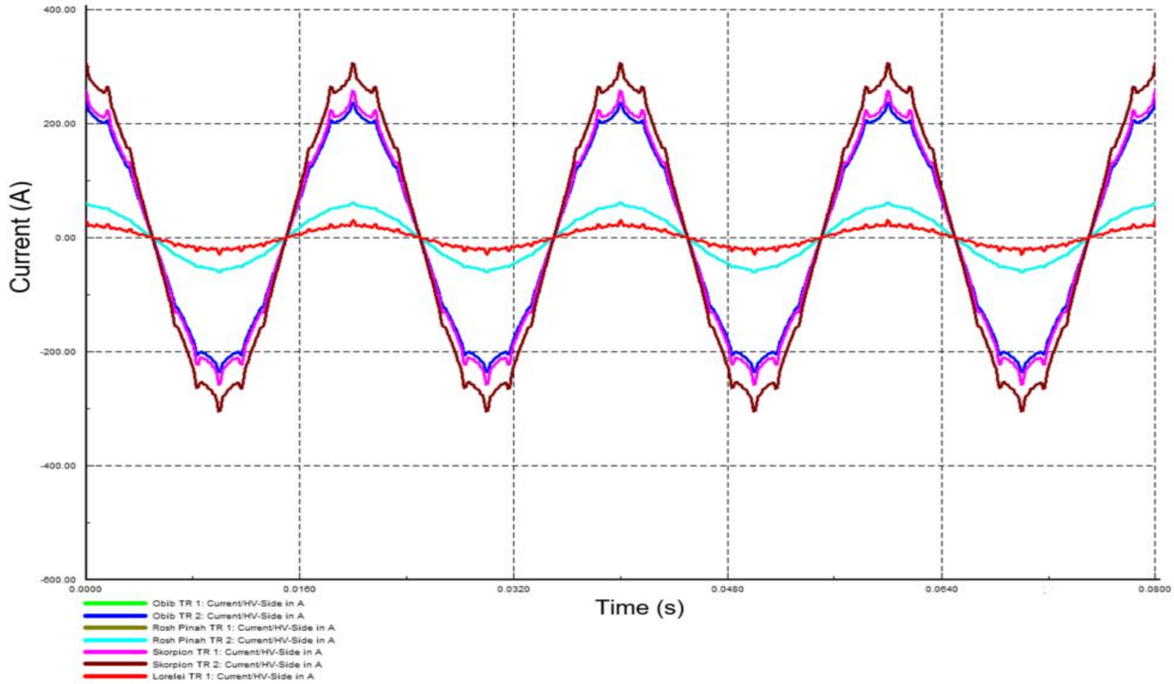


Figure 6.29: Case study 2 – Transformers current waveforms

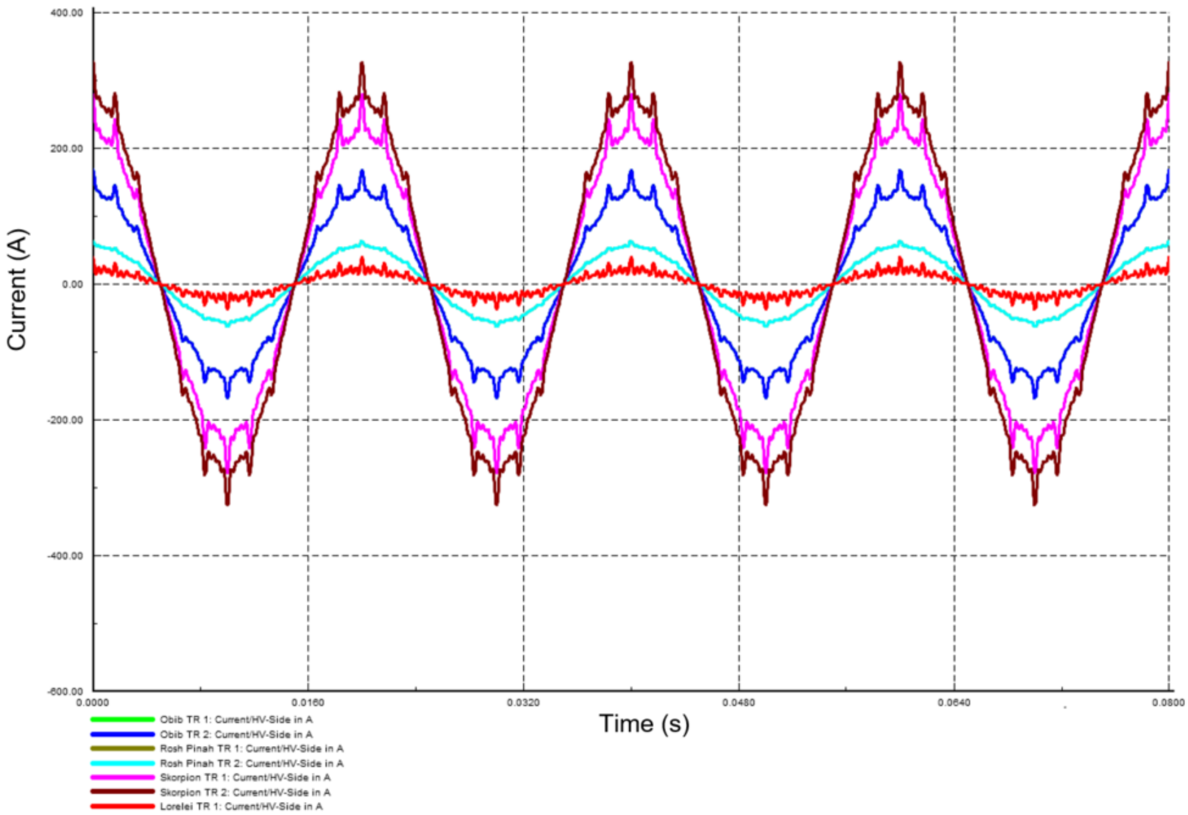


Figure 6.30: Case study 3 – Transformers current waveforms

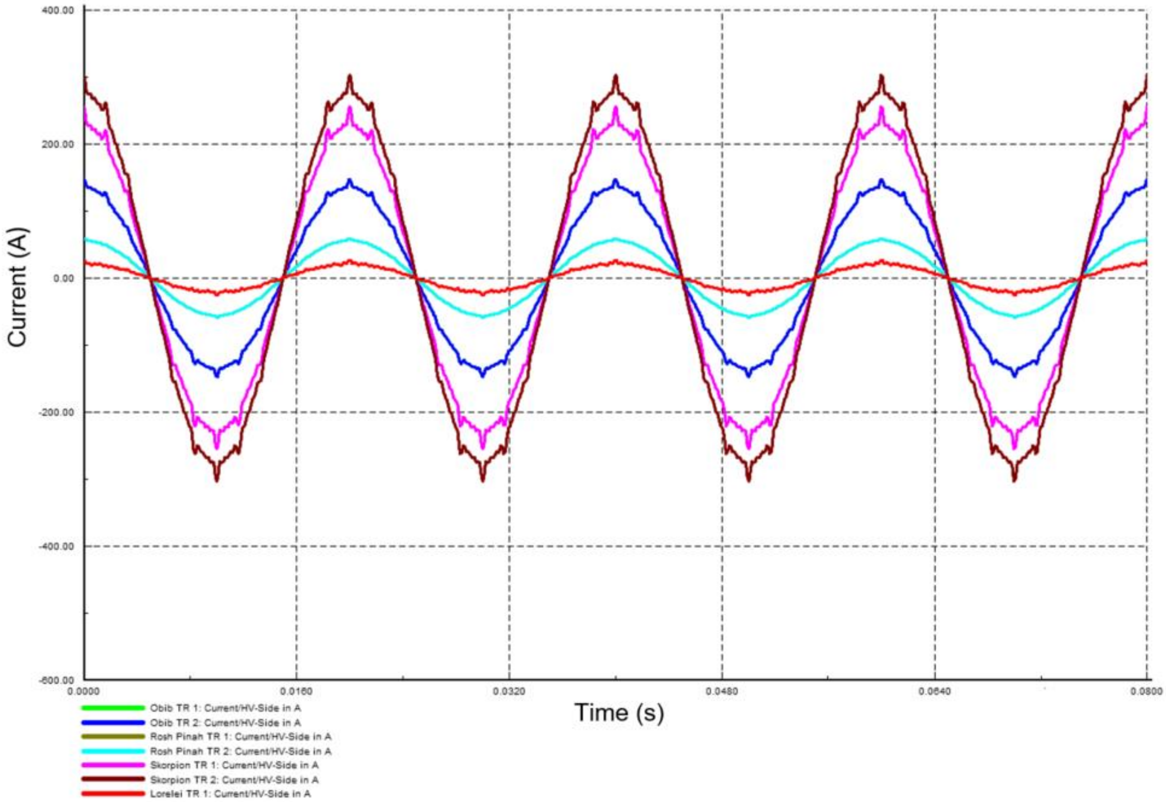


Figure 6.31: Case study 4 – Transformers current waveforms

6.7.4. Frequency sweep for resonant point

The frequency sweep (scan) was conducted at the PCC Obib 66 kV to determine the resonant point with its network impedance. Figure 6.32 – Figure 6.35 showed the frequency sweep for different case studies conducted. Table 6.56 indicated the resonant point with its network impedance of the case studies conducted. The resonant points for case studies 1 – 3 were within the same range, except that the network impedance differs significantly. Where the utility had initiated the installation of harmonic filters to mitigate the harmonic entering the busbars to protect the transformers, the resonant point was low with the highest network impedance.

