ASSESSING THE CONTRIBUTION OF HARMONICS AT THE POINT OF COMMON COUPLING IN NETWORKS

By

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DECLARATION

I hereby declare that this Thesis submitted for the Doctor of Philosophy degree to the

University of Johannesburg is my own work and has not been submitted in this or a similar form for a degree at any other tertiary institution

……………………………………………………………………………….

S. KASEMUANA MATOTOTO

"I waited patiently for the LORD; he turned to me and heard my cry. He lifted me out of the slimy pit, out of the mud and mire; he set my feet on a rock and gave me a firm place to stand". Psalm 40:1-2

Thank you, Jesus!

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ABSTRACT

The presence of harmonics in voltage and current waveforms is a result of an increase in use of nonlinear loads in power systems. Utility and end users are in disagreement over who is responsible of polluting the Point of Common Coupling (PCC) and therefore poor power quality. Hence, there is a need for dedicated techniques of analysis to determine the contributions of harmonics between utility and customer.

This thesis sought to determine the contribution of harmonics at the PCC between utility and end users in the electrical distribution network. To assess such contributions, both the utility and customers' systems must be fully characterised by their equivalent Thevenin sources and impedances. Their contributions can then be calculated. This study developed a methodology for determining the parameters of the Thevenin equivalent circuit at different points in time "A" and "B". Power descriptions such as IEEE 1459-2010 deals with one measurement slice in time and cannot provide the Thevenin equivalents necessary to determine harmonic contribution at the PCC. This study rather looks at the voltage and current at the PCC at different times. Before establishing this method, it is demonstrated how a Thevenin equivalent circuit for a resistive network can be determined without shorting and opening the source. Instead, two points are used on the load line. This demonstrates the approach used in this study.

This study suggested three steps to follow in determining contribution at the PCC: firstly, determine the dominant harmonics at the PCC by selecting the larger magnitudes that the transducers could measure with accuracy. Secondly, determine the Thevenin equivalent circuit per dominant harmonic by selecting two operating points in time (i.e time A and time B) for both the utility and customers when loads change. Lastly, define the main contributor of harmonics at the PCC per harmonic number by applying the principle of superposition to the Thevenin equivalents.

To demonstrate the effectiveness of the developed model, a case study is conducted at a metropolitan municipality; whereby a numerical analysis of current and voltage harmonics is performed in order to support the mathematical analysis and to verify the experimental results. The analysis conducted in the network involving two customers, a sport stadium and Johannesburg metropolitan company, indicated that that the sport stadium was the main contributor of harmonics at the PCC.

The main advantage of the proposed approach is that we wait for the load to change in time in order to calculate the system Thevenin equivalents. This is opposed to using injecting of currents and/or open circuit measurement that is normally done.

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LIST OF ABBREVIATIONS AND DEFINITIONS

ABBREVIATIONS	**DESCRIPTION**
AC	Alternating current
CFL	Compact Fluorescent lamp
CI	Critical impedance
CIGRE	International Council on Large Electric Systems
CIRED	International Conference on Electricity Distribution
CT	Current Transformer
DC	Direct current
DFT	Discrete Fourier transform
DPF	Distortion power factor
DSP	Digital Sound Processing
EHV	Extra High Voltage
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FFT	Fast Fourier Transform
FL	Fluorescent lamp
GPS	Global Positioning System
HV	High Voltage
IEC	International Electro technical committee
IEEE	Institute of Electrical and Electronic engineers
LV	Low Voltage
MV	Mean Voltage
NER	National Energy regulator
NERSA	National Energy regulator of the South Africa
NoSync	NoSynchronisation
NRS	National regulator power Quality Standard
O/C	Overcurrent
PCC	Point of Common Coupling
PF	Power factor
PQElspec	

PQSCADA	Power Quality Supervisory Control and data Acquisition
PWM	Pulse width modulation
RMS	Root Mean Square
SMPS	Switch Mode Power Suppliers
SNTP	Standard Network time protocol
SVC	Static var compensator
TCR	Thyristor-controlled reactor
TDD	Total Demand distortion
THD	Total Harmonic Distortion
THDi	Total Harmonic Distortion
THDv	Total harmonic Distortion Voltage
TIF	Telephone Influence factor
VAR	Volt Ampere Reactive
VT	Voltage Transformer

LIST OF SYMBOLS AND DEFINITIONS

SYMBOLS	DEFINITIONS
A	Ampere
V	Volt
W	Watt
VAR	Volt Ampere Reactive
kWh	Kilo Watt hour
kW	Kilo Watt
VA	Volt Ampere
ω	Angular frequency
f	Frequency
Vm	Maximum voltage magnitude
Im	Maximum current magnitude
S	Apparent power
I	Current
θ_a	Phase angle difference between voltage and its resulting current in the phase line a
θ_1	Current phase angle of the distorting load at the fundamental frequency
Q1	Fundamental reactive power
Vmax	Maximum value of the phase voltages measured from line to neutral
Imax	Maximum value of the phase currents measured from line to neutral
Qa	Reactive power through phase a
I1	Current at the fundamental frequency
I_H	Harmonic current
V1	Voltage at the fundamental frequency
V_H	Harmonic voltage
P1	Fundamental active power
P_H	Total harmonic power
S1	Fundamental apparent power

S_N	Nonfundamental apparent power
D_I	Current distortion power
D_V	Voltage distortion power
S_H	Harmonic apparent power
N_H	Total harmonic nonactive power
N	Nonactive power
Z	Impedance
E_u	Utility voltage source
E_c	Customer voltage source
δ	The phase angle difference between customer and utility side voltage sources
I_{PCC}	The current flowing at the PCC
U_{PCC}	The voltage at the PCC
$X_{\max}$	Maximum and minimum values for X
$X_{\min}$	Maximum and minimum values for X
Q_t	The transformed reactive
Arg(k)	The phase angle difference between these two equivalent voltages
E_{h0}	Harmonic voltage phasor of the supply network
V_h	Harmonic voltage phasor across the load
I_h	Harmonic current phasor flowing through the source connection backwards to the supply electrical network
Z_h	Impedance of complex supply network
Z_{hc}	Impedance of complex load
I_{hc}	The generated harmonic current phasor by the source of distortion.
E_{hc}	Emitted harmonic voltage from the distorting load into the supply network
Z_{h-ref}	Reference network impedance
I_n	Harmonic current components at harmonic order n.

Z_n	Impedance matrices components at harmonic order n.
I_N	The Norton equivalent current
THD_V	Total harmonic distortion voltage
THD_I	Total harmonic distortion current
Z_u	Utility impedance
Z_{C1}	Customer 1 impedance
Z_{C2}	Customer 2 impedance
V_u	Utility voltage source
V_{C1}	Customer 1 voltage source
V_{C2}	Customer 2 voltage source
$c_1 - n - pcc$	Related to the contribution of the customer 1 at the PCC at n th harmonic order
$c_2 - n - pcc$	Related to the contribution of the customer 2 at the PCC at n th harmonic order
$u - n - pcc$	Related to the harmonic current contribution of the utility at n th harmonic order
$c_1 - n$	Related to the Thevenin voltage and impedance of customer 1 at n th harmonic order at
$c_2 - n$	Related to the Thevenin voltage and impedance of customer 2 at n th harmonic order
$u - n$	Related to the Thevenin voltage and impedance of utility at n th harmonic order

$c_1 - n - pcc$	Related to the contribution of the customer 1 at the PCC at n th harmonic order
$c_2 - n - pcc$	Related to the contribution of the customer 2 at the PCC at n th harmonic order
$u - n - pcc$	Related to the harmonic current contribution of the utility at n th harmonic order
$c_1 - n$	Related to the Thevenin voltage and impedance of customer 1 at n th harmonic order at
$c_2 - n$	Related to the Thevenin voltage and impedance of customer 2 at n th harmonic order
$u - n$	Related to the Thevenin voltage and impedance of utility at n th harmonic order
$\overline{K}_V$	Represents the complex number of the ratio of the equivalent harmonic voltages.
θ_{V-I}	The phase angle difference between the equivalent voltages of utility and customer respectively
$\overline{K}_I$	Represents the complex number of the ratio of the equivalent harmonic current.
L_{hMV}	The planning level for voltage harmonics in the (MV or HV) system under consideration
T_{hMV}	The transfer coefficient of voltage harmonics from the upstream system to the system under consideration.
L_{hHV}	The planning level for voltage harmonics in the upstream system

E_{hMV}	The individual customer harmonic voltage emission limit at the PCC;
S_t	The total supply capacity of the considered system including provision for future load growth

CHAPTER 1: INTRODUCTION

1.1 Background

The term power quality "embraces all aspects associated with the amplitude, phase and frequency of the voltage and current waveforms existing in the power circuit" [1], [2]. Poor power quality in the power systems may occur due to transient conditions or from the installation of non-linear loads. Under normal conditions, power systems are designed to operate at a constant frequency and under perfect sinusoidal voltage and current waveforms [3], [4]. This operation, however, appears to be practically impossible because of the continued presence of non-linear loads.

Non-linear loads are loads characterised by a non-constant resistance during the applied voltage waveform. The associated non-linear current causes nonlinear voltages due to supply impedance. Switch Mode Power Supply (SMPS) loads for example are supplied by a 50 Hz sinusoidal voltage waveform and convert alternating current (AC) to direct current (DC). This draws current in short, high-amplitude pulses, which occur around the positive and negative peaks of voltage. Due to current rapid cycles on and off, the cyclic power draw distorts the original shape of the current waveform, carving the sinusoidal shape and imposing new waveforms of an entirely different shape called harmonics. The combination of the fundamental sine waves and its multiple causes harmonic distortion. These harmonics are reflected in the electrical installation. Harmonic current travels through the electrical system and distorts the voltage at the Point of Common Coupling (PCC) through the system impedance. The quality of supply delivered by the utility to end users is then affected by the harmonic distortions. Since the utility and end users are connected to the same PCC, studies have been conducted in this field in order to determine the responsibility of polluting the PCC [5], [6], [7]. In practice, however, these studies are not widely used. The quality of power delivered is currently a major issue worldwide. This makes harmonic analysis a novel analytical and modelling tool for the assessment of loads and systems connected to the same PCC, and their interaction at harmonic frequencies [8].

Due to an increased use of non-linear loads in power systems, power harmonics studies have become an important component of power system analysis. This chapter provides the basic introductory concepts of power quality and harmonics and analysis methods for power systems, particularly for degrading the Point of Common Coupling between Utilities and end users. The chapter also discusses the research aims, objectives, methodology and main contribution of the thesis.

1.2 Rationale and Motivation

Harmonic analysis is becoming a more complex problem than in the past for two reasons: (a) the existence of loads generating harmonics and distorting the Point of Common Coupling, and (b) the existence of other loads, which are sensitive to the harmonics produced by other loads.

Non-linear current drawn by loads causes voltage harmonics. These voltage harmonics propagate through the system and then interfere with equipment. It has been shown that a load-producing harmonic can adversely affect the loads that are very sensitive if “significant voltage distortion” is caused [18]. The voltage distortion caused by the load generating harmonic is a function of both the system impedance and the amount of harmonic current generated. This does not always mean that a distorted load current will adversely affect other loads connected to the same PCC. The problem becomes an issue in the presence of resonance with for example, power factor capacitors. This can cause erratic operation of telecommunication systems, computers, electronic test equipment, generators, or motor drives. A part from being a possible cause of harmonics, generators can be affected by other harmonic sources; for example, in terms of efficiency losses or overheating. One of the main reasons for this phenomenon is the high impedance of generators, which transfer current harmonic distortion into voltage harmonic distortion (i.e., affecting other loads supplied from that source). It has been shown, on the other hand, that a customer having large adjustable speed motor drives and compensating shunt capacitors can find himself billed for high harmonic currents and voltages levels emanating from another customer in case of resonance even though he does not have any significant non-linear load [10].

More and more end-users are better informed about such power issues that challenge the utilities to improve the quality of the power delivered. Both utilities and end-users of electric power are increasingly concerned about the quality of electric power. Although many studies have been conducted to assess power harmonics in the distorted power systems [5-7], [11-15], [17], [19], there is a need for dedicated techniques of analysis applicable to determine who is contributing with harmonics at the PCC between utility and end users. The challenge in measuring harmonic contributions at the PCC and therefore evaluating the responsibility of polluting the PCC is in determining the utility side and customer side Thevenin equivalent circuit [67]. This work focuses on this important issue.

1.3 Problem Identification

A simple and well-used manner of setting responsibility between utility and end user as well as the costs of power quality problems, including reactive power, is to state that voltage is the responsibility of the utility and current is the responsibility of the customer [7], [8], [9]. This statement is true and works well as long as the voltage and current characteristics do not interact excessively. In many cases, the customer pays the extra bill without being responsible for polluting the PCC. This is unfair because, at the PCC, three aspects need to be separated: (a) the customer produces non-sinusoidal currents leading to voltage harmonics, -*which is the customer fault*-. (b) The existence of voltage harmonics is only made possible by the presence of a network source impedance, -*which is the supplier's fault*. (c) Voltage harmonics can be caused by other customers. This is eventually due to their non-sinusoidal currents, and the utility's network impedance, -*which is the other customers' fault*-. The problem however resides in the unfair current billing of two or more nearby customers, say one with an inductive load and the other with the capacitive load. In practice, one or both customers might have to pay a fine for the reactive power, which in reality, cancels and causes no problem for the supplier. Moreover, the connection of a customer to the PCC with a perfect resistive load causes voltage harmonics and higher power components drawn by the load for which the customer cannot be charged. Therefore, the blame should be on the utility and on other customers, who should pay for their fault.

A major part of the impedance of harmonic current sources emerges from distribution transformers, which will, to some extent, act as a harmonic current barrier. Customers sharing a distribution transformer generally may have higher harmonic current amplitudes in their metering points. They might experience more substantial harmonic current interactions than consumers not sharing the same transformer might. However, the situation might be complicated further by the risks of resonance. The compensation of the fundamental reactive power produced by capacitors generally reduces most of the harmonic voltage levels in the system due to its ability to offer a low-impedance path for the current harmonics. In case of resonance, however, the harmonic current and/or the harmonic voltage will increase instead, at least locally. It has been demonstrated in [10] that a customer with a motor load and compensating shunt capacitors can find himself part of a resonance circuit for some harmonic currents emanating from another consumer. Therefore, a high harmonic current level and a high harmonic voltage level can be attributed to him without him having any significant nonlinear load.