Table 6.56: Case studies resonant point with its network impedance

Case studies	Resonant Point	Network Impedance (Ω)
Case study 1	18.012	17.235
Case study 2	18.004	23.841
Case study 3	18.020	42.767
Case study 4	8.252	113.553

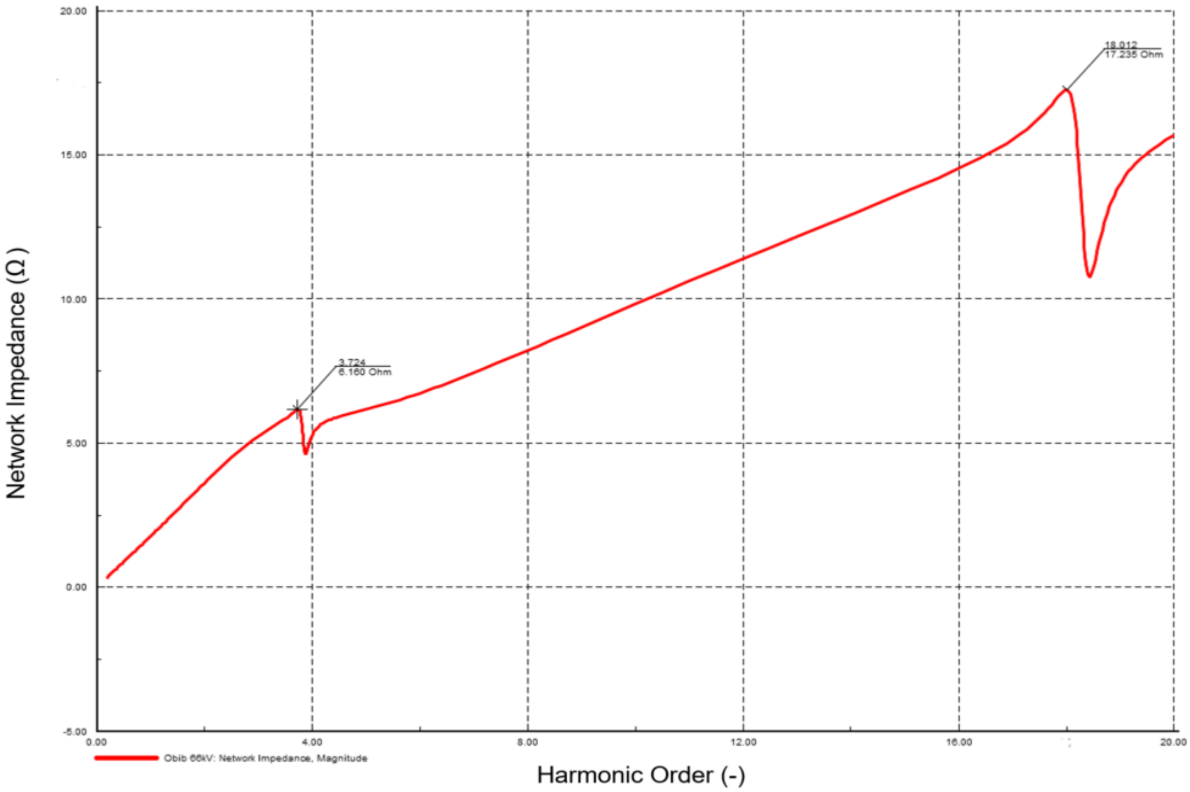


Figure 6.32: Case study 1 – Obib 66 kV frequency sweep

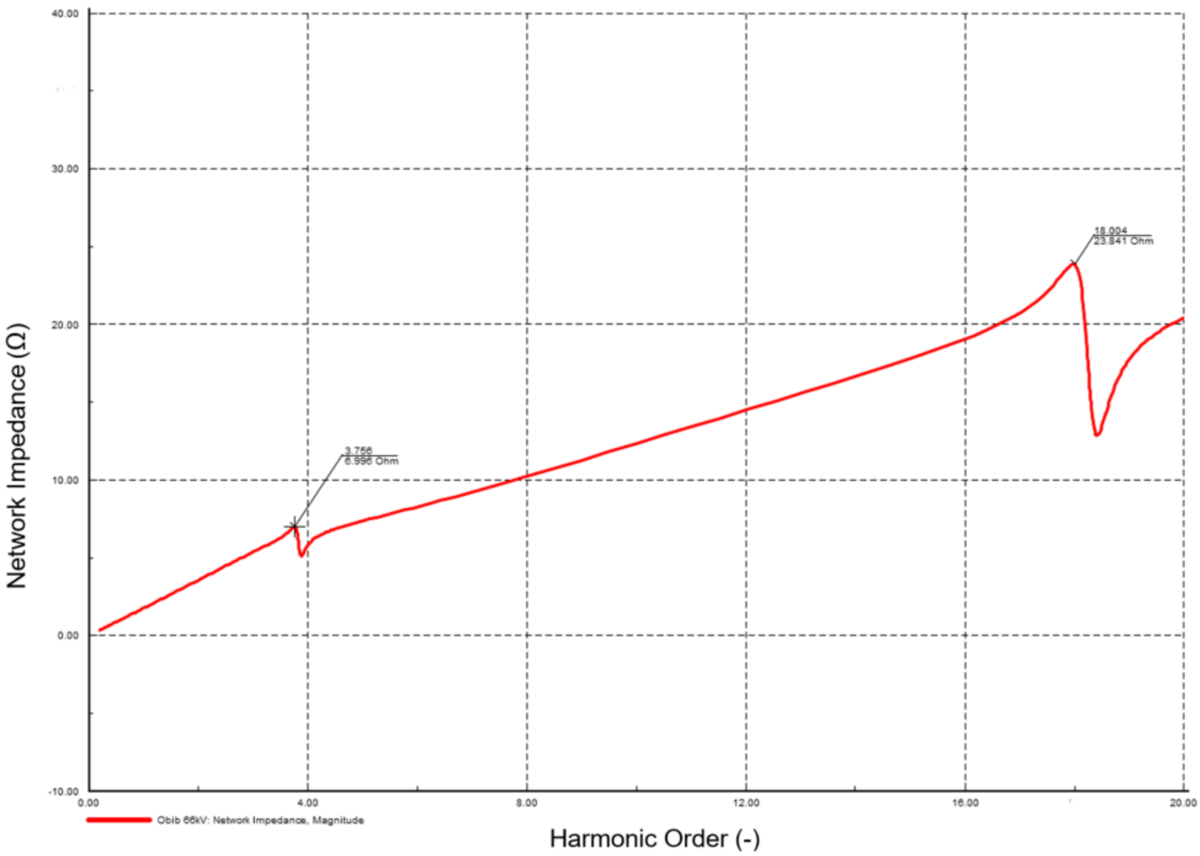


Figure 6.33: Case study 2 – Obib 66 kV frequency sweep

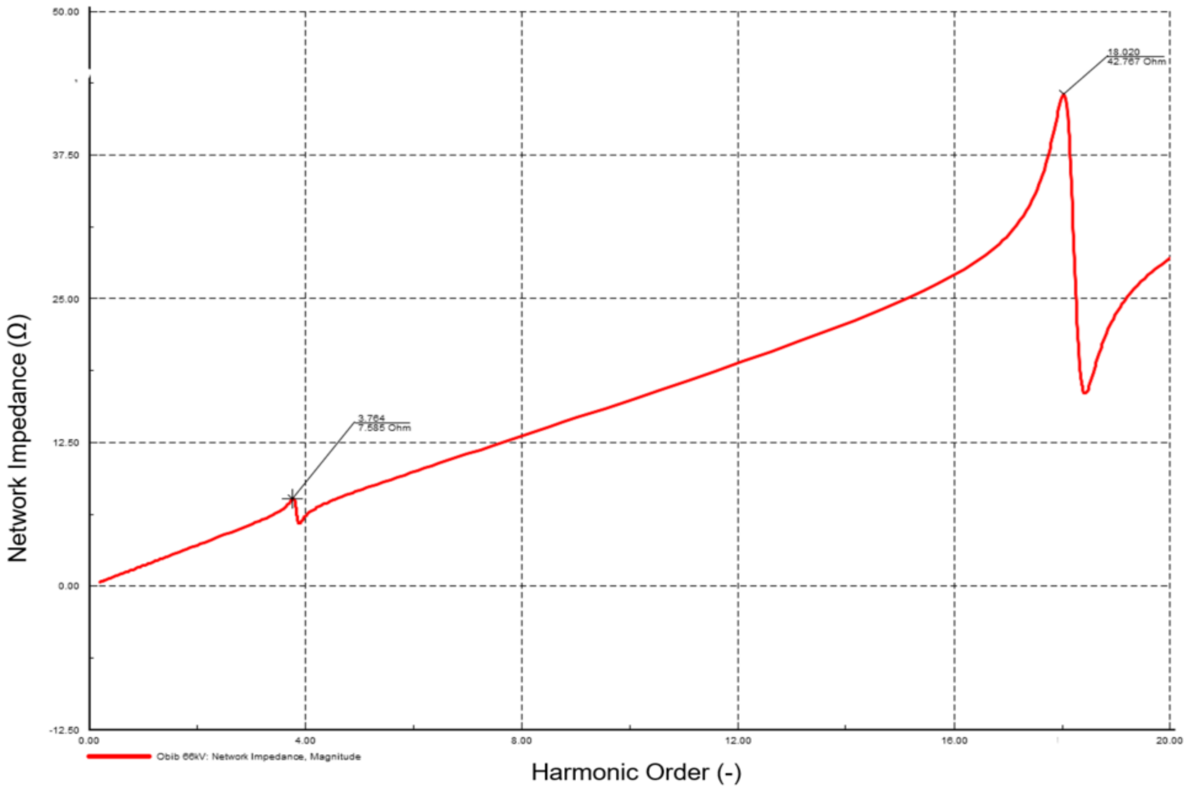


Figure 6.34: Case study 3 – Obib 66 kV frequency sweep

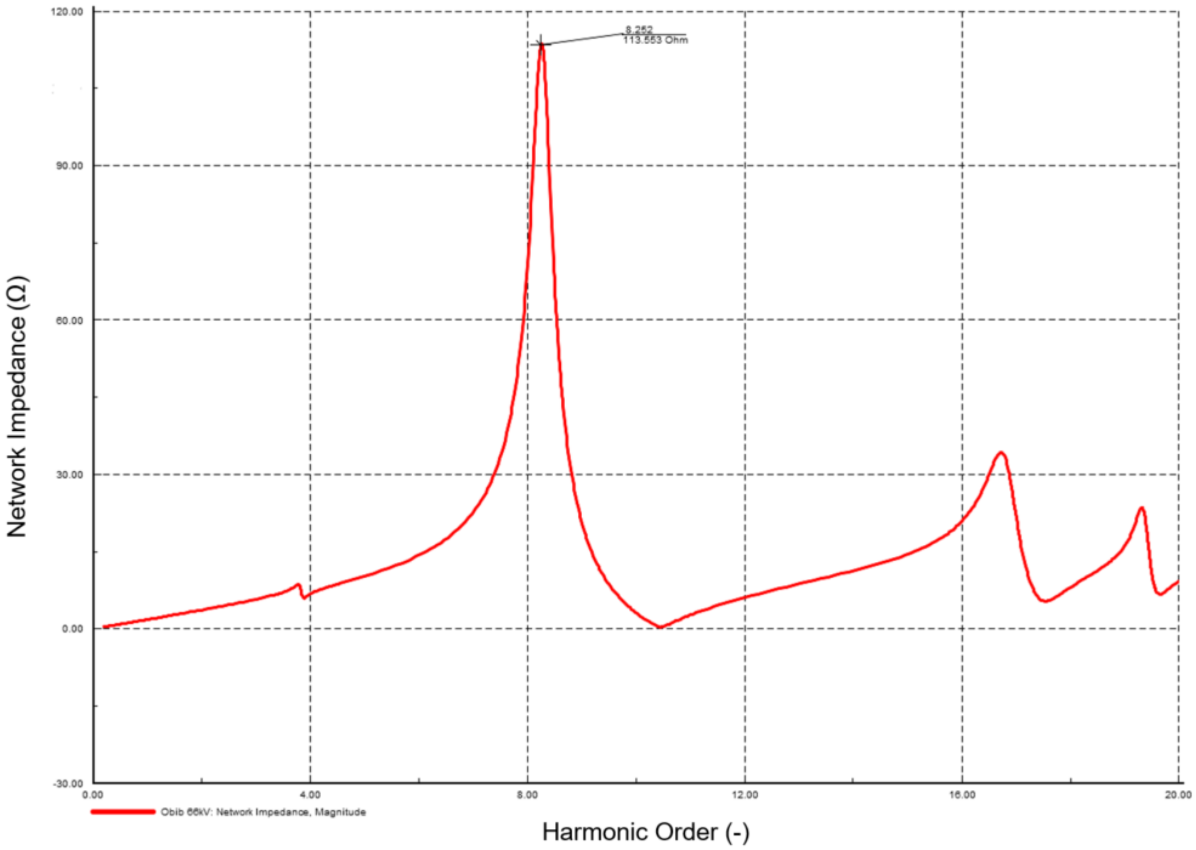


Figure 6.35: Case study 4 – Obib 66 kV frequency sweep

6.8. Measurement data for industrial network

The Unipower PQ meters are Class A as shown in Figure 6.36, used for PQ measurement at the PCC/PoC. These recorders give the PQ report, graphical data, and events list according to international power quality measurement standards, for instance, EN 50160 or user national standards like in Southern Africa, which uses NRS 048. The Unipower (UP-2210) can detect steady-state disturbance such as harmonics and voltage events such as voltage sag, etc. These meters are compliant with IEC 6100 - 4 - 7 for harmonics and IEC 61000 – 4 - 30 Class A for PQ measurement methods. These meters are installed at different sites in remote areas with a communication channel between the meters and a centrally placed database that can be situated at an office within a city.

Figure 6.36: Unipower 2210 Class A measuring unit
Adapted from Unipower (2013)

Today PQ meters measure many parameters apart from THD and individual harmonics that give a better overview of the grid power quality and offer the best harmonic monitoring management system. When harmonics are measured accurately, it provides an effective planning and design process. PQ meters use the software, which is called PQ Secure for a PQ management system that also complies with international standards. It is user friendly and gives detailed monitoring of the grid. It determines the disturbance direction, which is the focus of this study. The UP-2210 shows the harmonic power direction sign (+/-) which facilitates the interpretation of harmonic flow. The information given by this power quality analyser can be an effective measure for contractual verification between the utility and customers. The report generated can detect harmonic frequencies that exceed the limit. Thus, the information from the PQ secure is used for an industrial network to validate simulation results.

The measurement was compared with the simulation case study 1 where all the four 66 kV harmonic filters were part of the network. The individual and total harmonic distortion of the voltage was compared at certain busbars in the network as per measurements. The measurement was done at different intervals; the results could be represented daily, weekly, monthly, and yearly. Unipower PQ Secure gave reports that indicate whether the total harmonic distortion of the voltage is within the prescribed limit specified in NRS 048-2-2007 Section 4.2.5., which stipulates that THD of the supply voltage, including all harmonics up to the order of 40, should not exceed 4% for the HV network. For the MV network, the THD of the supply voltage including all harmonics up to the order of 40 should not exceed 8%. It also highlights the individual harmonic distortion of the voltage, whether it passes or fails the assessment. Once is within the limit prescribed by the national standard then it was regarded as having passed. When the value of the individual harmonic distortion exceeds the limit, this was regarded as having failed. The Unipower meter results also gave the event's history. The individual and total harmonic distortion of the voltage at different busbars were recorded for comparison with the simulated results. The results used were from May 2019 to November 2019. The compatibility level for the HV and MV network used to analyse and compare the simulated and measured results is given in Figure 6.57

Table 6.57: THD and compatibility level of individual HD as per NRS 048-2-2007

Harmonic order	**Compatibility level for 66kV**	**Compatibility level for 33kV**
5th	3	6
7th	2.5	5
11th	1.7	3.5
13th	1.7	3
17th	1.2	2
19th	1.2	1.8
23rd	0.8	1.4
25th	0.8	1.3