Analyzing the responsibility of polluting the PCC between utility and customers can be done in two ways. The first and simplest way of analysing pollution at the PCC emerges from the recommendation of IEEE Std. 519-1992 [9], [11] that the current and voltage harmonics can always be billed for a set limit. Such analysis however seems problematic, as this simplest solution, as stated earlier, may sometimes be unfair in the presence of resonance between two customers in close proximity. Furthermore, determining distortion power components with IEEE Std. 1459 only provides indications of the total distortion at the PCC, which in reality is the combined effect of harmonics from both the utility and customers [67].

The second way is to carry out a comprehensive and accurate measurement of harmonic power to distinguish the current flowing at the customer and utility sides. According to [6], [9] this way alone does not provide a full characterisation of loads and system impedance.

The best option is the measurement of harmonic impedance at the customer side as well as harmonics generated by the customer's loads and the system. In practice, this might be difficult. Many studies have developed methods based on the injection of disturbances into the power system [15-17], [20-25]. These studies recognise that the subject might not be feasible when switching is not allowed in practical installations and needs. As a result, this work intends to develop a methodology for determining the Thevenin equivalent impedances and sources voltages based on the measured current and voltage at different points in time and to evaluate the contribution of harmonics at the PCC.

1.4 Research Aims and Objectives

This work aims to contribute to the determination of harmonic interference at the PCC by end users and utilities.

The specific objectives to be achieved are as follows:

a) To evaluate the characteristics of current and voltage harmonics components measured both at the utility and at the customers' sides,

b) To evaluate the Thevenin equivalent impedances and voltage sources for the utility and end-users,

c) To quantify the contribution of harmonics current at the PCC between utility and customers.

1.5 Study Methodology

To achieve these objectives, a series of measurements is carried out to evaluate the characteristics of current and voltage harmonics components. All measurements are performed in the substation at the PCC and at the customers' side. To accomplish the first two objectives, an array of existent devices and equipment are selected for measurement and analysis. To undertake the evaluation and analysis, the characteristic of current and voltage harmonics measured at the PCC and at the customers' side are numerically assessed using a harmonic analysis method based on a Fast Fourier Transform (FFT). To clearly quantify the contribution of harmonic characteristics between utility and customers, a Thevenin equivalent circuit based approach is used where the impedance and source voltage characteristics both at the utility and at the customers' sides are calculated using the measured values of voltage and current occurring at different times. From the Thevenin equivalent circuits, the main contributor is determined by using the principle of superposition.

1.6 Main contribution of the thesis

Determining the contribution of harmonic pollution at the PCC between utility and end user has been a challenge for the decades. Analysing harmonic distortion with IEEE 1459 std 1459 only provides the combined effects of harmonics from the utility and the customers. A comprehensive and accurate measurement of harmonic powers should be carried out to analyse the current flowing at both utility and customer sides. In this regard, many studies have attempted to carry out a measurement of harmonic impedances at both the utility and end users' sides as well as the currents drawn by the customers'loads and the system. Other methods developed focused on the injection of disturbances. All these methods recognise that such measurement might not be a feasible in practical network.

The main contributions of the thesis are that:

1) A methodology is developed to overcome the shortcomings of the injection of disturbances method.
2) A model for calculating the Thevenin equivalent circuit parameters is developed for both the utility and end users' sides from measured values of current and voltage occurring at different time instances.

1.7 Outline of the thesis

This thesis consists of six chapters. Chapter 1 provides the basic concepts of power system harmonics and associated impacts on the power quality. It also discusses the problem identification, the adequate method to address the issue discussed, and the contribution of the study.

Chapter 2 presents a literature review of concepts, definitions and theories of power. The key points under discussion are basic concepts on power theories, harmonics identification methods based on power flow and on voltage-current used on power systems, measurement techniques and instruments. Different methods, their respective advantages and disadvantages are reviewed.

Chapter 3 discusses harmonics in power systems. The Harmonics, definitions, sources and effects of distortion are explored. The three main equipment groups, which are reviewed as source of harmonic are magnetic core equipment, conventional equipment and electronic and power electronic equipment. The review of the effects of harmonic distortion mainly focusses on the overheating of phase and neutral conductors, skin effect, motors and generators, transformers, capacitors, measuring instruments, relays and contactor protective systems and telecommunication interference. The general harmonic indices, power quality standards and recommended guidelines set to limit a certain amount of harmonic distortion generated either by the power utility or by the end user are reviewed.

Chapter 4 develops a model for calculating the Thevenin equivalent impedance and source voltages and presents an approach to evaluate the contribution of harmonic current based on the Thevenin equivalent circuits. A methodology is proposed to overcome the shortcoming of harmonic injection to evaluate the harmonic impedance.

Chapter 5 presents a case study. Numerical analysis of current and voltage harmonics components is performed out in order to support the mathematical analysis and to verify the experimental results and assess the contribution of harmonic current at the PCC between the utility and customers.

Chapter 6 discusses the results obtained in chapter four and five, concludes the study and makes suggestions for future research.

Four appendices are included at the end of the thesis. They contain the characteristics of current and voltage harmonics components measured at both utility and customers' sides. Numerical analysis of the current and voltage waveforms using IEEE 1459-2010 are also included. The statistical data of voltage, current, active power and reactive power over time per harmonic selected are also provided.

1.8 Summary

This chapter introduces the basic concepts of power system harmonics and its associated impact on power quality. It also presents the problem identification and discusses the way forward and the method to address the issue. It then highlights the specific contributions of the study.

A literature review of harmonic analysis methods is carried out in chapter 2 before embarking into an investigation of power systems.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This chapter provides a literature review of power theories and definitions. The main points include basic power theories, the harmonic identification methods based on power flow and voltage-current used on power systems, as well as the measurement techniques and instruments.

2.2 Introduction to Power Theory

This section discusses the fundamental and basic power theories related to power systems.

2.2.1 Single-Phase Voltage and Current for Perfect Sinusoidal Conditions

The instantaneous voltage and current in an electrical power network for perfect sinusoidal voltages and currents can generally be expressed as

$$v(t) = V_m \cos(\omega t + \alpha) \tag{2.1}$$

And

$$i(t) = I_m \cos(\omega t + \beta) \tag{2.2}$$

Where V_m and I_m are the maximum voltage and current magnitude respectively, ω is the angular frequency in radians per second (rad/s) and can be expressed as

$$\omega = 2\pi f \tag{2.3}$$

Where f is the frequency. The initial phase shifts of the voltage and current waveforms are given by α and β respectively. The time that the waveforms take to complete one cycle is called the period of the waveforms and is represented by T.

2.2.2 Single-Phase Power Definitions for Perfect Sinusoidal Waveforms

For sinusoidal quantities in single-phase electrical networks, electrical power can be separated into active, reactive and apparent powers. The instantaneous power absorbed by a load in a network can be defined by the following:

$$p = v(t)i(t) \tag{2.4}$$

2.2.2.1 Active Power

The active power is defined as "the time average of the instantaneous power over one period of the wave" [64]. At any time t_0, the active power is expressed as follows:

$$P = \frac{1}{T}\int_{t_0 - T/2}^{t_0 - T/2} p dt \tag{2.5}$$

Where P represents the active power

p : The instantaneous power

T : The period

For sinusoidal voltage and current, the active power is defined as the product of the Root Mean Square (RMS) of the voltage (V), the RMS of the current (I), and the cosine of the angle (θ) between voltage and current [64]

$$P = VI\cos\theta \tag{2.6}$$

Where the phase angle between the voltage and the current waveforms is expressed as:

$$\theta = (\alpha - \beta) \tag{2.7}$$

The cosine of the phase angle is generally known as the power factor angle.

$$pf = \cos(\alpha - \beta) \tag{2.8}$$

The power factor defined in (2.8), is always positive. If the load is inductive, then the current phasor lags the voltage phasor, $\alpha > \beta$ and the load is said to have a lagging power factor. On the other hand, if the load is capacitive the current phasor leads the voltage phasor, $\alpha < \beta$ resulting in a leading power factor.

2.2.2.2 Reactive Power

The reactive power is defined for sinusoidal quantities as the product of the voltage, the current, and the sine of the phase angle between RMS values of voltage and current [64].

$$Q = VI\sin\theta \tag{2.9}$$

Where Q expresses the average value of the power that oscillates between the load and the source without carrying out any net energy transfer

2.2.2.3 Apparent Power

The apparent power is defined for sinusoidal quantities as the square root of the sum of the squares of the active and reactive powers. Apparent power is the maximum quantity of power available in a system when the power factor is unity [64]

$$S = \sqrt{P^2 + Q^2} \tag{2.10}$$

The following espression (2.11) can be obtained if the voltage and current are both sinusoidal and have the same period:

$$S = VI \tag{2.11}$$

2.2.3 Three-Phase Voltage and Current Definitions for Perfect Sinusoidal Waveforms

Three-phase network are comparable to single-phase systems regarding voltage and current definitions. Three-phase network consist of three phases which are generally represented by phase a, b and c. The angle between each phase is equal to 120˚. If a positive phase sequence system is assumed, the voltage and current phasors are expressed by the following equations:

$$v_a(t) = V_{a\max}\cos(\omega t) \tag{2.12}$$

$$v_b(t) = V_{b\max}\cos(\omega t - 120°) \tag{2.13}$$

$$v_c(t) = V_{c\max}\cos(\omega t + 120°) \tag{2.14}$$

Where $V_{a\max}$, $V_{b\max}$ and $V_{c\max}$ are the maximum value of the phase voltages measured from line to neutral. The phase currents are:

$$i_a(t) = I_{a\max}\cos(\omega t + \theta_a) \tag{2.15}$$

$$i_b(t) = I_{b\max}\cos(\omega t + \theta_b - 120°) \tag{2.16}$$

$$i_c(t) = i_{c\max}\cos(\omega t + \theta_c + 120°) \tag{2.17}$$

Where $I_{a\max}$, $I_{b\max}$ and $I_{c\max}$ are the maximum value of the phase currents in each phase. The phase difference (power factor angle) between each phase voltage and its resulting current are represented by θ_a, θ_b and θ_c

2.2.4 Three-Phase Power Definitions for Perfect Sinusoidal Waveforms

The total power dissipated in a three-phase network is equal to the sum of the powers in each phase. From (2.6), (2.9), (2.11), the total power dissipated can be expressed:

$$S_{Total} = S_a + S_b + S_c \tag{2.18}$$

$$P_{Total} = P_a + P_b + P_c \tag{2.19}$$

$$Q_{Total} = Q_a + Q_b + Q_c \tag{2.20}$$

In a balanced three-phase network, the voltages across each phase and the currents in each phase are equal. Therefore, the powers in each phase are equal.

$$S_a = S_b = S_c \tag{2.21}$$

$$P_a = P_b = P_c \tag{2.22}$$

$$Q_a = Q_b = Q_c \tag{2.23}$$

Equations (2.18), (2.19) and (2.20) can be simplified to:

$$S_{Total} = 3V_a I_a^* \tag{2.24}$$

$$P_{Total} = 3V_a I_a \cos(\phi_a) \quad (2.25)$$

$$Q_{Total} = 3V_a I_a \sin(\phi_a) \quad (2.26)$$

Where I_a^* is the conjugate of phase current a

It should be noted that the definitions given in this section 2.2.4 are applicable to symmetrical and sinusoidal waveforms. In systems with asymmetrical and non-sinusoidal waveform conditions, these definitions are not applicable [33].

2.2.5 IEEE Standard 1459-2010

The IEEE working group on "nonsinusoidal situations: Effects on meter performance and definition of power" has suggested practical definitions for powers [30]. The main difference found between IEEE definition and other standards definitions is that it separates the fundamental quantities of active power P_1 and reactive power Q_1 from the rest of the apparent power components. The standard focuses rather on revenue metering than on compensation. The starting point emphasised in these definitions is a separation of the fundamental voltage and current harmonics from the total RMS values.

A number of researchers who followed up on the work of Budeanu [68] proposed more appropriate definitions by means of which distortion powers can be calculated [34], [35], [36], [38]. The IEEE Standards 1459-2010 suggest the decomposition of current and voltage signals into fundamental (I_1 and V_1) and harmonic contents [8-9]:

$$I^2 = I_1^2 + I_H^2 \quad (2.27)$$

$$V^2 = V_1^2 + V_H^2 \quad (2.28)$$

Where V_H, I_H represent respectively RMS of the voltage and current harmonics and are expressed as follow:

$$V_H^2 = \sum_{h \neq 1}^{\infty} V_h^2 \quad (2.29)$$

$$I_H^2 = \sum_{h \neq 1}^{\infty} I_h^2 \quad (2.30)$$

The active power is expressed as below:

$$P = P_1 + P_H \quad (2.31)$$

The fundamental and harmonic active power respectively (P_1) and (P_H) are expressed below:

$$P_1 = V_1 I_1 \cos\phi_1 \quad (2.32)$$

$$P_H = \sum_{h\neq 1}^{\infty} V_h I_h \cos\phi_h \qquad (2.33)$$

2.3 Harmonic Identification Methods

The identification of harmonic distortion sources is problematic in power systems due to the connection of the utility and customers to the same point of common coupling (PCC). In recent years, many studies have been conducted in order to settle the dispute between the utility and customers over who is responsible of polluting the PCC.

This section studies the harmonic source identification methods based on the direction of active power flow, reactive power flow and voltage-current method. Four methods considered to be related to the voltage-current are presented in this section. These include the voltage-current ratio method, the harmonic vector method, the current injection method and the Norton equivalent circuit model. The analysis of the harmonics source criterion and the reliability of these methods are discussed.

2.3.1 Harmonic Active Power Method

The harmonic active power method has been used in power systems to identify the dominant harmonic source at the PCC [58]. In this method, the utility is defined as the dominant harmonic generator if harmonic active power flows from utility to end user, and vice versa. This approach had been applied in electrical installations for many years, and later on its validity, which is based on the direction of harmonic active power, was called into question [26], [51]. It has been demonstrated that the method based on the flow of harmonic active power is theoretically incorrect [59].

The problems associated with the harmonic active power direction method between two sources AC circuits can be examined by simply using the case of $Z = jX$ in Fig. 2.1 and 2.2 below.

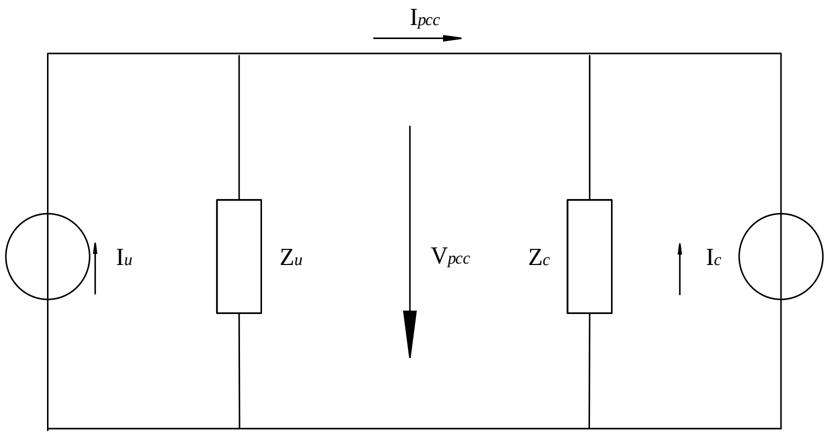


Fig. 2.1: Norton equivalent circuit for harmonic source detection

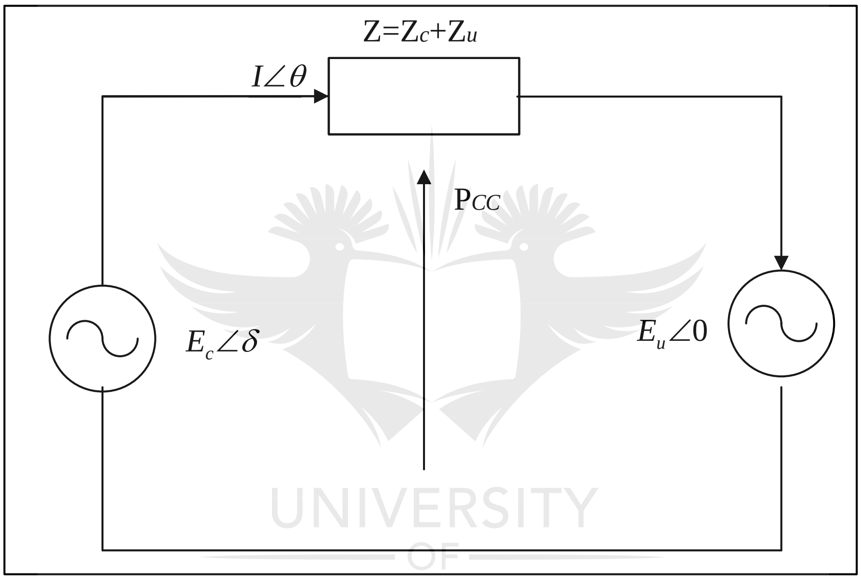


Fig. 2.2: Thevenin equivalent circuit for harmonic source detection

The active power flowing into sources can be determined with the classical power equation as:

$$P = E_u I \cos\theta = \frac{E_u E_c}{X} \sin\delta \qquad (2.34)$$

Where E_u utility voltage source

E_c Customer voltage source

δ The phase angle difference between customer and utility side voltage sources

X reactance of the impedance

An analysis of (2.34) above indicates that the direction of active power depends rather on the phase angle difference between customer and utility side voltage sources than on the magnitudes of the voltage sources. Moreover, this method is unable to reveal the difference between the magnitudes of the two sources. Therefore, the active harmonic power direction method is incorrect theoretically and cannot be a dedicated indicator to identify the dominant source of harmonics [26], [59]

2.3.2 Harmonic Reactive Power Method

It is known that the flow of active power is mainly affected by the phase angles of bus voltages while the flow of reactive power depends on the magnitudes of bus voltages [51]. One would therefore ask whether the reactive power direction could indicate the relative magnitudes of two sources of harmonics. An analysis of the reactive power Q flowing into utility voltage source E_u of figure 2.2 above indicates that the direction of reactive power depends on the voltage magnitudes between two harmonics sources

$$Q = E_u I \sin\theta = \frac{E_u}{X}(E_c \cos\delta - E_u) \text{ [51]} \quad (2.35)$$

An analysis of (2.35) indicates two effects: the utility side absorbs reactive power $(Q > 0)$, and the utility side generates reactive power $(Q < 0)$. In the case of utility side absorbing reactive power, E_u in (2.35) must be smaller than E_c. In order words, one can say that the customer contribute more with the current flowing at the PCC. It is true that the reactive power that E_u absorbs must originate from E_c. Since the impedance is reactive, E_c must have "a sufficiently high magnitude in order to push" the reactive power into source E_u. On the other hand, the utility side generating reactive power does not necessarily mean that the utility is the dominant source. In many cases, the generated reactive power may not reach the customer side due to power losses along the line. However, it has been proven that the method based on reactive power flow alone is not enough strong to clearly identify the dominant source of harmonics since the phase angle difference between two sources is still playing a role in the power flow. In any case, the active power method is improved at least by one direction of reactive power providing a theoretically correct conclusion [28].

To improve on this method, a new concept based on critical impedance has been proposed in [28]. This method is described in the following section.

2.3.2.1 Reactive Power Based Critical Impedance Method

The reactive power based critical impedance method here under discussion is part of reactive power flow. This approach has been proposed in the literature to address the case of reactive power ($Q < 0$). The critical impedance method is used to determine the main contributor of harmonic between the utility and the end-user. The process consists of an assessment of the impedance required to completely absorb the reactive power produced by the equivalent voltage source $E_u < 0$ and further compare it to half of harmonic impedance of both sides.

The different steps of this method are summarised as follows [28]:

1. Evaluate utility source voltage

As per Fig.2.2, equivalent voltage source E_u can be expressed by $E_u = U_{PCC} - I_{PCC} Z_u$ assuming that Z_u is known

2. Assess the reactive power Q and critical impedance (CI). The reactive power (Q) to be absorbed by the equivalent voltage source defined above is expressed by $Q = E_u I \sin\theta$ where θ is the phase angle between Z_u and I. A new index proposed in [28] and called critical impedance CI is expressed by $CI = 2\frac{Q}{I^2}$; the main contributor of harmonic can be identified as follows:

a). If $CI > 0$, the customer side is the main contributor;

b). If $CI < 0$, there is no evidence that utility would be the only main contributor. To address this issue, the method suggests looking at the maximum and minimum values of the impedance as follows:

- if $CI > Z_{\max}$, the utility side is considered as the main contributor .
- if $CI < Z_{\min}$, the customer side is considered as the main contributor;
- if $Z|_{\min} < CI| < Z|_{\max}$, no specific conclusion here can be drawn. In this case, the method proposes to consider the maximum and minimum values of the reactance X from E_u to the lowest voltage point.

$|CI| > X_{\max}$, would mean that the utility is the main contributor while $|CI| < X_{\max}$, would mean that the end-user is the main harmonic source.

Analysis of (2.35) indicates that the utility side delivers reactive power if $(Q < 0)$, $E_u > E_c$ will hold. Hence, the conclusion for the capacitive impedance is generally true for the 1st harmonic and not likely true at the harmonic frequencies. The second interesting case is $Z = R$ In this case, [28] demonstrated that the reactive power is a technical indicator of harmonic source identification. However, such a case rarely exists in a real electrical network.

Theoretically, the critical impedance method is more reliable than the active power direction method, and to a certain extend it addresses the shortcoming of reactive power direction method. However, some concerns instead raised with the critical impedance method. In practice, this method needs firstly to predict the information relating to the approximate impedance before starting the algorithm, and secondly the characteristic of system harmonic impedance should be the same everywhere in the power system to avoid a large error. The dominant source of harmonic can be identified, though the contribution of each side remains a challenge to determine. Furthermore, the method needs to perform practical experiments in order to determine the typical values of the impedance.

2.3.3 Voltage-Current Method

2.3.3.1 Voltage-Current Ratio Method

The voltage-current ratio method is a new concept used to identify not only the dominant source of harmonics at the PCC, but also to assess the contribution of harmonic distortion between the utility and the customer [60], [61], [62], [63]. The key principle of this method is the measurement of voltage and current at the PCC as well as the equivalent harmonic impedance of both the utility and the customer sides. The method allows for the determination of the magnitude of the harmonic voltage contribution ratio and the corresponding phase angle. This phase angle is necessary to investigate the weakness or the force of the utility or the customer side. The method is developed to identify the dominant equivalent harmonic voltage source. By defining the ratio of the equivalent harmonic voltages, this approach determines the dominant equivalent harmonic voltage source as follows:

The ratio of the equivalent harmonic voltage for each harmonic order considered is defined by:

$$\overline{K}_V = \frac{\overline{V}_u}{\overline{V}_c} \tag{2.36}$$

Where $\overline{K}_V$ represents the complex number of the ratio of the utility and customer equivalent harmonic voltages. Using the magnitude and phase angle, (2.36) can be expressed as $\overline{K}_V = K_V \angle \theta_{V-I}$, with

$K_V = \frac{V_u}{V_c}$: The magnitude of the utility and customer equivalent harmonic voltages.

θ_{V-I} : The phase angle difference between the equivalent harmonic voltages of utility and customer

The magnitude K_V determines the dominant harmonic voltage side in one of these conditions: (a) If $K_V > 1$, the equivalent harmonic voltage source of the utility side is dominant, and (b) If $K_V < 1$, the equivalent harmonic voltage source of the customer side is dominant.

Similarly, the method allows for the determination of the ratio of the equivalent harmonic current and identification of the dominant harmonic current side as follows:

$$\overline{K}_I = \frac{\bar{I}_u}{\bar{I}_c} \tag{2.37}$$

Where $\overline{K}_I$ represents the complex number of the ratio of the equivalent harmonic current. Using the magnitude and phase angle, (2.37) can be expressed as $\overline{K}_I = K_I \angle \alpha_{V-I}$, with $K_I = \frac{I_u}{I_c}$ which represents the magnitude of the utility and customer equivalent harmonic current.

α_{V-I} :The phase angle difference between the equivalent harmonic current of utility and customer.

The magnitude K_I determines the dominant harmonic current side in one of these conditions: (a) If $K_I > 1$, then the equivalent harmonic current source of the utility side is dominant, and (b) If $K_I < 1$, the equivalent harmonic current source of the customer side is dominant.

The validity of the method is based on the knowledge of the harmonic impedance at both utility and customer sides, whereas the harmonic voltage and current at the PCC are measured. In other words, these impedances are assumed to be known. In addition, the evaluation of customer impedance and utility impedance by comparing the position of the voltage/or current ratio in the complex plan cannot be carried out easily and accurately when this ratio is equal to one.

2.3.3.2 Harmonic Vector Method

The harmonic vector method is used not only to locate but also to quantify the existence of harmonic distortion by using one-time measurement [7], [27]. The harmonic voltage phasor across the load and the harmonic current phasor through the source connection are modelled as in Figure 2.3 below, where E_{h0} represents the harmonic voltage phasor at utilty side and V_h is the measured harmonic voltage phasor across the load at the point of connection to the load. I_h Indicates the harmonic current phasor flowing in the opposite direction of the electrical installation through the source connection. Z_h, the impedance of the complex supply network and Z_{hc} the impedance of complex load. I_{hc}, represents the generated harmonic current by the source of distortion.

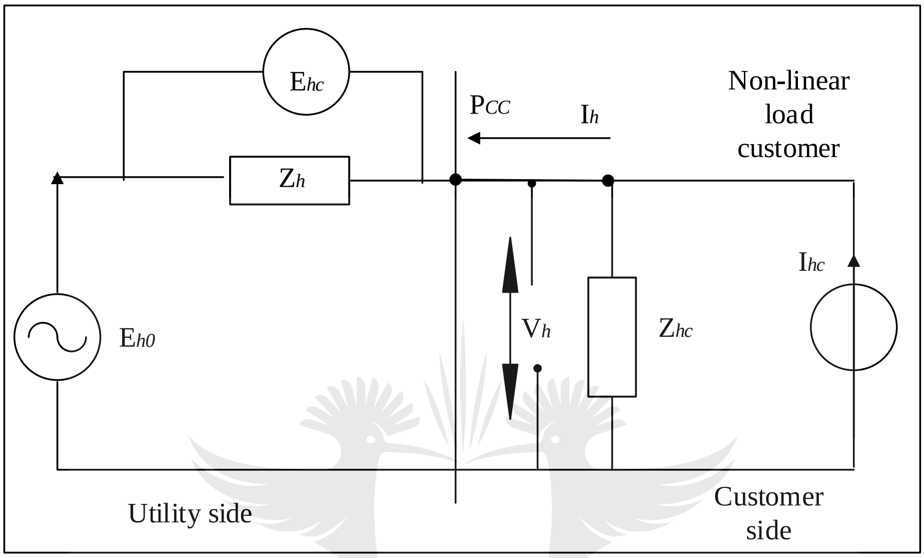


Fig. 2.3: Equivalent Network Circuit for harmonic analysis

According to [6], [7], [8], the harmonic vector method uses the principle of harmonic voltage at utility side and measured harmonic voltage across the load at customer side. To be able to use this method, one condition is required: $V_h < E_{h0}$. The magnitude of the harmonic voltage phasor E_{hc} is defined as the emitted harmonic voltage from the distorting load into the supply network. This is represented in Figure 2.4 below

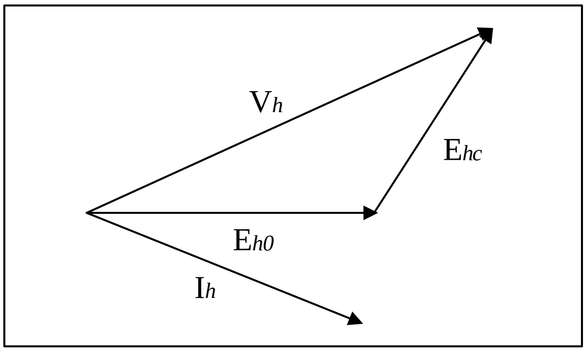


Fig. 2.4: Harmonic pollution: Phasor representation

From Fig. 2.4, the harmonic voltage phasor due to this emission is defined as:

$$E_{hc} = Z_h I_h = V_h - E_{h0} \tag{2.38}$$

It is clear (2.38) that the system impedance Z_h affects the contribution made by the non-linear load to the harmonic voltage distortion at the point of common coupling. Studies [34], [35] concluded that it is not always easier to obtain the actual value of the supply impedance in practical installations. Hence, the use of a reference network impedance Z_{h-ref} to represent the network impedance in (2.38) is utmost required. In this condition, the emitted harmonic voltage is then defined as the magnitude of the harmonic voltage phasor E_{hc}. It is showed that the harmonic vector method is valid only if $V_h > E_{h0}$ [4]. Otherwise, the harmonic emission is taken as zero. This is one of the limitations of this method.