THD (%)	4	8

Table 6.58 gave the comparison of the VTHD for the customers connected to the PCC. Customer B represents four individual customers, namely Rosh Pinah mine 66 kV, Zincum

66kV, Aloe PV plant 33kV, and Lorelei 33kV (Orange river 1 and Spitskop 1). The other customer was Skorpion Zinc mine with two feeders. The VTHD of each Skorpion feeder gave a higher value than for Lorelei 66kV feeder. Therefore, from these results, measured or simulated, the harmonic contributor at the PCC was Skorpion Zinc mine. The measurement was also able to check the THD of the utility side which in this case has lower THD than Skorpion Zinc mine. From the simulation results, the THD for Skorpion – Obib 1 and 2 exceeded the limit. The Simulation and measured results of Skorpion – Obib 1 and 2 summations exceeded the harmonic limit based on NRS 048-2-2007.

Table 6.58: THD of the voltage for the customers connected at the PCC

Busbar name	**THD simulation results (%)**	**THD measured results (%)**
Obib – Lorelei 66kV (Customer B)	3.55	2.935
Skorpion - Obib 1 66kV	**4.10**	3.640
Skorpion – Obib2 66kV	**4.07**	3.615
Skorpion - Obib 1 and 2 Summation	**5.78**	**5.13**
Obib – Skorpion 1 66kV	-	2.940
Obib – Skorpion 2 66kV	-	2.945
Obib – Skorpion 1 and 2 Summation		**4.16**

Table 6.59 gave Customer B VTHD to determine the highest contributor among these customers. The customers within Customer B who were a source of harmonic (has a load which injects the harmonics) was Aloe PV plant 33 kV and Rosh Pinah mine 66kV, thus the Rosh Pinah mine was a harmonic contributor at Lorelei 66kV as indicated in Table 6.59.

Table 6.59: THD of the voltage for the customers within the Customer B category

Busbar name	**THD simulation results (%)**	**THD measured results (%)**
Aloe PV Plant 33 kV	4.53	4.125
Lorelei 33 kV	4.51	4.120
Rosh Pinah Mine 66 kV	3.62	4.255
Zincum 66 kV	3.66	4.290

The individual voltage harmonic distortion was compared for the two customers connected at the PCC in Table 6.60 – Table 6.62.

Table 6.60: HD voltage comparison for Lorelei 66kV measured and simulated results

Harmonic order	Compatibility level	95% highest (%) measured	Compliance measured	Simulated result	Compliance simulated
5th	3	1.33	Passed	0.02	Passed
7th	2.5	0.93	Passed	0.05	Passed
11th	1.7	1.37	Passed	1.73	Failed
13th	1.7	1.60	Passed	1.50	Passed
17th	1.2	0.23	Passed	0.06	Passed
19th	1.2	0.08	Passed	0.02	Passed
23rd	0.8	1.21	Failed	1.11	Failed
25th	0.8	1.21	Failed	1.02	Failed

Table 6.61: HD voltage comparison for Skorpion – Obib 1 66kV measured and simulated results

Harmonic order	Compatibility level	95% highest (%) measured	Compliance measured	Simulated result	Compliance simulated
5th	3	1.30	Passed	0.01	Passed
7th	2.5	0.90	Passed	0.01	Passed
11th	1.7	1.83	Failed	2.18	Failed
13th	1.7	2.02	Failed	1.95	Failed
17th	1.2	0.22	Passed	0.01	Passed
19th	1.2	0.10	Passed	0	Passed
23rd	0.8	1.56	Failed	1.52	Failed
25th	0.8	1.51	Failed	1.40	Failed

Table 6.62: HD voltage comparison for Skorpion – Obib 2 66kV measured and simulated results

Harmonic order	Compatibility level	95% highest (%) measured	Compliance measured	Simulated result	Compliance simulated
5th	3	1.33	Passed	0.01	Passed
7th	2.5	0.94	Passed	0.01	Passed
11th	1.7	1.83	Failed	2.18	Failed
13th	1.7	1.96	Failed	1.95	Failed
17th	1.2	0.23	Passed	0.01	Passed
19th	1.2	0.13	Passed	0	Passed
23rd	0.8	1.61	Failed	1.51	Failed
25th	0.8	1.47	Failed	1.39	Failed

The Lorelei 66 kV individual voltage harmonic distortion for the 11th simulated exceeded the limit and the 23rd and 25th harmonic orders for both simulation and measured results also exceeded the limits set on NRS 048-2:2007. However, the individual voltage harmonic distortion of Skorpion – Obib 1 and 2 66kV for the 11th, 13th, 23rd, and 25th harmonic orders exceeded the harmonic limits and failed the standard compliance for both simulation and measured results. This also indicated the harmonic contributor. Table 6.63 – Table 6.68 gave the individual harmonic distortion of the different busbars. Table 6.63 and Table 6.64 showed that the individual voltage harmonic distortion was within the prescribed harmonic limits set by standard except for the 23rd and 25th harmonic orders. These results could not be compared in the simulation as it was not possible.