2.3.3.3 Current Injection Method

The current injection method analysed in this section, is one of the methods among the so called voltage-current method in power system harmonic analysis between the utility and the end-user [36]. The method uses the frequency-domain matrix equations for each harmonic emission to determine the harmonic voltage components. These components are expressed by the following equation:

$$V_n = Z_n . I_n \tag{2.39}$$

Where Z_n and I_n are respectively impedance matrices and harmonic current components at harmonic order n.

The values obtained in (2.39) are converted in time-domain by applying the superposition principle for each network bus m using the following equation:

$$V_m(t) = \sum_{n=1}^{N} V_n^m \sin(n\omega_1 t + \delta_n^m) \tag{2.40}$$

Where N, the highest harmonic order under consideration.

The magnitude and phase angle of harmonic current source (I_n & θ_n) are determined using the following relationships [64]:

$$I_n = I_1 . \frac{I_{sh}}{I_1} \tag{2.41}$$

Where (I_1) represents the distorting load current at the fundamental frequency and I_{sh} is the standard harmonic current spectrum (to be measured, calculated or obtained from manufacturer's data) of the distorting power electronics load.

The concern with this method is found in the case of several sources of harmonics involving converters. Studies showed that, in most cases, however, the phase angles of the harmonic current source might often be ignored, restricting the assessment method to the magnitude analysis only [24], [36], [37], [38]. Further analysis of this method was conducted in several studies on the topic [36], [40], [41] and [42].

2.3.3.4 Norton Equivalent Circuit Model

In this method, a Norton equivalent circuit at each harmonic frequency represents the harmonic source.

The Norton equivalent model is expressed following the equation below:

$$I = f(V) \tag{2.42}$$

Where *V* and *I* represent current and voltage harmonic vectors respectively [31], [32].

Equation (2.42) can be made linear at any given operating point (*V, I)* of harmonic order *n* to obtain the equation below:

$$I_N = Y_N V_n - I_n \tag{2.43}$$

Where (I_N) is the Norton equivalent current and (Y_n) represents the Norton admittance.

The Norton equivalent circuit model provides a direct solution for the interaction between the harmonic source and the network. It facilitates a better convergence in terms of its solution process. This modelling technique forms the backbone of a number of software-based methods of harmonic computation (Frequency scan, Harmonic power flow analysis, and so on). This model is iteratively improved by solving the network nodal equations for each harmonic involved, whereas the solution process should stop, as the changes in the Norton equivalent current sources are sufficiently small. However, this model would be difficult to implement in practical installations if the source of harmonic is a converter, due to switching mechanism [36]. An analysis of the Norton equivalent circuit model as extended to three-phase circuits is discussed in the existing literature [35], [40], [43], [44], [45], [46].

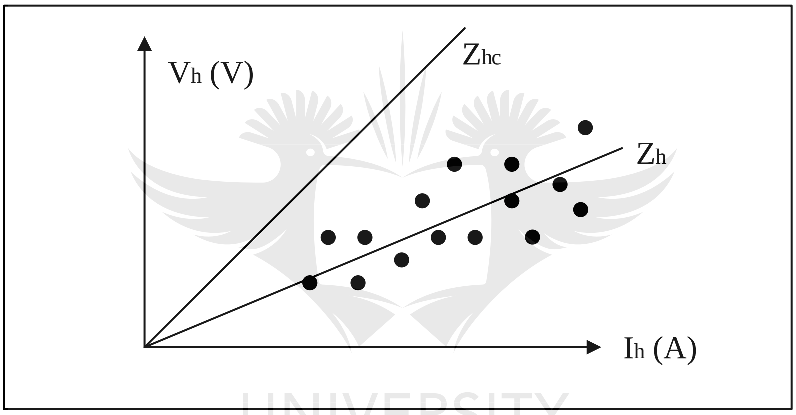
2.4 Harmonics Measurement Techniques and Instruments

2.4.1 Harmonics Measurement Techniques

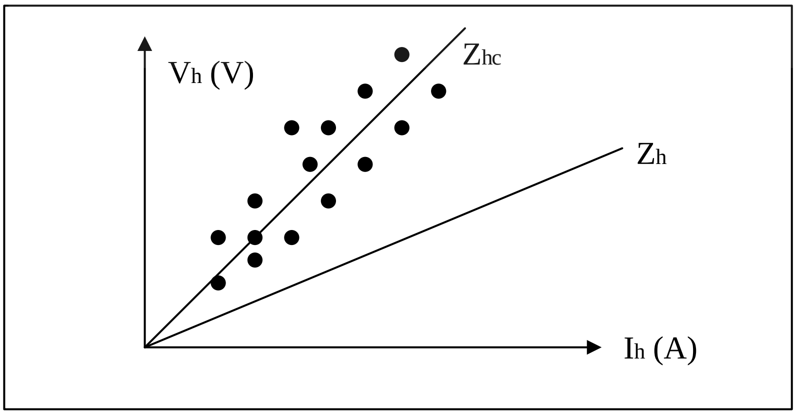
2.4.1.1 Measurement Techniques for Assessing Harmonic Contribution in Power System

One of the approaches widely used is a long-duration simultaneous measurement of harmonic voltage and current magnitudes. According to this approach, the magnitude of harmonic impedance at both sides, power supply and customer load must be known and remain constant.

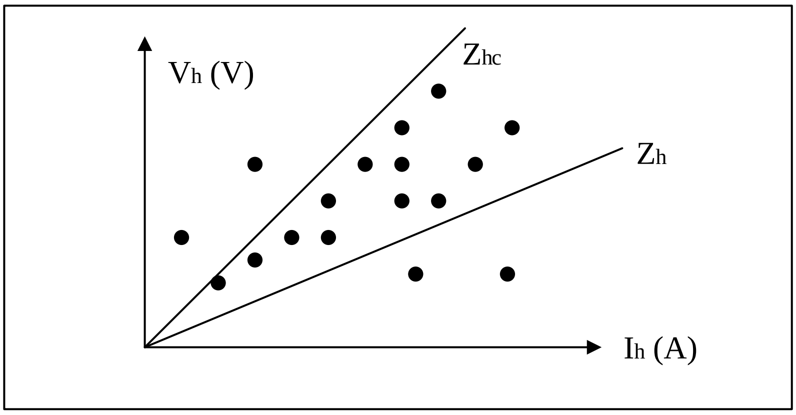
However, these conditions may be problematic in practice. Studies [31] demonstrated that the system impedance (*Zh*) might be obtained by means of simulation while the end user impedance (*Zhc*) is calculated as being equal to the impedance of the transformer of distribution connecting the network to the end user. As shown in Fig. 2.5 below, the dominant source of harmonic will depend on the clustering of measurement points around either the *Zh* impedance or the *Zhc* impedance. Jaeger [31] considers three scenarios: (a) the end user is the dominant source of harmonic if the measurement points are clustered around the *Zh* impedance line. (b) The installation is absorbing harmonic from the network, if the measurement points are clustered around the Zhc impedance line. (c) Combined network and installation contributions are considered if the points are scattered over the area delimited by the two straight lines drawn on a voltage vs. current plot. These cases can be seen in Fig. 2.5 a, b and (c) below.



(a) Installation dominant source



(b) Installation absorbing network harmonics



(c) Combined network and installation contributions

Fig. 2.5: Long-duration simultaneous measurement of harmonic voltages and currents method [50]

Alternatively, the emission voltage phasor can be assessed by the harmonic vector method if the harmonic voltage phasor measurements are available [29]. Harmonic power is one of an interesting approach used to assess the origin of harmonic emissions. In this approach, the customer is not responsible for polluting the PCC if the harmonic active power is in the same direction as the fundamental active power (Fundamental active power is considered positive when flowing from the utility side into PCC). The customer is considered responsible when the harmonic active power is in the opposite direction to the fundamental active power. It has been proved that this method is unsuitable in the harmonic source identification. The harmonic active power depends on the phase angle between voltage and current harmonic, which can lead to uncertainty in relation to the sign when this phase angle approaches 90˚ [50] [51] [52]. Further, many studies including the work done by Li, Xu and Tayjasanant [28], demonstrated that in identifying the source of the harmonic, the harmonic reactive power measurement approach is more accurate than the harmonic active power method. Unfortunately, the method does not work for the quantification of harmonic contribution in the power system [28] [53] [54].

2.4.1.2 Harmonic Impedance Measurement Techniques

- **Non-invasive methods**

Non-invasive methods are one of the two groups of methods defined by the CIGRE-CIRED Working Group C4, 109 for the estimation of the harmonic impedance. The methods do not need to disrupt the operating conditions of the network. To calculate the impedance, the only requirement is the use of the event occurring naturally as a source of the disturbance. One of the non-invasive methods uses the significant harmonic source in the power system i.e. arc furnace or cycloconverter to vary the harmonic voltages and currents at the point of interest. This variation can be concluded by changing the operating conditions without disconnecting the loads from the network. The shortcoming of this approach is that the accuracy of the results is improved after multiple measurements of voltage and currents [31]. Studies [55], [56] proposed a linear regression approach or more advanced statistical methods, including the graphical representation and statistaical method to estimate the impedance based on the measurement data.

Another approach used utilises a switching transient or a natural variation as a source of disturbance in the power system or a natural variation. It has been shown that currents from the switching operations i.e capacitor banks may be unsymmetrical depending on the switching duration and then may affect the accuracy of the results [35] [50].

A further method dealing with the estimation of the harmonic impedance at the customer and utility sides, the "natural variations in harmonic currents and voltages over a given time interval", is described in the literature [31] [55] [57]. The method is based on the sign of the ratio of harmonic voltage and harmonic current to determine the dominant source of the change in harmonic current and voltage. The network impedance is determined by changes caused by the customer installation while the customer installation impedance can be estimated based on changes caused by other sources in the network. Although these methods apparently provide accurate results, the approach needs a significant variation in harmonic levels, which requires the variations of upstream and downstream parameters. This appears to be a drawback [31].

- **Invasive methods**

Invasive methods form the second group of methods defined by the CIGRE-CIRED Working Group C4, 109. These methods use the injection process of harmonic or interharmonic current into the power system. Various harmonic sources like saturated transformers, dedicated harmonic generators are proposed as a means to inject harmonic or interharmonic current into the system.

2.4.2 Instruments

To ensure accurate measurements in harmonic analysis method, the recorded data need to conform to the requirements of IEC 61000-4-30 on equipment [47]. In this regard, accurate voltage and current transformers, with a wide bandwidth must be used in order to measure higher order harmonics. However, in practical installations, this becomes a challenge since most power utilities install their own instruments following their design specifications.

2.4.2.1 Sampling Frequency

The minimum sampling frequency for an instrument required by the IEEE 1459-2010 should at least be 4900 Hz or 2500 Hz for a fundamental frequency, while harmonic measurement should be done up to the 49^{th} harmonic or the 25^{th}, if the 49^{th} is no concern.

2.4.2.2 Synchronisation

The synchronisation of instruments is required when comparing data measured at different locations in power system. This process is fulfilled using time synchronised signal sources. In the literature, there exist many time-setting systems among them: The Earth-based radio signal, Global positioning System (GPS), and the time-setting signals via the internet used in setting the computers time. The well-known and most used system is the GPS [48]. The time setting via Internet requires computers to have a dedicated software and Internet connection. This system is easier and faster than the other methods. The working conditions of radio signals system depend on certain regions, as the Electromagnetic Interference (EMI) may often interfere in a high voltage power environment. However, these disadvantages render this method inaccurate.

2.5 Summary

This Chapter presented a literature review of the definitions, concepts and theories of power, harmonics identification methods based on power flow and on voltage-current. Different methods including a harmonic injection approach to calculate harmonic impedance, their respective advantages and drawbacks were reviewed. It showed that the current injection process is a time consuming method. A recent theory conducted by Safargholi *et al.* [60], [61] for calculating the harmonic contributions at the PCC, when the Thevenin equivalents are known, was discussed. Instruments synchronization was also discussed. The analysis of different methods used in harmonics identification indicated that there is still a need for a dedicated method in harmonic impedance measurement. Before embarking in a new dedicated method for harmonic impedance determination, the following chapter reviews the concepts related to power harmonics disturbances.

CHAPTER 3: POWER HARMONICS DISTURBANCES

3.1 Overview

For the past decades, the quality of power provided has been poor due to harmonic voltage and current problems. Lately, these problems have worsened due to an increase in the use of non-linear loads in power systems. Understanding the harmonic phenomenon in power systems becomes crucial before embarking on any harmonic data collection. The harmonic operating function and definitions are discussed in section 3.2; while sources of harmonic distortion are presented in section 3.3. This section is divided into three main equipment groups: magnetic core equipment, conventional equipment and electronic and power electronic equipment. The effects of harmonics are discussed in section 3.4. These include effects on the following equipment: phase and neutral conductors, skin effect, motors and generators, transformers, capacitors, measuring instruments, relays and contactor protective systems and telecommunication. Section 3.5 presents the general harmonic indices. The total harmonic distortion (THD) as the most common index is defined in this section. The power quality standards related to harmonic distortion or recommended guidelines, used to limit the amount of harmonics generated by either power utility or end users, are presented in section 3.6.

3.2 Harmonic Definitions

The term "Harmonics" is defined as "sinusoidal components of a periodic wave with a frequency, which is an integral multiple of the fundamental frequency" [69], [70]. Therefore, the frequency of the nth order harmonics is nf_0 where f_0 is called fundamental frequency. In many cases, harmonics in power systems are used to define distorted currents and voltages of different amplitudes and frequencies. As stated in Chapter 1, harmonics are generated by non-linear loads. The current drawn by this type of loads is non-linear. The non-linear current causes a non-linear voltage due to system impedance. The nonsinusoidal waveform voltage or current can be decomposed into sinusoidal waveforms of different frequencies by means of a Fourier Transform. The nonsinusoidal waveform will therefore be represented by the sum of these individual sine waves and can be expressed by the equation below:

$$v(t) = V_1 \cos(\omega t) + V_2 \cos(2\omega t) + ... + V_n \cos(n\omega t) \qquad (3.1)$$

Where V_1 is the peak magnitude of the fundamental frequency and $V_2 ... V_n$ are the peak magnitudes of the harmonic frequencies present in the waveform. A Square waveform and some of its harmonic components are presented in Fig. 3.1 below:

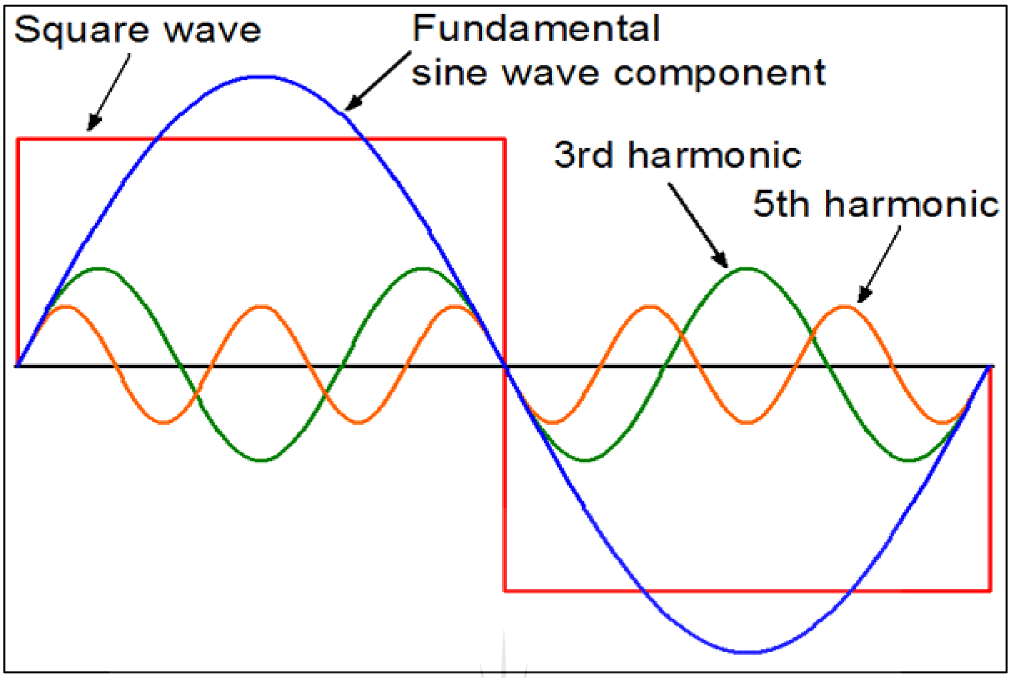


Fig. 3.1: Representation of harmonic waveforms [39]

3.3. Sources of Harmonics

Non-linear loads draw a non-linear current in instantaneous pulses, which is disproportionate to the applied voltage. These results in the imposition of new waveforms, which are multiples of the original signal and called harmonics. A distorted current, as shown in Fig.3.2 below, is the sum of superimposed harmonics.

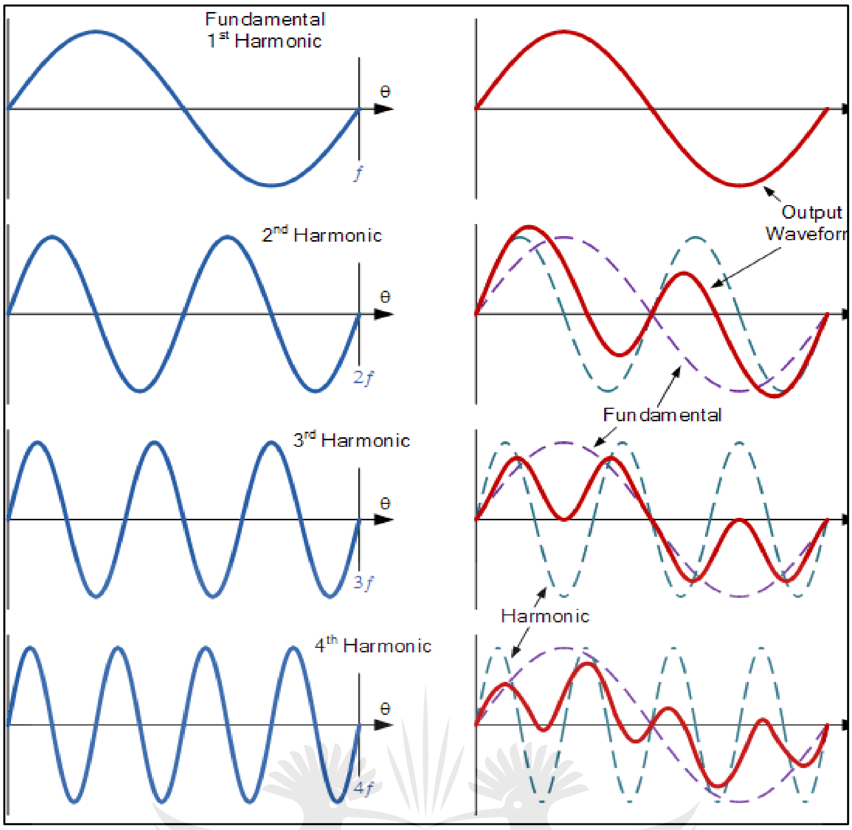


Fig. 3.2: Harmonic waveforms and its harmonics orders: harmonic waveforms (left); complex waveform (right) [39]

The sources of harmonic currents and voltages in power systems can be classified into three main groups of equipment [71], [72].

1) Magnetic core equipment: this include transformers, electric motors, generators, etc.
2) Conventional equipment: Arc furnaces, arc welders, high-pressure discharge lamps, etc.
3) Electronic and power electronic equipment.

Further information on these sources is provided in the following: [70], [73], [75], [76].

3.3.1 Magnetic core equipment

3.3.1.1 Transformers

The transformer is one of the iron core devices and source of harmonics. Under a certain range of flux density, the magnetic characteristics of iron are almost linear, but quickly saturate as the flux density increases. The magnetic field intensity and the resulting exciting current will not be sinusoidal due to the non-linear relationship between the flux density and the magnetic field intensity. This non-linear magnetic characteristic is known as a hysteresis curve. As a result of the nonlinearity of a hysteresis curve, the excitation current waveform is not sinusoidal and contains many harmonics. Studies of the excitation current waveform have revealed the existence of a significant third harmonic component, typically approaching 40% of the total RMS exciting current. Other non-tripplen, odd harmonics is present in the excitation current waveform, but to a lesser degree. Fig3.3 below shows the hysteresis curve of a transformer.

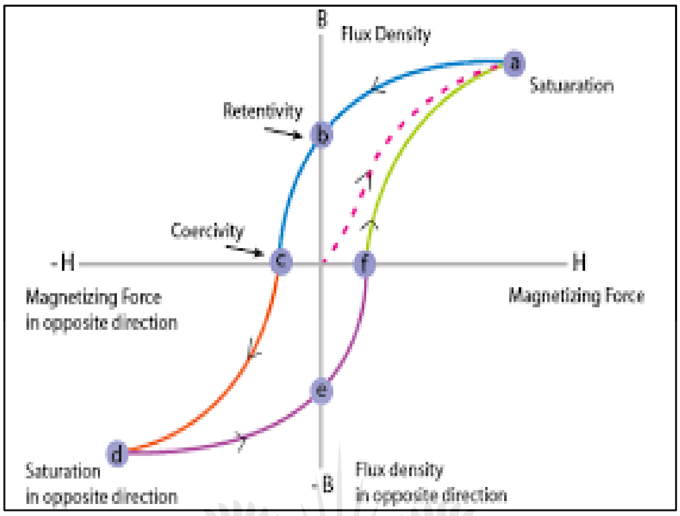


Fig. 3.3: Hysteresis curve of transformer

Traditionally transformers are operated near the knee of the saturation curve, where the excitation is at most 1 or 2% of the full load current. They do not cause harmonic problems under normal operating conditions. However, the contribution of harmonics to the system by transformers can be significant during sustained periods of system over voltage**.** As the voltage applied to the transformer's primary terminals is increased above its rating, the magnetic field increases to the point where the core becomes saturated. Studies have revealed that in this saturated state, even a small increase in voltage applied to the primary terminals of the transformer will result in a large increase in excitation current to produce the required magnetic field [73] [78], [80].

To eliminate the problem of third harmonic distortion in secondary voltages, industrial plants use delta-wye connected transformer connections to form a low impedance path for the third harmonic excitation current through the delta winding [78]. In this case, the third harmonic component will circulate in the delta winding of the transformer and cannot propagate throughout the rest of power system. Further information on the sources of harmonics due to transformers is provided in [73].

3.3.1.2 Motors and generators

The contribution of motors in generating harmonics is minimal compared to the transformers described above. It has been shown that the motor magnetising characteristic is much more linear than that of the transformer. This is due to the presence of an air gap in the motor. The pitch of motor winding can also cause the harmonic currents. Motors with five to seven slots per poles can generate the fifth or seventh harmonic. The third harmonic is produced during motor starting and changes. This is due to the excitation current required to produce a rotating magnetic field in the magnetic core of the stator.

Generators are also a source of harmonics. They generate the fifth harmonic voltages due to the distortions of magnetic flux occurring near the stator slots and nonsinusoidal flux distribution across the air gap. The third harmonic is usually found to be dominant in generator voltage.

3.3.2 Conventional equipment

3.3.2.1 Arc Furnaces

Arcing devices are among harmonic producers as a result of the non-linear characteristics of both the arcing and voltage that occur in these devices [72]. Arc furnaces operate at a lower power factor than in the past and are presently an important issue because of their common usage in power systems. Distortion of arc furnace currents and voltages has an impact in the increasing rated power of the compensating capacitors. This, however results in a lowering of the resonant frequency. Arc furnaces present the most severe problems and a relatively large source of harmonics especially when concentrated in one geographical location. Thus, steel or other kinds of scrap metal are melted and refined by means of a high-energy arc [78]. During the initial period when the scrap steel is being melted down, the dominant second and third harmonics can each have magnitudes approaching 25% of the fundamental frequency magnitude. After the initial period, when the scrap is being redefined, the surface of the metal is relatively smooth and the arc is therefore more stable. The dominant second and third harmonics now have magnitudes of 7-8% of the fundamental frequency magnitude [77]. It has been shown that due to the rectifying action and the single-phase characteristic of the arc, all harmonics are produced, including even and triplen harmonics [73], [77].

3.3.2.2 Fluorescent lighting

The fluorescent lamp (FL) belong to the category of discharge type lightings. These devices have become popular due to their improved energy efficiency compared to incadescent bulbsi.

Unfortunately, they generate a considerable amount of harmonics in the supply system current. Today, compact fluorescent lamps (CFLs) are sold in the market as replacements for the so-called tungsten filament bulbs. The key element in these lamps is a small electronic ballast, installed in the connector casing and controlling a folded 8 mm diameter fluorescent tube. These types of lamps widely used today lead to serious harmonic problems. Intrinsically compact fluorescent lamps are non-linear in nature as they rectify the voltage to produce direct current (DC) and power electronics produce high frequency harmonics due to a switching converter.

Studies have shown that the harmonic characteristics of compact fluorescent lamps remain dependent on their circuit topology. There are four groups of CFLs, namely, excellent, good, average and poor CFLs. Although these devices provide similar energy savings, more harmonic losses are caused by the poor compact fluorescent lamp. It is essential to ensure that in the installation the CFLs inject the lowest level of harmonics and that the device is at a reasonable price. Some papers have found that though compact fluorescent lamps reduce power consumption in the power system, the observed increase in core loss and hysteresis effects are harmful to the fuses and relays in the network [111].

3.3.3 Electronic and Power Electronic Equipment

This group of equipment includes Switched mode power supplies, Rectifiers, Static VAR compensators etc.

3.3.3.1 Switch Mode Power Suppliers (SMPS)

Switch mode power supplies (SMPS) generate significant harmonic voltages as they “abruptly chop voltage waveforms” in the period between conducting and cut off phases [111]. The Switch Mode Power Supplies (SMPS), together with single-phase rectifiers and direct controlled rectification of the supply are used in power electronics to feed the major part of electronic devices to obtain output voltage and current. It should be pointed out that although the main advantage is that the weight, size and cost are reduced, a large amount of third and higher order harmonics that these devices draw cannot go unnoticed. Instead of drawing a continuous current from the supply, these devices draw pulses of current containing harmonics.

3.3.3.2 Three Phase Rectifier

Three-phase bridges, also known as six-pulse bridges produce current harmonics of order $6n \pm 1$(n=1,2,3, 4,..) with decaying amplitude for increasing harmonic order in their supply networks as there are six voltage pulses per cycle on the DC output. Studies conducted in [79] demonstrated that the magnitude of each harmonic produced should be theoretically equal to the reciprocal of the harmonic number, so there would be an amount of distortion around 20% of the 5th harmonic and 9% of the 11th harmonic. There exists two rectifting systems for three-phase bridges. One called rectifying topology and another called rectifying mode. The rectifying topology is essentially used in higher applications and consists of a front end for the connection of three phases. The rectifying mode is defined in terms of controlled or non-controlled. The first mode is related to diodes as key elements and the second related to thyristors or transistors. Fig. 3.4 below shows the connection of three-phase thyristor controllers with resistive load.

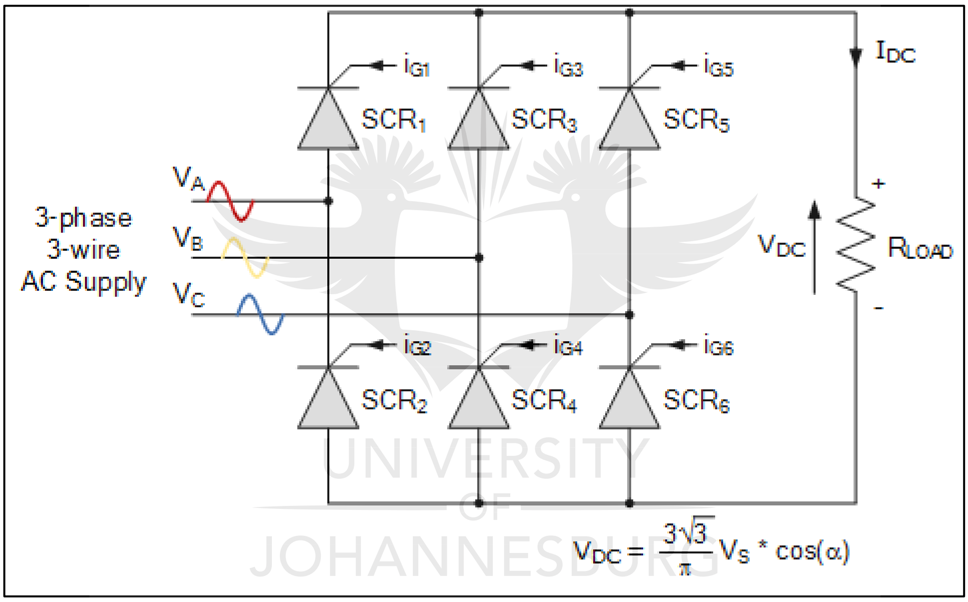


Fig. 3.4: Three phase Thyristor controllers with Resistive load

The amplitudes of the harmonics produced by the three -phase rectifier are similar to those for a single- phase rectifier. However, the only difference is their phase angles. To illustrate this, simulations indicated that the phase angles for the fifth and seventh harmonics have opposite sign at 180 degrees' phase angle difference compared to those of a single- phase rectifier [79].