Table 6.63: HD voltage for Obib – Skorpion 1 66kV measured results

Harmonic order	Compatibility level	95% highest (%) measured	Compliance measured	Simulated result	Compliance simulated
5th	3	1.37	Passed	-	-
7th	2.5	0.93	Passed	-	-
11th	1.7	1.38	Passed	-	-
13th	1.7	1.59	Passed	-	-
17th	1.2	0.23	Passed	-	-
19th	1.2	0.08	Passed	-	-
23rd	0.8	1.21	Failed	-	-
25th	0.8	1.29	Failed	-	-

Table 6.64: HD voltage for Obib- Skorpion 2 66kV measured results

Harmonic order	Compatibility level	95% highest (%) measured	Compliance measured	Simulated result	Compliance simulated
5th	3	1.37	Passed	-	-
7th	2.5	0.93	Passed	-	-
11th	1.7	1.35	Passed	-	-
13th	1.7	1.61	Passed	-	-
17th	1.2	0.23	Passed	-	-
19th	1.2	0.08	Passed	-	-
23rd	0.8	1.21	Failed	-	-
25th	0.8	1.28	Failed	-	-

Table 6.65 – Table 6.66 showed that the measured results for 23rd and 25th harmonic orders individual harmonic exceeded the standard and failed compliance while the simulation results were within the limits. This could be because of the events that occurred in the plant at different periods such as switching off the 66kV filters. However, the results in Table 6.67 – 6.68 indicated that the 23rd and 25th harmonic orders exceeded the limit for both measured and simulation results. The simulated results of the 11th harmonic order also exceeded the limit

Table 6.65: HD voltage comparison for Aloe PV plant 33kV measured and simulated results

Harmonic order	Compatibility level	95% highest (%) measured	Compliance measured	Simulated result	Compliance simulated
5th	6	1.31	Passed	0.10	Passed
7th	5	1.43	Passed	0.20	Passed
11th	3.5	1.48	Passed	2.02	Passed
13th	3	1.92	Passed	2.07	Passed
17th	2	0.47	Passed	0.18	Passed
19th	1.8	0.28	Passed	0.26	Passed
23rd	1.4	2.20	Failed	0.43	Passed
25th	1.3	2.77	Failed	0	Passed

Table 6.66: HD voltage comparison for Lorelei 33kV measured and simulated results

Harmonic order	Compatibility level	95% highest (%) measured	Compliance measured	Simulated result	Compliance simulated
5th	6	1.34	Passed	0.10	Passed
7th	5	1.42	Passed	0.20	Passed
11th	3.5	1.48	Passed	2.02	Passed
13th	3	1.89	Passed	2.06	Passed
17th	2	0.48	Passed	0.18	Passed
19th	1.8	0.30	Passed	0.26	Passed
23rd	1.4	2.22	Failed	0.40	Passed
25th	1.3	2.74	Failed	0.01	Passed

Table 6.67: HD voltage comparison for Rosh Pinah 66kV measured and simulated results

Harmonic order	**Compatibility level**	**95% highest (%) measured**	**Compliance measured**	**Simulated result**	**Compliance simulated**
5th	3	1.08	Passed	0.02	Passed
7th	2.5	0.69	Passed	0.05	Passed
11th	1.7	1.07	Passed	1.72	Failed
13th	1.7	1.38	Passed	1.49	Passed
17th	1.2	0.27	Passed	0.06	Passed
19th	1.2	0.14	Passed	0.03	Passed
23rd	0.8	2.21	Failed	1.11	Failed
25th	0.8	3.20	Failed	1.02	Failed

Table 6.68: HD voltage comparison for Zincum 66kV measured and simulated results

Harmonic order	**Compatibility level**	**95% highest (%) measured**	**Compliance measured**	**Simulated result**	**Compliance simulated**
5th	3	1.11	Passed	0.02	Passed
7th	2.5	0.69	Passed	0.05	Passed
11th	1.7	1.06	Passed	1.72	Failed
13th	1.7	1.37	Passed	1.49	Passed
17th	1.2	0.28	Passed	0.06	Passed
19th	1.2	0.15	Passed	0.03	Passed
23rd	0.8	2.21	Failed	1.11	Failed
25th	0.8	3.23	Failed	1.03	Failed

6.9. Summary

The best software to use for harmonic source detection analysis was DIgSILENT, as it gave the direction of active power flow at different frequencies. The IEEE PES benchmark test system was used to establish the methodology of harmonic source detection based on the direction of the active power method. The industrial network with different harmonic sources was analysed and validated with the measurement results. Therefore, the method based on the direction of active power proves to be practical and economically viable for use by power quality engineers.

CHAPTER 7: CONCLUSIONS AND FUTURE WORKS

7.1. Conclusions

Modern power systems are not designed to work in a harsh harmonic environment. When a power system or its equipment fails, harmonic distortion is usually excluded in the investigation report. Measurement of harmonic distortion becomes a challenge due to multiple harmonic sources connected at the point of common coupling (PCC). This brought up harmonic source detection as well-known and ongoing research. Harmonic active power flows either from upstream or downstream of the supply point.

The contribution of this thesis is summarised as follow:

- A harmonic monitoring management system is proposed as a benchmark evaluation during the planning phase when the utility and the customers are setting up an Electricity Supply Agreement (ESA).
- Thevenin and Norton's equivalent circuits are adapted through a mathematical model to represent a practical power system with multiple customers connected at the PCC.
- A harmonic detection method based on the direction of active power flow was modified and used. It incorporated the direction of active power at the combined frequencies (fundamental and harmonic frequencies) and gave the overview of determination of the harmonic source depending on the power categories (total active power at the PCC, power at the PCC, and harmonic power). The modification of the method was achieved through three main stages:
    - Identify the side of the harmonic source (utility or customer) and quantify the contribution of each side.
    - Identify the contributor in case of the customer side and quantify each customer contribution.
    - Prove the dominant harmonic order of the contributor.

Utilities should use the proposed harmonic monitoring management system for their new customers and harmonic distortion limit should be set up in their Electricity Supply Agreement (ESA) as this could solve the problem of harmonic source detection when multiple customers are connected at the PCC. Much research has described the use of Thevenin and Norton equivalent circuits for harmonic source detection which have proven inaccurate in this study as only single customers were assumed to be downstream of the PCC. This does not represent a true practical power system that consists of multiple customers. A proposed new adapted mathematical model for the equivalent circuits was validated by simulation case studies. It was concluded that the equivalent circuits’ model cannot be used for harmonic source detection; however, it could be used for circuit analysis. A modified practical and economically viable solution based on the direction of the active power flow method was identified. This method was tested using case studies of a benchmark IEEE PES test system and an industrial network and validated with the measurement results of an actual industrial network. The modified method based on the direction of active power flow was proved to be viable and could be used by engineers to determine the individual voltage harmonic contributor at the PCC as well as the VTHD main contributors.

The DIgSILENT software package was used for harmonic source detection as it gave an overview of the direction of active power flow at different frequencies. The harmonic limits were prescribed in the national and international standards; these limits should have been well understood and used in the ESA. This reduced harmonic source detection challenges. The proposed scenario was for the utilities to monitor the current total harmonic distortion for the transformers and take corrective measures to mitigate these harmonic levels. The utilities should not rely on the customers' harmonic filters, as they have no control over the customer's operation as well as equipment maintenance. Therefore, it was recommended that utilities install their harmonic mitigation units. It was also recommended that utilities investigate equipment failure by taking harmonic distortion into account, as it may be the cause of failure.

7.2. Future works

Background harmonic analysis under no-load and load condition should take place: investigation should be conducted using measurements to analyse the trends of background harmonics at the PCC, comparing these trends and finding the conclusion of their behaviours. Harmonic distortion penalty processes must be developed, involving a mathematical model for processing of harmonic distortion penalties, taking into account national and international standards. A mathematical model of notified maximum demand penalties should be understood in detail and a baseline should be set up for harmonic distortion penalty charges per individual customer at the PCC. Analysis of utilities' harmonic mitigation should be conducted.

Analysis of harmonic distortion of unbalanced distribution networks with renewable energy sources (RES) must be conducted, as well as power quality analysis of the operation of wind energy. It is crucial to investigate renewable energy sources' efficiency optimisation. The economic impacts of power quality on utility and customers should be reviewed. Harmonic analysis of energy storage systems for future power systems should be undertaken. With the increase of electrical vehicles integrated into the power system, research on harmonic distortion analysis is required.

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APPENDICES

APPENDIX A: SELECTION OF PUBLICATIONS WITH THEIR ABSTRACTS

Appendix A.2 relates to Chapter 3 of this thesis and was written during March and April 2019. It was submitted at IEEE Access in May 2019 and is accepted and published by IEEE Access in June 2019.

Paper A.1

Sinvula, R., Abo-Al-Ez, K.M. & Kahn, M.T. 2019, March. Total Harmonic Distortion (THD) with PV System Integration in Smart Grids: Case study. In *2019 International Conference on the Domestic Use of Energy (DUE)* (pp. 102-108). IEEE. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8734285

Abstract - The share of renewable energy systems in modern smart grids has increased in many countries, and with that increase, the quality of power becomes a major concern for power system operators, especially at the load side. Among the most important power quality challenges, the harmonics come on top, as they affect the voltage and current quality at the point of common coupling (PCC), and negatively affect the loads. One of the most used renewable generators is the solar photovoltaic (PV) system, where it is connected to the low voltage distribution grid using power electronics inverters, and with the increased penetration level, the massive harmonic current is injected into the network. There is a need to analyse the resulting harmonics distortion and highlight its possible constraints. This paper presents a case study of a radial distribution network with a connected 5 MW Solar PV plant. The system is modelled and simulated using DIgSILENT software to assess the total harmonics distortion (THD) at the PCC. The simulation is performed with increasing the connected PV modules, and the results are analysed showing a high level of THD with the increased PV penetration at the PCC considering a higher loading level of the distribution transformer. The methodology of the introduced analytical study is recommended for distribution system operators to develop the appropriate solution to mitigate the effect of the harmonics.

Index Terms - distorted waveform, harmonic distortion, Smart distribution grid, PV systems.

Paper A.2

Sinvula, R., Abo-Al-Ez, K.M. & Kahn, M.T. 2019. Harmonic Source Detection Methods: A Systematic Literature Review. *IEEE Access*, *7*, pp.74283-74299.
https://ieeexplore.ieee.org/abstract/document/8731953

Abstract - Ensuring the quality of power supply is the main target of power utility companies worldwide. Harmonic distortion is one of the power quality problems that can result either from upstream (utility side) through background harmonic, downstream (customer's side) through non-linear loads, or renewable energy generators. The detection of harmonic sources at the point of common coupling (PCC) is a major concern for both utilities and customers. Various methods have been proposed since the 1990s to be used for harmonic source detection. These methods have been classified into three categories based on the direction of active power flow, reactive power, and voltage-current ratio. In this paper, a systematic literature review is done on the state of the art of current research on the harmonic source detection methods, to select the method that gives better practical and commercial results to be used when multiple customers are connected at the PCC. This systematic literature review recognized that most studies concentrated only on harmonic source detection between a customer and utility but the practical power system has multiple customers connected to the PCC with different load conditions. Therefore, the results obtained from this paper review will be useful for researchers and engineers working in the modern grids, who aim to develop a practical and commercial method to quantify the harmonic contribution for different customers and utility.

Index Terms - Harmonic distortion, harmonic source detection, renewable energy sources and distributed power generation.