3.3.3.3 Static VAR Compensator

Static VAR compensators (SVCs) fall under the converter category. SVCs are used in transmission systems to provide a continuous control of the reactive power compensation level. Basic SVCs consist of static switch connected in series with an inductor. Most SVCs use a thyristor-controlled reactor (TCR), which is a reactor in series with two parallel inverse thyristors gated symmetrically. The purpose of this configuration is to allow the thyristors to control the time for which the reactor conducts and thus controls the fundamental current component. The thyristor-controlled reactor due to its non-linear characteristics generates harmonic currents because thyristors only allow conduction in the reactor for a portion of the cycle. The thyristor firing angle plays a key function in the variation of harmonic current magnitudes. Harmonic current magnitudes vary as long as the firing angle of the thyristors vary. An increase of the firing angle of the thyristor reduces the current value and causes this current to discontinue [112]. The filtering of harmonics is achieved through capacitors connected in parallel to the Thyristors controlled reactor (TCR), as shown in Fig.3.5 below. This configuration, referred to as Static Var Compensator (SVC), is used to stabilise any continuous decrease of source voltage in a system due to an increase in load demand. SVCs are essential in the power system for their contribution to the balancing of the three-phase systems.

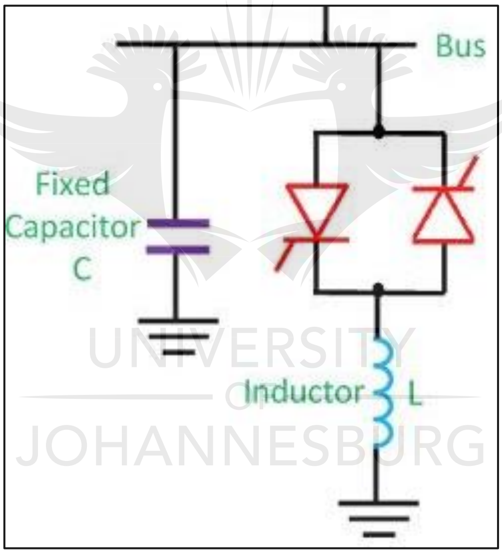


Fig. 3.5: Static Var Compensator (SVC)

3.4 Effects of Harmonics

The effects of harmonics on the power system are numerous [70-71]. Harmonic emissions affect the equipment connected to the electrical network in different ways. This reduces the ideal operational conditions and the efficiency of the power system. Therefore, it becomes important to describe the different effects of harmonics in electrical networks, to understand the concept and mechanism of harmonic emission in power networks. The effects of harmonics on different equipment are discussed in this section of the thesis.

3.4.1 Overheating of Phase and Neutral Conductors

Harmonics currents can affect both the phase conductors and neutral conductors leading to overheating problems. It is shown that in low voltage networks where harmonic emissions are a serious issue, the neutral conductor may be overloaded even though the neutral current does not exceed the nominal phase current circulating in the single-phase loads [73]. In addition, instead of summing to zero as it is the case in balanced fundamental currents and other harmonic currents, triplen harmonic currents increase arithmetically in the neutral conductors. Therefore, neutral currents experience more overloading problems than the phase currents. As a result, the neutral current is significantly higher than the currents circulating in the conductor phases. It is important to notice that a current flow in the neutral conductor when the star-loads connected in a three-phase system is not balanced because of the sum of vectors of the three-phase currents.

3.4.2 Skin Effect

Skin effect is defined as the tendency for higher frequency currents to flow near the surface of the conductor. Harmonic currents produced by harmonic voltages at higher frequencies encounter much higher impedances as they flow through the installation than the fundamental frequency current does. The resistance of conductors therefore become nonlinear. The more the frequency rises, the more the current tends to flow on the outer skin of a conductor. As a negligible amount of the high-frequency current penetrates far beneath the surface of the conductor, less cross-sectional area is used by the current. In the power system with the presence of high-order harmonics, it is necessary to consider skin effect for any design process because it affects the life of cables. Significant additional heating and loss are of concern when the skin effect is above the frequency of 350 Hz. The ratio between the AC resistance and the DC resistance depends on the radius of the conductor. The latter depends on the current penetration thickness (δ). The current penetration can be defined by the expression, $\delta = 2\rho\omega\mu$ where μ express the magnetic permeability (H/m), ω the frequency (rad/sec); and ρ the resistivity ($\Omega m/m^2$) [2]. This current penetration δ depends on the frequency and decreases as the frequency increases. As result, in a harmonic rich environment, cable design should be done properly and skin effect taken into consideration. The design of multiple cable cores or laminated busbars is becoming an alternative solution to overcome the effect of harmonics on skin effect.

3.4.3 Motors and Generators

Harmonics in motors and generators can cause an increase in the RMS value of current resulting in an increase of the loss in stator and rotor windings. The effect of harmonics in electric motors is a great concern as even a minimal distortion in harmonic voltage can lead to an increase in additional magnetic and currents in both core and rotor winding. It can also lead to an additional active power, an increase in temperature and a decrease in machine efficiency. Harmonic voltages are caused by non-linear currents drawn and run through the generators. A synchronous machine is not exempted from the impact of harmonics. The stator windings and damping cage are mainly subjected to additional losses associated with high harmonics. The most significant harmonics forming a negative-sequence system (5^{th}, 11^{th}, 17^{th}, 23^{rd}…) are present in the synchronous stator winding. Compared to sine wave current, harmonic currents can increase the acoustic noise emission [73], [77].

3.4.4 Transformers

Harmonic voltage and currents cause an increase in the hysteresis and eddy current losses within the transformer, which in turn increases the heat, which the transformer insulation has to dissipate. This additional heat can lead to overstress of the insulation. Harmonic voltages increase iron losses. The harmonic currents through a transformer also cause an increase of copper losses [73] and [80].

Higher frequency harmonic currents in the transformer are of greater concern than in a conventional conductor because the “resistive skin effect” is enhanced within closely spaced transformer windings. This is referred to as proximity effect.

3.4.5 Capacitors

The effects of harmonics on capacitors in the power system depends on the harmonic voltages in the system [10]. In low voltage, capacitors are usually affected by harmonic overcurrents rather than by harmonic overvoltages. However, in high voltage, capacitors are usually more sensitive to harmonic voltage than to harmonic overcurrents. Harmonic overvoltages stress the capacitor dielectric, while harmonic overcurrents cause heat due to the equivalent series resistance. [10], [80], [81]. A phenomenan like harmonic resonance, which is the combination of harmonics and capacitors usually leads to the shortening of the life of capacitors. Capacitors, even if installed in the electrical power system as power factor correction devices to filter harmonics (aside from the reactor), are not free from the negative effects of harmonics. In the presence of high harmonic distortion levels, capacitor banks are vulnerable to damage.

Harmonic currents, which mainly originate from non-linear loads increase, the conduction and dielectric losses in the capacitor plates. These losses can be expressed by the total power equation of the capacitor as follows [73]:

$$P_{Loss} = \sum_{n=1}^{\infty} (\omega_1 c \tan\delta).V_n^2 \tag{3.2}$$

Where $\tan\delta = R_s \omega c$ (series connection)

$\tan\delta = \dfrac{1}{\omega c R_p}$ (Parallel connection)

$\tan\delta$ Express the capacitor loss factor.

$\omega_n = 2\pi f_n$ The angular frequency and V_n the rms harmonic voltage at harmonic order n.

Equation (3.2) shows that the total power loss in the capacitor strongly depends on both the magnitude and harmonic frequency of the distorted voltage. Capacitors subjected to higher harmonic frequencies, higher voltage amplitudes will overheat, and eventually breakdown. Therefore, the design of capacitors becomes critical in power systems with harmonic content.

3.4.6 Measuring Instruments

Harmonics may affect meters and other instrumentation devices to make errors in the readings. This is particularly observed in induction-type devices such as ammeter, voltmeter and energy meters, which are still mostly used in industry. These induction-type devices rely on the torque produced because of the interaction between the magnetic field of the current to be measured and that of eddy currents induced in the metal disc or drum.

The deflecting torque produced in induction-type metering devices requires a similarity between the frequency of the current to be measured and the instrument-calibrated frequency. In the presence of harmonic components to be measured, the device can provide errors in its readings. The scenario will be similar at any time if such a device is in use because of frequent distorted waveforms [14], [15]. Further information on instances of incorrect meter reading is provided in the following studies: [10], [80], [82], [83-84].

3.4.7 Relay and Contactor Protective Systems

Studies conducted in [85] show that both three-phase electromechanical or static overcurrent (O/C) relays, mostly used for earth fault protection or other purposes, are prone to misbehaving when subjected to non-sinusoidal operating conditions. There are negative effects of current harmonics on relays. It has been shown that under harmonic distortion, O/C relays pick up either at $100 \pm 10\%$ of the nominal RMS sinusoidal current value and produce a time delay or 45% shorter or up to 26% longer than the nominal time delay under no harmonic conditions [85].

The under-frequency relay is another type of relay, which can be affected by harmonic disturbances. The design of such a relay is intended to detect a severe generation deficit and shed load when the frequency decays below a certain set point on the system. The measurement of power line frequency can be done in many ways, usually by counting the number of zero crossing in the waveform. The under-frequency relay is sensitive in the presence of harmonic voltages and can thus develop additional zero crossings within one measured voltage or current cycle [85]. This would cause miscounting of the power line waveform (current or voltage) frequency and possibly the disagreement of the protective device in question.

3.4.8 Telecommunications Interference

Studies conducted in [86], [87], [88] have shown that communication interference is caused by magnetic (or electrostatic) coupling between electrical power circuits and communication circuits. The principle of communication interference dictates that a current flowing in the power circuit produces a magnetic (or electrostatic) field, which will induce a current (or voltage) in the nearby conductors of the communication circuit. Hence, the amount of interference will depend on the magnitude of the induced current (or voltage), frequency, and the efficiency of the magnetic (electrostatic) coupling. The main concern is that the small signal electronics can be saturated and malfunction [88]. Among the most prominent causes of interferences with communication and control circuits cited in the literature are high frequency currents resulting from converters and voltage fluctuations induced by electric arc furnaces or static power converters [89]. For example, the energising of a large rectifier can trigger severe noise in the circuit, which eventually leads to an interruption of telephone conversations [10], [80], [84]. In the recent years, telephone interference was one of the biggest problems caused by harmonics when using the telephone influence factor (TIF). In [9], the IEEE 519 definie the TIF as a measure of the "sensitivity of the telephone system and the human ear" to noise at various discrete frequencies.

3.5 General Harmonic Indices

Under normal operating conditions, voltage/current distortion in the power systems can be defined in either the time or the frequency domain. To describe the distortion current/voltage in the time domain requires finding the differences between the actual distorted waveform values and the reference sine wave values. This is however difficult to accurately assess. In many cases, the description of distortion in the frequency domain is mostly used to determine the magnitude and phase angle of the signal.

3.5.1 Total Harmonic Distortion

The total harmonic distortion (THD) is the most common harmonic index used in power systems. It is defined as the ratio of RMS value of the sum of all the harmonic components up to a specified order to the RMS value of the fundamental component and can be expressed in terms of the voltage or the current [5]:

$$THD_V = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \tag{3.3}$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_1} \tag{3.4}$$

Where V_n and I_n are respectively the single frequency RMS voltage and RMS current at the harmonic n; N is the maximum harmonic order to be considered; V_1 and I_1 are respectively the fundamental RMS voltage and fundamental RMS current. It is sufficient to consider the harmonic range from the 2nd to the 25th for most applications if risk of resonance is less at higher orders, but most standards specify up to the 50th.

3.5.2 Distortion power Factor

The distortion power factor is one of the general harmonic indices. This index is used to quantify how a load efficiently utilises the current drawn from the AC power system. Therefore, the distortion power factor (dpf) is described as:

$$dpf = \frac{I_1}{I_{RMS}} \tag{3.5}$$

Where I_1 is the fundamental RMS current

I_{RMS}, the total RMS current component is defined by:

$$I_{RMS} = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + ...}$$

The distortion power factor can be expressed in terms of the total harmonic distortion defined in (3.4) above. Therefore, this indice becomes

$$dpf = \frac{1}{\sqrt{1+THD_i^2}} \quad (3.6)$$

Where $THD_i = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + ...}}{I_1}$, the total harmonic distortion of the load current.

With respect to the total harmonic distortion, it can be assumed for this definition that the voltage remains non-distorted. This assumption can be considered as a good approximation in the distribution network where voltage sources should not be affected by any change in loads downstream.

3.6 Power Quality Standards Related to Harmonic Distortion

Standards in general were created in order to specify limits for the adverse effects of harmonic distortion in the power plant equipment of utilities and their customers. The most commonly used are IEEE 519, 1159 and IEC 61000-series.

3.6.1 International Standards

3.6.1.1 IEEE Standards 519 and 1159

The current IEEE standard 519 (IEEE Std. 519-1992) originated in 1981 and was then updated in 1992. The purpose of these standards was to provide a recommended limit for total harmonic voltage and current distortion. Today, this standard is being used for harmonic and reactive power control in industrial and commercial facilities. Additionally, this standard includes limits to the various disturbances recommended to the power distribution system. The basic themes of IEEE Standard 519 are designed into two-fold. Firstly, the power utility has the responsibility of producing good quality voltage sine waves. Secondly, end-user customers have the responsibility to limit the harmonic currents their circuits draw from the line. The limits set in these standards are based on the ratio of available short circuit current (I_{sc}) to the maximum demand load current (I_L). Analysis in the context of IEEE standards is often performed at the point where a facility power system is connected to the power utility system. This point is referred to as the Point of Common Coupling (PCC). This point is also called the point of common connection. Morever, the standard allows one to evaluate the harmonics at any point within the installation, where linear and non-linear loads meet. This point may be the secondary of a supply transformer. Overall IEEE standard 519-1992 represents a consensus of guidelines and recommended practices by the utilities and their customers intended to minimise and control the impact of harmonics generated by nonlinear loads. Table 3.1 below shows the standards limits for current where TDD represent the total demand distortion.