Paper A.3

Sinvula, R., Abo-Al-Ez, K.M. and Kahn, M.T., 2019, November. Efficiency in Distribution Network with Harmonic Distortion. *In AIUE Proceedings of the 17th Industrial and Commercial Use of Energy conference*. https://ssrn.com/abstract=3638104

Abstract— Smart grids are reliable and easy to operate though they increase the challenges of harmonic distortion due to many electronic devices. Traditionally, harmonic distortion is neglected when efficiency in distribution networks is determined. It is usually calculated using fundamental frequency only. The efficiency of equipment and the overall efficiency of the network is negatively affected by the harmonic distortion. Thus, this paper seeks to develop a methodology and new formulae for determining individual and overall efficiencies when harmonic distortion is present in a distribution network. The methodology and new formulae are developed using directional active power flow. A radial distribution network with two harmonic sources (non-linear load and solar photovoltaic (PV)) and a capacitor bank is used for analysis. The method and case-specific formulae are applied in this case study and results are generated. A harmonic filter is designed and implemented. It is indicated that the overall efficiency of the distribution network as well as the individual efficiency of the network is affected by the presence of harmonic distortion. Once the harmonic filter is implemented the overall efficiency of the network is improved significantly. The methodology and formulae have shown to be effective since it gives a better understanding of efficiency when distortion exists and its application is recommended for industrial use.

Index Terms — directional active power flow, fundamental frequency, harmonic frequency, renewable energy sources, non-linear loads, and efficiency.

Paper A.4

Sinvula, R., Abo-Al-Ez, K.M. and Kahn, M.T., 2020, August. Design of Utility Harmonic Mitigation Filters for Power Transformers. In *2020 IEEE PES/IAS PowerAfrica* (pp. 1-5). IEEE. https://ieeexplore.ieee.org/abstract/document/9219866

Abstract— Power transformers are the most expensive assets for power utilities. They are exposed to harmonic distortion causes negative effects on their operation. Traditionally, harmonic mitigation filters were installed by large power users on the customer side of the power system and the utilities had no control over their operation. Utilities should invest in harmonic mitigation filters to grant them full controllability on the harmonic content coming from either side (utility/customer). This paper presents a proposed design of harmonic mitigation filters installed by the power utilities for power transformers. DIgSILENT software is used for the modelling, analysis, and implementation of the proposed filter design and the verification case studies. A comparative study shows the significant reduction of the total harmonic distortion (THD) for power transformers using the designed filters. With this THD reduction, the negative impacts are reduced and the designed life expectancy of the transformers would be increased.

Index Terms-- harmonic analysis, harmonic distortion, harmonic filters, power transformers

Paper A.5

Sinvula, R., Abo-Al-Ez, K.M. and Kahn, M.T., 2020. A Proposed Harmonic Monitoring System for Large Power Users Considering Harmonic Limits. *Energies*, *13*(17), p.4507. https://www.mdpi.com/1996-1073/13/17/4507

Abstract - Most power utilities within Southern Africa are faced with the challenges of harmonic distortion due to the high penetration of renewable energy sources (RES) and the use of electronic devices. There is an excessive total harmonic distortion (THD) measured at the point of common coupling (PCC). In this paper, a proposed harmonic monitoring system for large power users (LPUs) is developed. This proposed system considers harmonic limits of the individual and THD of the customers allowed injecting into the network, which should be part of the contractual electricity supply agreement (ESA). Hence, it will enable the monitoring of harmonic distortion to be smooth by determining whether the customer has passed or failed compliance for individual harmonic order and the THD of the voltage. The measurements of harmonic distortion are done using the Unipower power quality (PQ) analyzers that are connected at different points within the industrial network. Measurements of harmonic distortion of an industrial site are compared to the simulation results performed by DIgSILENT software to validate the proposed harmonic monitoring system. Based on the validation results, it is recommended that the ESA between the power utilities and the customers should consist of the harmonic limits.

Keywords: harmonic distortion; harmonic monitoring; harmonic limit; electricity supply agreement; harmonic measurement

Paper A.6

Sinvula, R., Abo-Al-Ez, K.M. and Kahn, M.T., 2020. Harmonic Source Detection for a Typical Industrial Network with Hybrid Wind and Solar Energy Systems. Book Chapter Accepted for the book titled: "Modelling and Control of Wind Energy Grid Integration".

Abstract - In modern electrical networks, grid connection of renewable energy systems brings more challenges, the most related to power systems operators and controllers are the power quality (PQ) issues. In developing countries, solar Photovoltaic (PV) systems are widely used as compared to wind energy systems due to certain legislative and economic constraints. Therefore, wind energy PQ impacts are less analyzed compared to solar PV ones. But with the expected increase of wind energy penetration at the distribution networks in these countries such as the Southern Africa countries, it is inevitable to pay attention to wind energy PQ effects. On top of the PQ issues, the issue of harmonic distortion is a major concern especially with the use of power electronics interface of renewable energy systems, and the wide use of non-linear loads. The quality of power for the distribution network is minimized because of harmonic distortion. The total harmonic distortion (THD) of the current and voltage is exceeding the harmonic limits specified by the national and international standards. The harmonic sources in the distribution network need to be found whether it is from the upstream or downstream of the network. The dominant harmonic order needs to be found as well, as this plays a major factor in designing the harmonic mitigation for the distribution network. The comprehensive wind turbine modeling in the DIgSILENT software package is presented in this chapter, along with a novel model for Variable Speed Drives (VSDs) which is used for harmonic analysis. THD at the Point of Common Coupling (PCC) is analyzed when the numbers of wind farms are increasing, using a typical case study of an industrial network with mining industries in Southern Africa. Lastly, this chapter proposes modified harmonic source detection based on the direction of active power flow which is practical and commercially viable.

Paper A.7

Sinvula, R., Abo-Al-Ez, K.M. and Kahn, M.T., 2020. Harmonic Power Flow Direction Method for Smart Grids. *Accepted for AIUE Proceedings of the 18th Industrial and Commercial Use of Energy conference*.

Abstract - Active power flow direction is a common method used by most industries to determine the flow of harmonics in the distribution network and for data monitoring analysis. This method is integrated into most power quality analysers and commercial software. Therefore, this paper seeks to examine the harmonic power flow direction method and quantify the size of the harmonic contribution of each harmonic source connected at the Point of Connection (PoC). A radial distribution network with harmonic loads is used and modelled in the DIgSILENT power factory. It was found that the harmonic power flow depends on the flow of harmonic current within the power system. It can be that the harmonic sources have negative power at a harmonic frequency which means it injects the harmonic current, but the dominant contribution is only from one or two harmonic sources. Thus, the load with the highest percentage of individual and total harmonic distortion is the dominant contributor to harmonics. DIgSILENT gives the contribution of each load connected at the PoC by indicating the percentage of total harmonic distortion. The active power flow direction method is the practical and commercial method to use in the industries. This gives a solution for the ongoing harmonic source detection research. It is recommended to use DIgSILENT, it shows the direction of harmonic current flow and quantifies the harmonic content within the network.

Keywords: active power flow, harmonic current, total harmonic distortion, harmonic frequency.

Paper A.8

Sinvula, R., Abo-Al-Ez, K.M. and Kahn, M.T., 2020. New Adapted Norton and Thevenin Equivalent Circuits. Under Review for the *IEEE Transactions on Power Delivery*.

Abstract - Traditionally, the power system was designed with only one customer connected at the Point of Common Coupling (PCC). A practical power system has multiple customers connected to the PCC. The customers cannot be represented as one because of different operating and load conditions. The equivalent circuits were designed to represent the one customer connected at the PCC which no longer holds. Therefore, this study seeks to develop adapted Norton and Thevenin equivalent circuits that include the new phenomenon of a practical power system. The existing equivalent circuits are adapted based on the number of customers connected at the PCC, which should be able to increase or decrease. Two case studies are investigated with single and three customers connected. This is achieved by the calculation of the current and voltage at the PCC with single and three customers. The voltage and current at the PCC differ between the two case studies. Therefore, the newly adapted circuits demonstrate that the number of customers cannot be represented as one. Thus, it is recommended that during the harmonic source detection method the new adapted circuits should be used.

Index Terms— Circuit analysis, Equivalent circuits, Harmonic distortion, Point of common coupling, Power systems

APPENDIX B: NETWORK EQUIPMENT DATA

The equipment details for the Benchmark IEEE PES test system is given in Table B.1 to Table B.4

Table B.1: Transformer data

Transformer	**TR 4**	**TR 1**	**TR 2 and TR 3**
Rated 3ϕ power (MVA)	20	0.4	1
Line – Line Voltage (kV)	110/21	21/0.42	21/0.42
Vector group	YNyn	Dyn	Dyn
Positive sequence short-circuit voltage (%)	11	4	6
No load losses (W)	0	0	0
Copper losses (W)	0	0	0

Table B.2: Line data

Line type	**OHL 1**	**CAB 1**	**CAB 2**	**CAB 3**	**CAB 4**	**CAB 5**	**CAB 6**
Nominal voltage (kV)	20	20	20	0.4	0.4	0.4	0.4
Resistance (Ω/km)	0.57	0.5	0.5	0.006	0.002	0.002	0.0015
Inductance $(\mathrm{mH/km})$	0.38	0.45	0.45	0.3	0.1	0.2	0.05
Capacitance $(\mu\mathrm{F/km})$	0	0.09	0.09	0.0005	0.0002	0.0003	0.0001
Length (km)	1	2	1.5	1	1	1	1

Table B.3: Grid harmonic spectrum for the background harmonic

Frequency	**Harmonic spectrum (kV)**	**Harmonic spectrum (p.u.)**
1st	$89.9\angle 0°$	$0.82\angle 0°$
5th	$224.5\angle 80°$	$0.00204\angle 80°$
7th	$188.6\angle -5°$	$0.00171\angle -5°$
11th	$224.5\angle -30°$	$0.00204\angle -30°$
13th	$53.9\angle -140°$	$0.00049\angle -140°$

Table B.4: Busbars and terminals voltage level

Busbars	**Terminal**	**Voltage (kV)**
	Terminal	110
MV, PCC 1, PCC 2, PCC 3		21
PCC 4, LV 1, LV 2, LV 3		0.42
	AC 1, AC 2, AC 3, AC 4	0.42
	DC 1, DC 2	0,55*

*indicate the DC voltage supplying the DC motor

The equipment details for the Industrial network are given in Table B.5 to Table B.14.