Table 3.1: IEEE- Standards-519-Current distortion limits (in % of I_L) [9]

I_{SC}/I_L ratio	<11	$11<h<17$	$17<h<23$	$23<h<35$	$35<h$	$TDD-I$ limits
<20	4.0	2.0	1.5	0.6	0.3	5%
20<50	7.0	3.5	2.5	1.0	0.5	8%
50<100	10.0	4.5	4.0	1.5	0.7	12%
100<1000	12.0	5.5	5.0	2.0	1.0	15%
1000Up	15.0	7.0	6.0	2.5	1.4	20%

The distortion limits in Table 3.1 is for odd harmonics only. They are only permissible if the transformer supplying the customer from the utility side do not exceed, in harmonics, 5% of the transformer rated current. The standards address the case of even harmonics by limiting them to 25% of the odd harmonics within the same range [9]. IEEE 519-1992 also established a set of criteria for voltage distortion limits. The standards recommend an acceptable amount of harmonic voltage limits. These limits are designed to ensure that the consumers' equipment will operate satisfactorily. Based on the current distortion limits provided in Table 3.1, it is assumed that the voltage distortion limits will not exceed those given in Table 3.2 below. It has been established that any consumer who "degrades the voltage" at the PCC would be required to correct the problem. However, the problem of distorting the PCC with the voltage is not only for the consumer, but also for the power utility [9]. IEEE-519 sets harmonic limits on voltage at 5% for total harmonic distortion and 3% for the fundamental voltage of any single harmonic.

Table 3.2: IEEE- STD 519-Voltage distortion limits (in % of V_1)

PCC Voltage	Individual Harmonic Magnitude (%)	THD_V
$\leq 69kV$	3	5
69-161kV	1.5	2.5
$\geq 161kV$	1	1.5

The problem of voltage distortion at the PCC is a concern in power systems. The quality of power delivered to end-users is affected by the level of voltage distortion at the PCC. Voltage distortion is the result of harmonic current through the impedance of the power system. Therefore, voltage distortion will always be higher downstream where the harmonic currents are generated and where system impedance is highest.

The IEEE has also released IEEE Standard 1159 (IEEE Std. 1159-1995), which establishes recommended methods for measuring and monitoring power quality standards and defines recommended limits for events, which can degrade power quality.

3.6.1.2 IEC 61000-Series

The International Electro-Technical Commission (IEC) presents standards on electromagnetic compatibility (EMC) in several publications covering types of electrical disturbances. With regards to harmonic current emissions, the IEC standards published three different studies: two publications deal with emissions in the LV network and one presents emission in MV and HV networks [98]. The standards IEC 61000-3-2 and IEC 61000-3-4 concern harmonic emission in LV Networks. The standards IEC 61000-3-2 considers emissions in LV network of equipment of which the input current is less than 16A. Therefore, the equipment manufacturer is requested to take steps to reduce harmonic current. Therefore, the manufacturer has an obligation to manufacture the equipment with emission levels within the standard limits. It is important to notice that the standard IEC 61000-3-2 is not concerned by the size of the system at the PCC as suggested by the IEEE 519. To limit the input current correctly, IEC 61000-3-2 have classified equipment into four classes:

Class A: this class includes balanced three-phase equipment, household equipment, tools (excluding portable tools), dimmers and audio equipment. Class B: this class deals with portable tools and arc welding equipment, which is not falling into professional equipment. Class C: this class is related to lighting equipment. Class D: the class includes all personal computers, personal computer monitors and television receivers designed for a rated input current, which is less than or equal to 600W. Further information on these four classes is detailed in [31].

The IEC 61000-3-4 specifies for equipment with input current higher than 16A. Therefore, the equipment user is requested to get approval or consent from the supply authority for the connection of the equipment to the supply system. Before connecting the equipment to the supply system, the standards are based on three assessment stages. Further information on the recommended emission limit for equipment with input current higher than 16A is provided in [98].

IEC 61000-3-6 is related to harmonic emissions in MV and HV networks. The standard is designed to ensure that the allocation of all harmonic emission rights to customers is equitable for all connected to the same PCC [99]. In other words, every customer having the same agreed power (S_i) and connected to the same point of common coupling has the right to draw equal distorted current from the power supply. The agreed power S_i is defined as the size of a load, which a particular consumer is supposed to have. The principle of equitable emissions is based on the global available harmonic voltage available (G_h) for MV loads to be allocated to all customers connected and potential future customers [100-101]. More about the IEC 61000-3-6 are furnished in the following literature [47], [53], [97], [100].

3.6.2 National Standards

3.6.2.1 South African Power Quality Standards (NRS 048-2 & NRS 048-4)

The quality of supply standard NRS 048 [91] is the South African standard that defines a framework for management of power quality. In 1996, the National Electricity Regulator-NER (now the National Energy Regulator of the South Africa-NERSA) introduced the first regulator, power quality standard (NRS 048-2 Edition 1) as a licence condition. Afterwards, several changes to the standard have been effected. In order to address these concerns, the NER developed a framework for power quality management in 2003 and included in the NER power quality directive of 2003 [95]. Part 2 of the NRS 048 guidelines and specifications sets "minimum standards" for the quality of the electricity supplied by South African utilities to end customers. These "minimum standards" include limits for voltage harmonics and inter-harmonics, voltage flicker, voltage unbalance, voltage regulation, and frequency [93].

Voltage harmonic distortion limits

Voltage harmonic distortion limits are described in NRS 048-2 [91]. These standards contain the compatibility levels for voltage harmonic distortion limits and planning that the network in South Africa ideally shall not exceeds. The NRS 048 has not established limits for harmonics voltage for HV and EHV systems, the customers supplied at those systems will have compatibility levels into contracts based on recommended planning levels given by IEC 61000-3-6 planning levels [92], [96].

3.7 Summary

This chapter discusses harmonics in power systems and their associated problems, starting from their definition, to the harmonic-pollution sources, in which three main groups were explored: the magnetic core equipment, conventional equipment and electronic and power electronic equipment. The increased use of these non-linear loads in power systems has an enormous impact in harmonic distortion, which cannot be neglected in power quality.

The effects due to the presence of harmonics distortion in power networks were also discussed. Starting from overheating of phase and neutral conductors to the communications interference, passing by motors and generators, transformers, capacitors, measuring instruments, relays and contactor protective systems, the study showed the negative impact of harmonics on such instruments in power systems.

General harmonic indices were established to serve as the assessment techniques to the requirements of harmonic measuring equipment. Standards were also presented with focus on international and national standards. IEEE Standard 519, 1159 and IEC were dealt with as the main international standards dealing with harmonic emission. Within the national standards, South African power quality standards, namely, the NRS 048-2 and NRS 048-4 were discussed. It was found that any network ideally should not exceed a certain amount of harmonic voltage and current in the limits prescribed by the standards in order to comply with the permissible harmonic level in the network to minimise the impact on the system performance.

As nonlinear loads generate harmonics, the current drawn by this type of loads are nonlinear. The nonlinear current drawn by the nonlinear loads flows through the installation and causes nonlinear voltage due to system impedance. To analyse the presence and then a contribution of harmonics at the PCC of both power utility and end users, Chapter 4 undertakes the development of a model to calculate the Thevenin equivalent circuits parameters.

Chapter 4: Development of a Model for Calculating Thevenin Equivalent Circuit Parameters

4.1. Introduction

This chapter proposes a new model for the calculation of the Thevenin equivalents impedance and voltage source necessary to assess the contribution of harmonics current at the PCC between the utility and the customers. Measuring harmonics at a single point in time at the PCC does not determine the contribution of harmonics between the utility and the customer [30]. This important issue might be solved by looking at the voltage and current at the PCC at different times. Before establishing a calculation model, a harmonic analysis based Fourier analysis method is used to assess the dominant harmonic order injected at the PCC for which the Thevenin equivalents impedance and voltage sources will be determined.

4.2. Evaluation of Voltage and Current Components Based on IEEE 1459-2010 using Fourier Analysis Method

The IEEE 1459-2010 presents practical definitions for power. This includes measures on how to deal with distortion power. Study [102] presents IEEE Std. 1459-2010 as the "most useful and powerful tool" for calculating power distortion. Though the standards do not specify a calculation method for harmonics components of a waveform [103], [104], [105], [106], this thesis uses an approach based on the Fourier analysis method to calculate the components of a voltage and current waveforms measured at the PCC customers' side. This approach decomposes the signal into different signals containing different frequencies. The results in the Fourier analysis are obtained by combining Fourier series and the Discrete Fourier Transform (DFT).

A. Fourier Series

Fourier components are used in the identification of frequencies carried in a given continuous and periodic distorted waveform [8]. Eq. (4.1) below define Fourier's theorem:

$$y(t) = C_0 + \sum_{n=1}^{\infty}(a_n \cos\frac{2\pi nt}{T} + b_n \sin\frac{2\pi nt}{T}) \tag{4.1}$$

Where C_0 is DC component and is zero for AC power systems, T (sec) is the period and a_n, b_n are called Fourier coefficients. Fourier analysis method uses the Discrete Fourier Transform (DFT) to analyze the frequencies and amplitudes, which are not visible in the time domain waveform.

B. Discrete Fourier Transform (DFT)

The DFT and Fourier series are interrelated and the Fourier coefficients found in (4.1) can be expressed as:

$$a_n = +\frac{2}{N}\mathrm{Re}\{Y(k)\}, \qquad b_n = -\frac{2}{N}\mathrm{Im}\{Y(k)\} \tag{4.2}$$

C. Fourier's Theorem in terms of Sum of Sinusoidal Components

Equation (4.1) can be expressed with only sinusoidal terms as according to [105] as:

$$a_n \cos\frac{2\pi nt}{T} + b_n \sin\frac{2\pi nt}{T} = C_n \sin(\frac{2\pi nt}{T} + \theta_n) \tag{4.3}$$

Where $C_n = \sqrt{{a_n}^2 + {b_n}^2}$ (4.4)

$$\theta_n = \tan^{-1}(\frac{a_n}{b_n}) \tag{4.5}$$

The Fourier series coefficients in (4.1) can be calculated by equations depicted in (4.6) and (4.7) below in the time domain representation as:

$$a_n = \frac{1}{\pi}\int_0^{2\pi} y(t).\cos\frac{2\pi nt}{T}.dt \tag{4.6}$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} y(t).\sin\frac{2\pi nt}{T}.dt \tag{4.7}$$

Based on (4.1) and (4.3), the signals of voltage and current can be expressed as in (4.8), (4.9), and their respective phase angle as in (4.10) and (4.11). This needs to have the measured voltage and current samples as well as the harmonic contents from the DFT.

$$v(t) = \sum_{n=1}^{\infty} C_{nV} \sin(\frac{2\pi nt}{T} + \alpha_n) \tag{4.8}$$

$$i(t) = \sum_{n=1}^{\infty} C_{nI} \sin(\frac{2\pi nt}{T} + \beta_n) \tag{4.9}$$

$$\alpha_n = \tan^{-1}(\frac{a_n}{b_n}) \tag{4.10}$$

$$\beta_n = \tan^{-1}(\frac{a_n}{b_n}) \tag{4.11}$$

Where a_n and b_n are Fourier coefficients calculated based on current and voltage waveforms.

α_n and β_n are phase angle of voltage and current respectively.

The RMS values (fundamental and harmonics) of (4.8) and (4.9) are expressed in (4.12) below:

$$V_n = \frac{C_{nV}}{\sqrt{2}} \text{ and } I_n = \frac{C_{nI}}{\sqrt{2}}, \; n = 1,... \tag{4.12}$$

Where V_n and I_n, represent the RMS voltage and current respectively

These RMS values are used to calculate the IEEE 1459-2010 power indices as developed in this work.

4.3. Evaluation of the utility and the customer Thevenin Equivalent Circuit Parameters

In recent years, the evaluation of harmonic impedance characteristics has been a challenge. Several studies have proposed various methods to determine the harmonic impedance in a power system [11], [12], [13], [28]. However, these methods suggest either the determination of the short-circuit network impedance and the open circuit voltage, which might not be feasible in practical installations particularly when switching operation is not allowed. Other studies proposed the direct injection of harmonics sources into the power system [15], [108], [109]. However, the results of these studies found that the accuracy of the measurement might not be achieved. The proposed sources of injection such as saturated transformers, harmonic generated or ripple control systems may contribute to an increase in harmonics, which might affect the measurement data. Several methods, which cannot result in a disruption of the operating conditions, are suggested in the literature. The most common sources of disturbance considered in these methods are naturally occurring events. These methods calculate the harmonic impedance by adjusting the harmonic voltage and current at the point of evaluation [31]. However, the disadvantage of these methods is that accurate results may only be obtained by carrying out multiple measurements of voltage and current at the point of evaluation.

This thesis develops a methodology to determine the Thevenin equivalent impedance and source characteristics of both utility and customers at different points in time. The determination of the equivalent circuits can allow for an accurate assessment of the contribution of harmonics at the PCC. It should be noted that the respective contributions of the utility or the customer could not be determined by conducting the measurements at a single point in time at the PCC. Measuring at a single point in time at the PCC provides an accurate indication of the total harmonics present at the PCC combining the effect of harmonics from both the utility and the customers [9] [67]. Determining the utility and customers' sides Thevenin equivalent circuits pose a challenge for the measurement of harmonics contributions at the PCC.

The method used in this thesis is illustrated as follows: when we consider the resistive Thevenin circuit as represented in Fig. 4.1 with voltage V and current I, the single port network can contain a number of sources and resistances. According to the theory of linear circuits, voltage V is considered as the equivalent Thevenin voltage V_{Th} if the port is open. This equivalent Thevenin voltage is the combination of all the voltage sources that the network represents. A current I limited by an equivalent Thevenin resistance R_{Th} flows when the port is shorted. R_{Th} , represents the combination of all the resistors present in the one port network.