Table B.5: Transformer data for industrial network

Transformer	Obib TR 1 & 2	Skorpion TR 1 & 2	Rosh Pinah TR 1 & 2	Lorelei TR 1	Solar PV_1, Solar PV_2, Solar PV_3, Solar PV_4 & Solar PV_5	TR REC 1A & 2A & 3A & 4A	TR REC 1B & 2B & 3B & 4B	Boiler 1 TR & 2	3.3/0.4kV 2MVA TR	3.3/0.4kV 1.6MVA TR	3.3/0.525kV 400kVA TR	3.3/0.525kV 800kVA TR
Rated 3 Ø power (MVA)	160/160/10	40	5	10	1.25	12.665/8.955/8.955	12.665/8.955/8.955	15	2	1.6	0.4	0.8
Line - Line Voltage (kV)	400/66/22	66/11	66/3.3	66/33	33/0.4	66/0.651/0.651	66/0.651/0.651	11.55/11	3.3/0.4	3.3/0.4	3.3/0.525	3.3/0.525
Vector group	YNynd1	YNd1	YNd1	Dyn11	Dyn11	Dyn1yn7	Yynyn6	Dyn11	Dyn11	Dyn11	Dyn11	Dyn11
Positive sequence short-circuit voltage (%)	13/1.2/2.1	10	8.47	9.02	2	6.26/6.26/6.26	6.26/6.26/6.26	8.85	5	5	5	5
Zero sequence short-circuit voltage (%)	13/1.2/2.1	10	8.47	9.07	6	3/3/3	3/3/3	3	5	5	5	5
No load losses (kW)	0	0	0	0	2.4	0	0	0	0	0	0	0
Copper losses (kW)	0	0	0	0	6.9	0	0	0	0	0	0	0

Table B.6: Line data for industrial network

Line type	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7
Nominal voltage (kV)	66	66	66	66	66	66	33
Nominal current (kA)	0.32041	0.32041	0.32041	0.32041	1.05403	1.05403	0.24
Conductor type	Hare	Hare	Hare	Hare	Pelican	Pelican	Rabbit
Bundle spacing (m)	-	-	-	-	0.15	0.15	-
DC resistance (20°C) (Ω/km)	0.2733	0.2733	0.2733	0.2733	0.1189	0.1189	0.5426
GMR (equivalent radius (mm)	5.136	5.136	5.136	5.136	7.85	7.85	3.645
Outer Diameter (mm)	14.16	14.16	14.16	14.16	20.7	20.7	10.05
Earth conductor	-	-	-	-	2	2	-
The nominal voltage of earth conductor (kV)	-	-	-	-	220	220	-
Nominal current of earth conductor (kA)	-	-	-	-	1	1	-
DC resistance (20°C) (Ω/km) for the earth conductor	-	-	-	-	3.97	3.97	-
GMR (equivalent radius (mm) for the earth conductor	-	-	-	-	3.54	3.54	-
Outer Diameter (mm) for the earth conductor	-	-	-	-	9.75	9.75	-
Length (km)	14.4	0.43	1.63	7.29	3.523	3.523	3.328

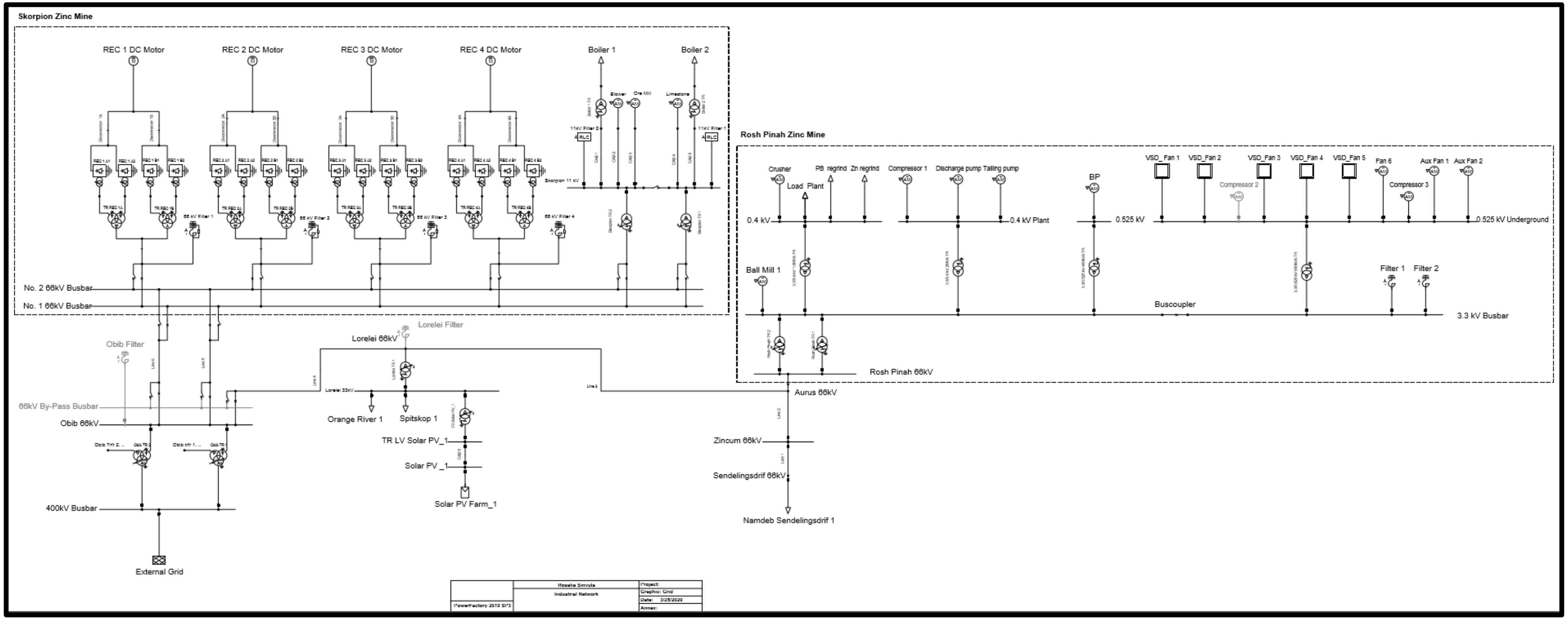

Figure B.1: Industrial network

Table B.7: Cable data for industrial network

Cable	**CAB 1 & 5**	**CAB 2**	**CAB 3 & 4**
Nominal voltage (kV)	11	11	11
Length (km)	0.369	0.682	0.523
Number of parallel line	3	2	2

Table B.8: Load data

AC Load	**Boiler 1 & 2**	**Orange River 1**	**Spitskop 1**	**Namdeb Sendelingsdrif 1**	**PB & Zn Regrind**	**Load Plant**
Active Power (MW)	13	4.17	0.96	1	0.35	0.545
Power Factor	0.9	0.9412	0.9412	0.9295	1	1
Load model	Impedance model 1					

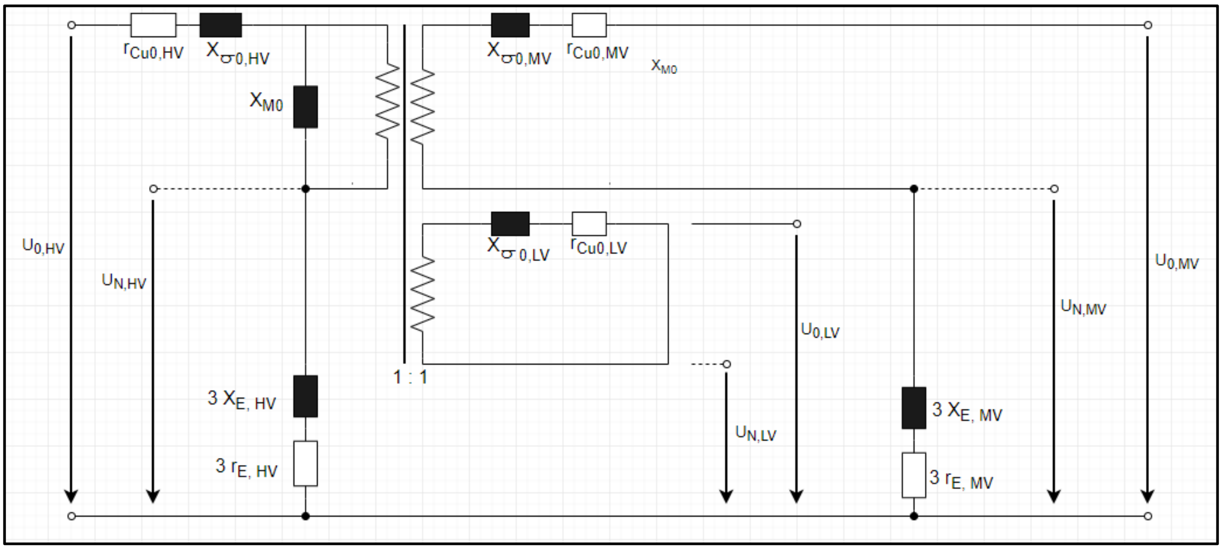

Figure B.2: Zero-sequence model of YN-yn-d transformer

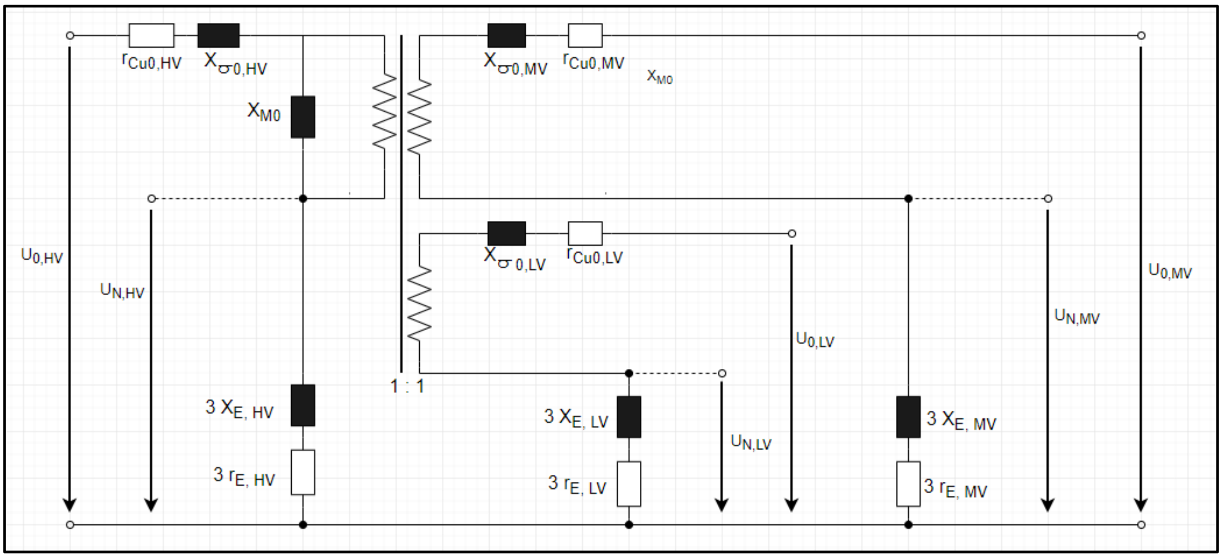

Figure B.3: Zero-sequence model of YN-yn-yn transformer

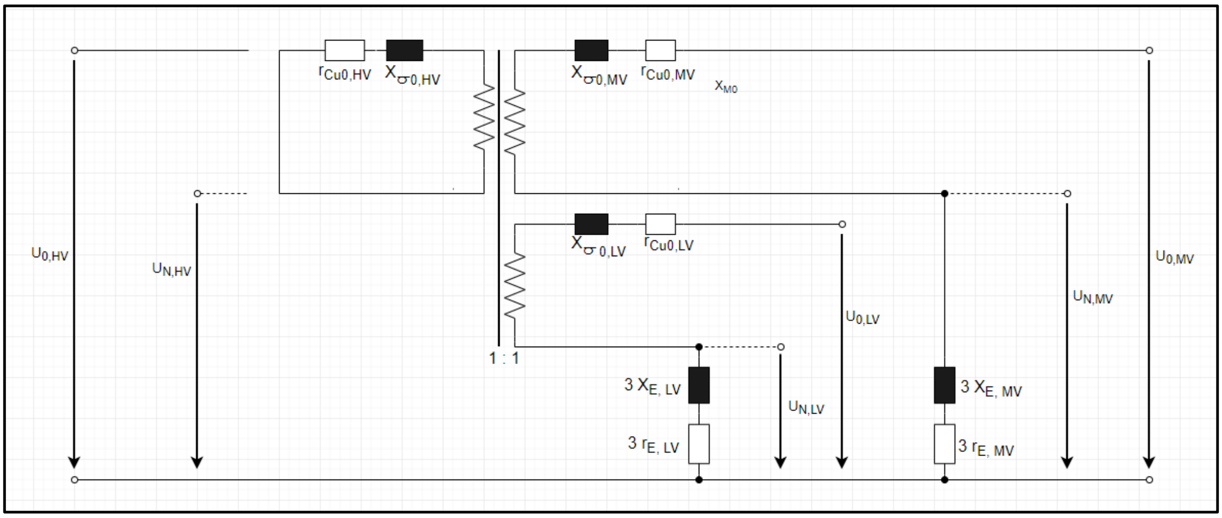

Figure B.4: Zero-sequence model of D-yn-yn transformer

Table B.9: DIgSILENT library harmonic spectrum for a 12-pulse rectifier

Harmonic frequency	Current (%)	Angle (˚)
11	9.090909	180
13	7.692308	0
23	4.347826	180
25	4	0
35	2.857143	180
37	2.702703	0

Figure B.5 showed how the 66kV harmonic filter was modelled in DIgSILENT and layout parameters needed to design a shunt filter.

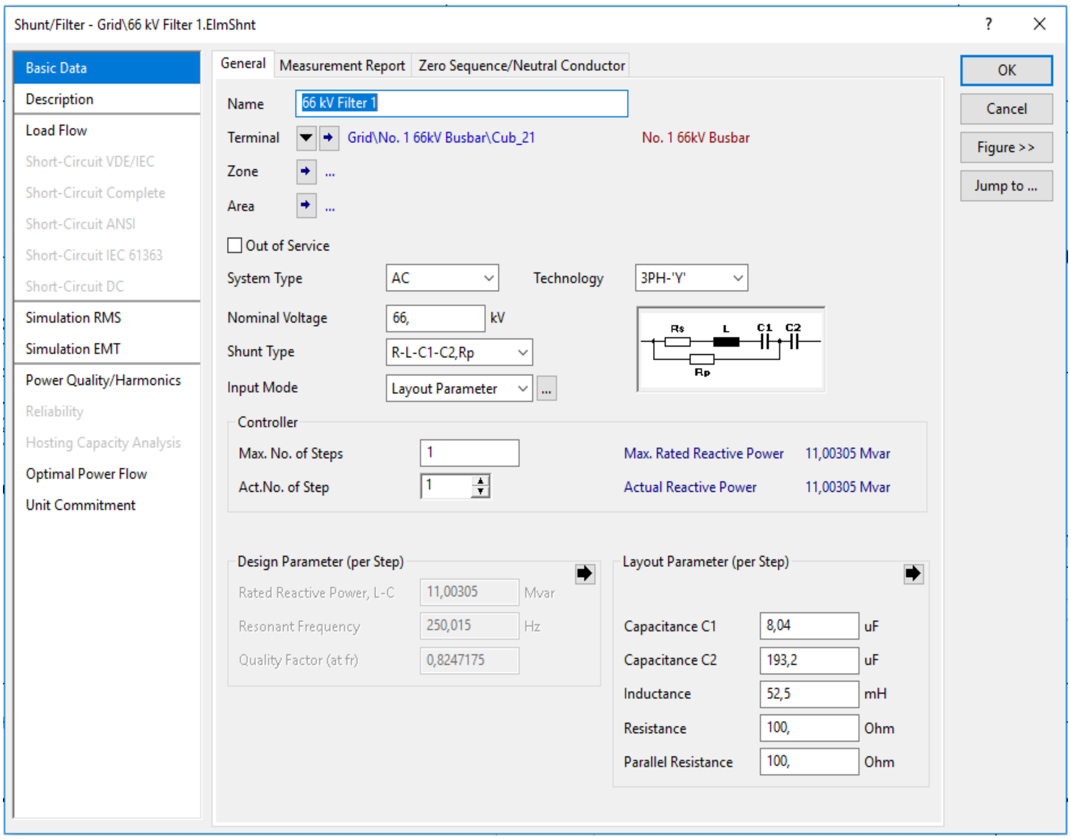

Figure B.5: 66kV Harmonic filter model in DIgSILENT

Figure B.6 showed how the 11kV harmonic filter was modelled in DIgSILENT and layout parameters needed to design a damped 2nd Order harmonic filter.

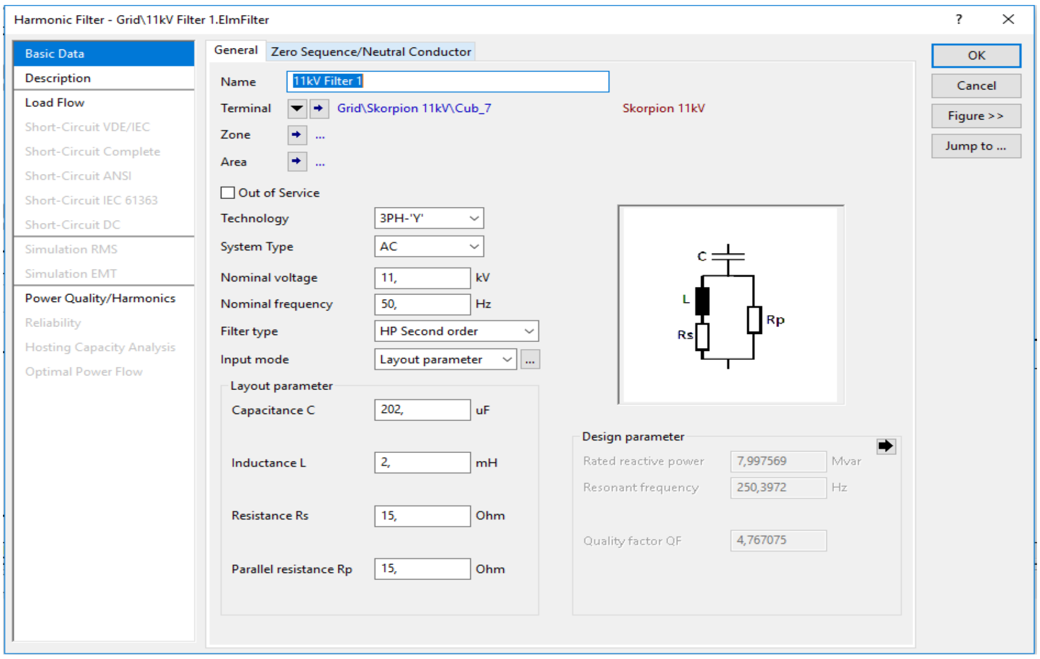

Figure B.6: 11kV damped 2nd Order Harmonic filter model in DIgSILENT

Table B.10: Harmonic filter data

Harmonic Filter	66 kV Filters	33kV Filter	11kV Filters	3.3 kV Filters	
Name	66 kV Filter 1 66 kV Filter 2 66 kV Filter 3 66 kV Filter 4	33kV Filter 1	11kV Filter 1 11kV Filter 2	3.3 kV Filter 1	3.3 kV Filter 2
Type	Shunt R – L – C1- C2, Rp	Shunt R-L-C	HP Damped 2nd order	Shunt R-L-C	Shunt R-L-C
Reactive power (MVAr)	All are 11	0.1	All are 8	1	2
Purpose	PFC and harmonic mitigation	Harmonic mitigation	PFC and harmonic mitigation	PFC and harmonic mitigation	PFC and harmonic mitigation

Table B.11: Asynchronous machine data

Asynchronous Machine	Blower	Ore Mill	Lime stone	Ball Mill	Crusher	Compr. 1	Discharge pump	Tailing pump	BP	Compr. 2	Compr. 3	Fan 6	Aux Fan 1	Aux Fan 2
Voltage (kV)	11	11	11	3.3	0.4	0.4	0.4	0.4	0.525	0.525	0.525	0.525	0.525	0.525
Motor starting method	Direct on Line (DOL)	Liquid starter	Liquid starter	Liquid starter	Soft starter	DOL	DOL	DOL	DOL	DOL	DOL	Soft starter	Soft starter	Soft starter
Power (kW)	2450	4000	2300	1000	160	160	160	275	160	166	181	110	75	45
PF	0.9	0.87	0.88	0.87	0.9	0.9	0.94	0.94	0.9	0.9	0.9	0.94	0.94	0.94
Number of Parallel machine	1	1	1	1	3	3	2	1	12	2	3	1	9	11
Nominal speed	1492	993.5	1489	994	1492	1492	990	990	1492	1492	1492	990	990	990
No of pole pairs	2	3	2	3	2	2	3	3	2	2	2	3	3	3
Connection	Δ (Delta connected)													
Efficiency (%)	99													

Table B.12: Solar PV farm cable data

Cable	CAB 7	CAB 8	CAB 9, CAB 11, CAB 13, & CAB 18	CAB 10	CAB 12	CAB 14	CAB 15	CAB 16	CAB 17
Nominal voltage (kV)	33	33	0.4	33	33	33	0.4	33	33
Rated current in ground (kA)	0.262	0.26	0.178	0.26	0.26	0.26	0.178	0.26	0.26
Nominal Cross section area (mm^2)	120	150	120	150	150	150	120	150	150
Cable cores	1	3	3	3	3	3	3	3	3
Insulation Material	XLPE	PVC	PVC	PVC	PVC	PVC	PVC	PVC	PVC
Conductor Material	Al	Al	Al	Al	Al	Al	Al	Al	Al
Length (km)	0.1	0.061	0.175	0.053	0.101	0.176	0.105	0.125	0.245
Derating factor	1	0.67	0.56	0.78	0.78	0.78	0.56	0.78	0.67
Number of parallel line	1	1	36	1	1	1	36	1	1

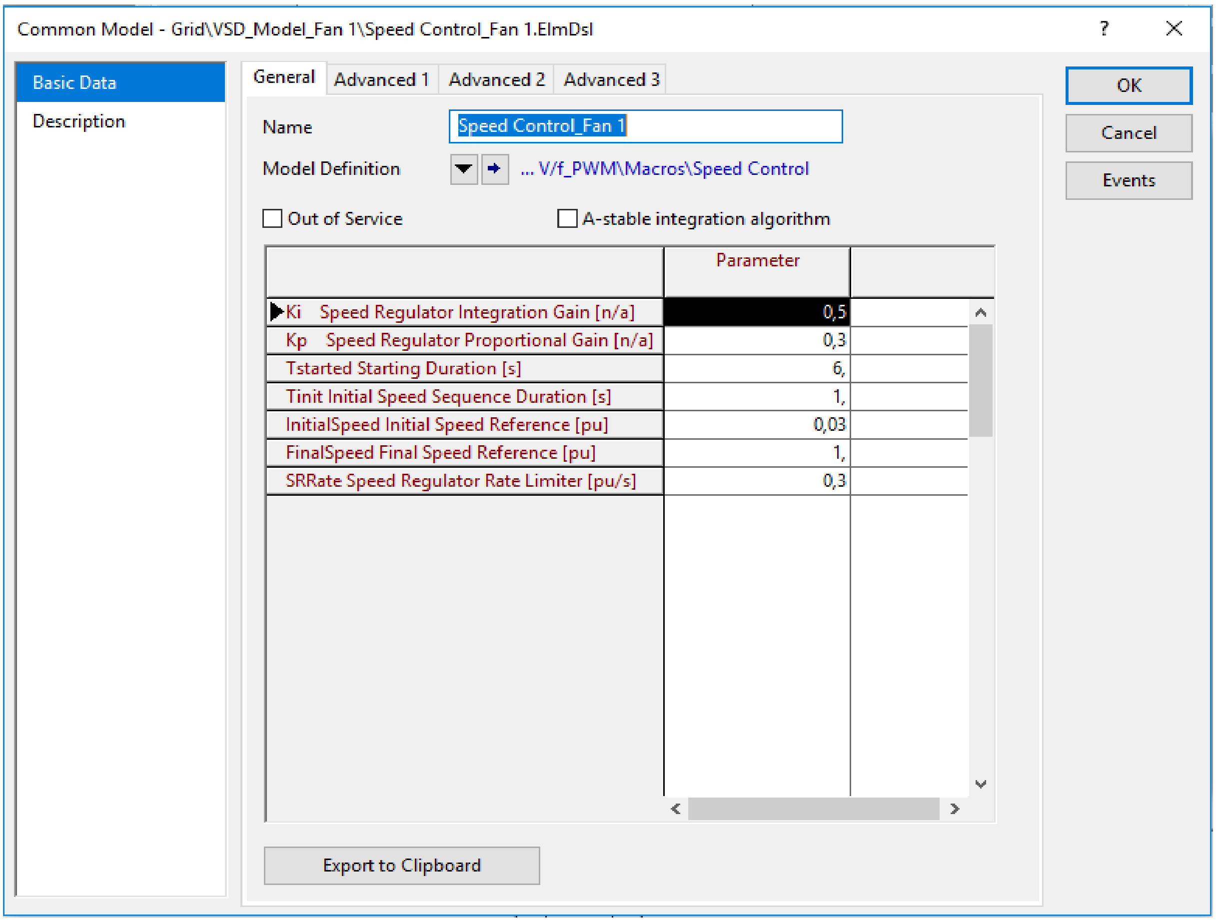

Figure B.7: Speed control block parameter

Table B.13: Harmonic spectrum for solar PV farm

Harmonic frequency	Current (%)
5	1.49
7	2
11	0.23
13	0.69
17	0.04
19	0.2
23	0.04
25	0.06
29	0.04
31	0.05
35	0.04
37	0.05
41	0.05
43	0.04
47	0.03
49	0.03

```
! Variable definintion
vardef(start_command) ='0/1';'Motor Start Command OFF/ON' ! Switch off/on the motor
vardef(Tstarted) = 's';'Starting Duration'        ! Motor Speed reference becomes rated value at (Tstarted+Tconnect) seconds
vardef(Tinit) = 's';'Initial Speed Sequence Duration'     ! Keep initially the motor voltage constant for Tinit seconds
vardef(InitialSpeed) = 'pu';'Initial Speed Reference' ! Set here what the value of the initial voltage applied to the motor should be
vardef(FinalSpeed) = 'pu';'Final Speed Reference'
vardef(Kp) = 'n/a';'Speed Regulator Proportional Gain'
vardef(Ki) = 'n/a';'Speed Regulator Integration Gain'
vardef(SRRate) = 'pu/s';'Speed Regulator Rate Limiter'
vardef(wmot) = 'pu';'Motor Speed Feedback'
vardef(wref) = 'pu';'Motor Speed Reference'
vardef(wout) = 'pu';'Speed Reference to V/F scalar control'

! Initialisation
inc(wref_init)  = wref
inc(start_command) = 0; ! 0=do not start; 1=start motor
inc(starting)=select(wmot>0.97*wref,1,0);      !
inc(xVref) = select(wmot>0.97*wref,wref,InitialSpeed);      ! per unit value for initializing period
inc0(wref) = FinalSpeed  ! Initialize to this value only if wref is not connected
inc(xKi) = wref
inc(xwout) = select(wmot>0.97*wref,wref,0)
inc(xKp) = select(starting,
&    Kp*(wref-wmot),    ! Proportional term of controller
&    0)                 ! Do not change during starting period

inc(wout) = select(wmot>0.97*wref,wref,0)
inc0(wmot) = 0;     ! Initializes the motor speed if the motor is not connected
inc(xT) = time();

! Controller for steady state operation

! Close breaker at specified Tconnect time

event(1,start_command-0.5,'create=EvtSwitch target=Switch name=ConnectMotor i_switch=1')

xT.= select(start_command>0.5,0,1)
! PI controller is active only after starting procedure.
starting = picdro(wmot>0.97*wref_init  ,0.001,9999); ! toggle variable "starting" when speed gets close to nominal

xKi.=select(starting,
&    Ki*(wref-wmot),    ! Integral term of controller
&    0)                 ! Do not integrate error during starting period

xKp.=select(starting,
&    (Kp*(wref-wmot)-xKp)/0.001,    ! Proportional term of controller
&    0)                 ! Do not change during starting period

w=select(starting,
&  lim(limstate(xKp,-1,1)+limstate(xKi,-1,1),-1,1), ! Controller active during normal operating conditions
&  select(time()<xT+0.02,0,limstate(xVref,0,1) )) ! starting ramp for voltage reference
xwout.= lim((w - xwout)/0.001,-SRRate,SRRate)
wout= xwout

xVref. =select(time()>xT+Tinit .and. time()<Tstarted/wref_init, ! defines the starting ramp
&       (1-InitialSpeed)/(Tstarted/wref_init-(Tinit+xT)), ! after initial period
&       0);
```

Figure B.8: Speed control equations

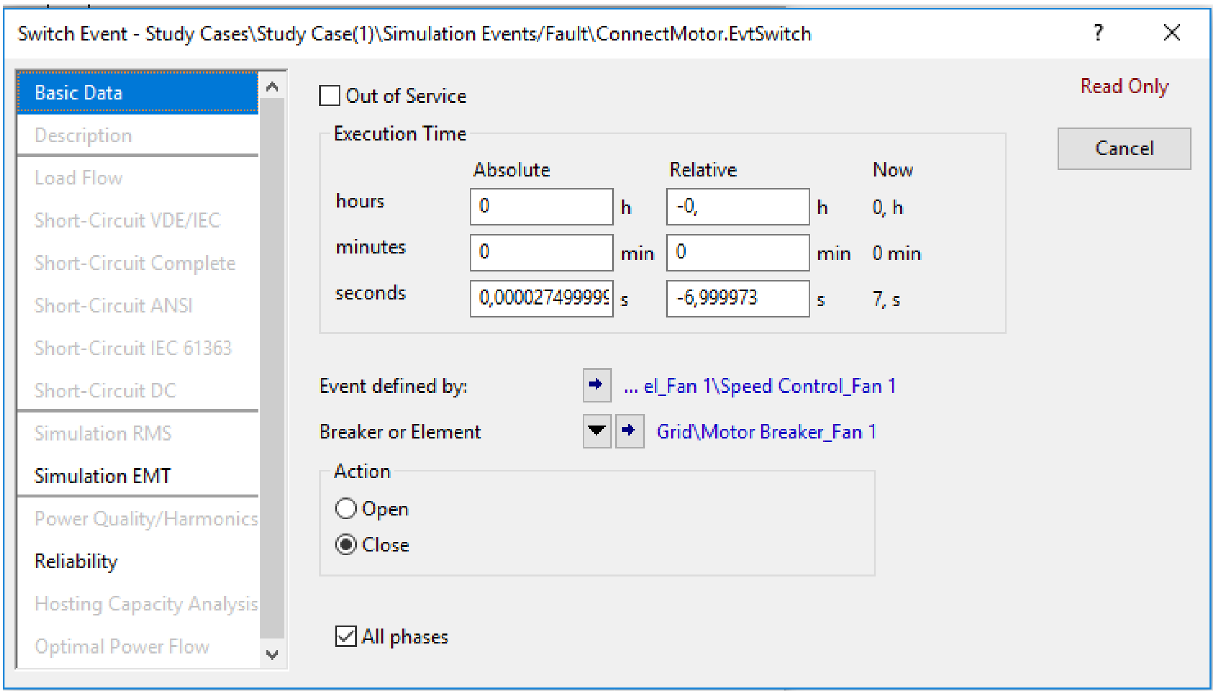

Figure B.9: Switch events for the motor breaker