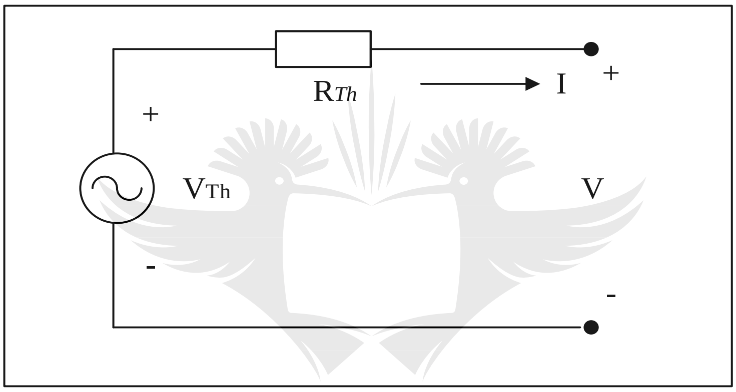


Fig. 4.1: Thevenin equivalent resistive circuit [67]

When the load is connected to Fig. 4.1, the characteristics of the Thevenin equivalent resistive circuit can be determined along a load line as depicted in Fig. 4.2 below.

A Thevenin equivalent is usually determined by its open circuit voltage ($V_{TH} = V_{OC}$ at $I = 0$) and by the short circuit current at $V = 0$

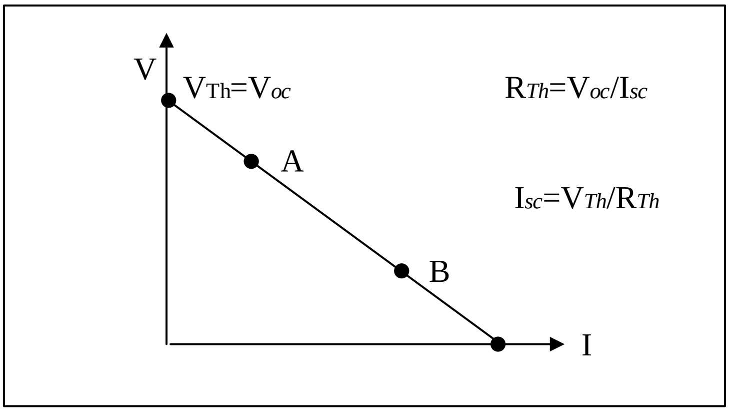


Fig. 4.2: Load line of the Thevenin equivalent resistive circuit

Where:

V_{Th}: Thevenin equivalent voltage

V_{oc}: Voltage at open circuit

I_{sc}: Short circuit current

R_{Th}: Thevenin equivalent resistive

The line intercepting voltage and current in the Fig. 4.2 above is called a load line.

In a practical installation, it might not be feasible to have a network open (no-load) or shorted to determine the Thevenin equivalent circuit of a utility or a customer network. During normal operation, a network measurement may vary on the load line between point time A and point time B as per Fig. 4.2. Therefore, if the voltages and currents at the points A and B in time are known, V_{Th} can be determined by extrapolation and then R_{Th} by determining the slope of the load line. This understanding is true in a network where the Thevenin equivalent impedance is purely resistive. Unfortunately, in a practical installation with reactance, V_{Th} and R_{Th} cannot be determined in this way. This is because the Thevenin equivalent impedance is complex with a Thevenin equivalent resistive (R_{Th}) and Thevenin equivalent reactive (X_{Th}) parts. Fig.4.2 indicates the Thevenin equivalent circuits of a network using a load operating at a point in time A and waiting for the load to change to obtain the voltages and currents at point in time B.

Considering that, IEEE 1459-2010 [30] cannot provide the Thevenin equivalents required to determine harmonic contributions at the PCC. Looking at the voltage and current at the PCC at different times might be the solution. For this to be achieved at least two points in time are needed. To obtain these two points, we need statistical data on behaviour over time, as described in chapter 5.

In Fig.4.3 below, two operating points in time A and B are used to determine the Thevenin equivalents circuits for the utility and two customers called "C_1"and "C_2" connected to the same PCC with resistive and reactive (i.e. complex) impedances.

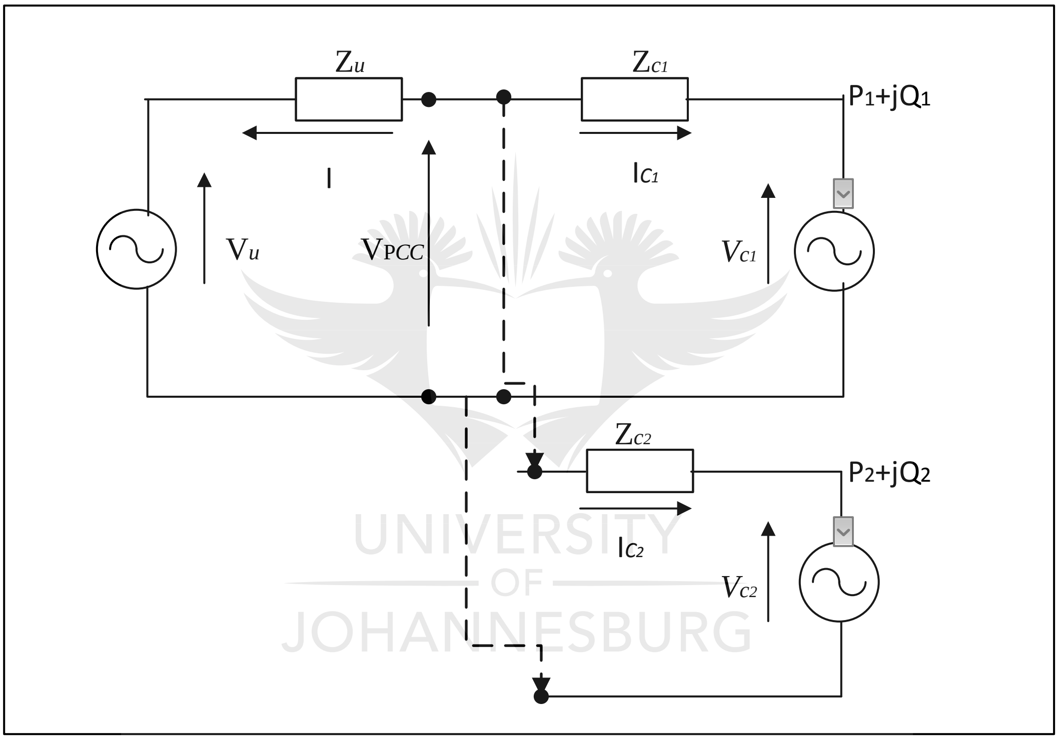


Fig. 4.3: Thevenin equivalent model of utility and customers.

Where $Z_u = R_u + jX_u$: represent utility impedance

$Z_{C1} = R_{C1} + jX_{C1}$: Customer 1 equivalent Thevenin impedance

$Z_{C2} = R_{C2} + jX_{C2}$: Customer 2 equivalent Thevenin impedance

$V_u = V_{u-\mathrm{Re}} + jV_{u-\mathrm{Im}}$: Utility equivalent Thevenin voltage source

$V_{C1} = V_{C1-\mathrm{Re}} + jV_{C1-\mathrm{Im}}$: Customer 1 equivalent Thevenin voltage source

$V_{C2} = V_{C2-\mathrm{Re}} + jV_{C2-\mathrm{Im}}$: Customer 2 equivalent Thevenin voltage source

$V_{PCC} = V_{PCC-\mathrm{Re}} + jV_{PCC-\mathrm{Im}}$: Voltage at the PCC

$I = I_{\mathrm{Re}} + jI_{\mathrm{Im}}$: Current flowing at utility side.

From Fig.4.3, the study first needs to determine the model of the Thevenin equivalent circuit at the customer's side and then at the utility side with the assumption that the load changes between time instant A and time instant B. This model is defined by the components, Z_{C1}, Z_{C2}, V_{C1}, V_{C2}, Z_u, and V_u.

To evaluate these components, we assume that the voltage and current harmonic at the PCC are complex, as stated earlier. We also assume that the real and imaginary part of respective voltages and current harmonics, $V_{PCC-\mathrm{Re}}$, $V_{PCC-\mathrm{Im}}$, I_{Re}, and I_{Im}, are known at two instants time A and B. We should first determine the Thevenin equivalent harmonic circuit at customer 1 and then at the customer 2 and finally at the utility side.

a) Customer 1

For this customer 1, it is necessary to determine the Thevenin equivalent harmonic voltage and Thevenin equivalent impedance. The model needs at least two changing instants times A and B.

At point in time A:

In Fig. 4.3, the following equation can be determined

$$V_{PCC-A} = (R_{C1-A} + jX_{C1-A})I_{C1-A} + V_{C1-A} \tag{4.13}$$

Where $V_{PCC-A} = V_{PCC-\mathrm{Re}-A} + jV_{PCC-\mathrm{Im}-A}$

$I_{C1-A} = I_{C1-\mathrm{Re}-A} + jI_{C1-\mathrm{Im}-A}$

$V_{C1-A} = V_{C1-\mathrm{Re}-A} + jV_{C1-\mathrm{Im}-A}$

The subscript "A" denotes the point in time A

$V_{PCC-\mathrm{Re}}$, and $V_{PCC-\mathrm{Im}}$ represent V_{PCC} real and imaginary part of the measured voltage at the PCC, of which the contribution of the sources, customer1 and customer 2, will be determined in chapter 5.

$I_{C1-\mathrm{Re}}$, and $I_{C1-\mathrm{Im}}$ represent I_{C1} real and imaginary part of the customer 1 current.

$V_{C1-\mathrm{Re}}$, and $V_{C1-\mathrm{Im}}$ represent V_{C1} real and imaginary part of the customer 1 voltage.

The development of (4.13) leads to the equation below:

$$V_{PCC-\mathrm{Re}-A} + jV_{PCC-\mathrm{Im}-A} = R_{C1}I_{C1-\mathrm{Re}-A} - X_{C1}I_{C1-\mathrm{Im}-A} + jR_{C1}I_{C1-\mathrm{Im}-A} + jX_{C1}I_{C1-\mathrm{Re}-A} + V_{C1-\mathrm{Re}-A} + jV_{C1-\mathrm{Im}-A}$$

The following equations can be obtained when we separate real and imaginary parts from the equation above:

$$V_{PCC-\mathrm{Re}-A} = V_{C1-\mathrm{Re}-A} + I_{C1-\mathrm{Re}-A}.R_{C1} - I_{C1-\mathrm{Im}-A}.X_{C1} \qquad (4.14)$$

$$V_{PCC-\mathrm{Im}-A} = V_{C1-\mathrm{Im}-A} + I_{C1-\mathrm{Im}-A}.R_{C1} + .I_{C1-\mathrm{Re}-A}.X_{C1} \qquad (4.15)$$

Equations (4.14) and (4.15) are valid for a single point in time, here point A. In these equations, there are two measured quantities with their associated complex components: $V_{PCC-\mathrm{Re}}$, $V_{PCC-\mathrm{Im}}$, $I_{C1-\mathrm{Re}}$, and $I_{C1-\mathrm{Im}}$ and four quantities ($V_{C1-\mathrm{Re}-A}$, $V_{C1-\mathrm{Im}-A}$, R_{C1} and X_{C1}) to be determined. Equations (4.14) and (4.15) form a system of two equations and four quantities to be determined. The theory of linear circuits reveals that this kind of system of equations is impossible to solve. To obtain a system of four equations, another instant in time i.e point in time B needs to be measured. Then a customer can be fully characterised by its Thevenin voltage and impedance.

At point in time B,

It is assumed that the load changes between time A and B.

From Fig.4.3, the following equation can be obtained:

$$V_{PCC-B} = (R_{C1-B} + jX_{C1-B})I_{C1-B} + V_{C1-B} \qquad (4.16)$$

Where $V_{PCC-B} = V_{PCC-\mathrm{Re}-B} + jV_{PCC-\mathrm{Im}-B}$

$$I_{C1-B} = I_{C1-\mathrm{Re}-B} + jI_{C1-\mathrm{Im}-B}$$

$V_{C1-B} = V_{C1-\text{Re}-B} + jV_{C1-\text{Im}-B}$

The subscript "B" denotes the point in time B

The development of (4.16) as for the time instant A leads to the two following equations:

$$V_{PCC-\text{Re}-B} = V_{C1-\text{Re}-B} + I_{C1-\text{Re}-B}.R_{C1} - I_{C1-\text{Im}-B}.X_{C1} \quad (4.17)$$

$$V_{PCC-\text{Im}-B} = V_{C1-\text{Im}-B} + I_{C1-\text{Im}-B}.R_{C1} + .I_{C1-\text{Re}-B}.X_{C1} \quad (4.18)$$

To make the process simple, we assume that voltage V_{PCC} at the PCC is complex and its components are V_{Re} and V_{Im}. The harmonic current components at the PCC are I_{Re} and I_{Im}.

Depending on the side from which analysis is done, I_{Re} and I_{Im} will be identified as current flowing into customer 1 or customer 2. The real sign of current at customer 1 or customer 2 will be defined after the development of a model

With regard to the subscripts denoted for a customer 1, the quantities in (4.14), (4.15), (4.17) and (4.18) can be expressed as follows:

$V_{PCC-\text{Re}-A} = V_{\text{Re}-A}$	$V_{PCC-\text{Im}-A} = V_{\text{Im}-A}$	$V_{PCC-\text{Re}-B} = V_{\text{Re}-B}$
$V_{C1-\text{Re}} = V_{Th-\text{Re}}$	$V_{C1-\text{Im}} = V_{Th-\text{Im}}$	$V_{PCC-\text{Im}-B} = V_{\text{Im}-B}$
$R_{C1} = R$	$I_{C1-\text{Re}-A} = I_{\text{Re}-A}$	$I_{C1-\text{Re}-B} = I_{\text{Re}-B}$
$X_{C1} = X$	$I_{C1-\text{Im}-A} = I_{\text{Im}-A}$	$I_{C1-\text{Im}-B} = I_{\text{Im}-B}$

From the expressions above, the Thevenin equivalent circuit parameters to determine are $Z_{Th} = R + jX$ and $V_{Th} = V_{Th-\text{Re}} + jV_{Th-\text{Im}}$.

From (4.14), (4.15), (4.17) and (4.18) it follows:

At point in time A

$$V_{\text{Re}-A} = V_{Th-\text{Re}} + I_{\text{Re}-A}.R - I_{\text{Im}-A}.X \quad (4.19)$$

$$V_{\text{Im}-A} = V_{Th-\text{Im}} + I_{\text{Im}-A}.R + I_{\text{Re}-A}.X \quad (4.20)$$

At point in time B

$$V_{\text{Re}-B} = V_{Th-\text{Re}} + I_{\text{Re}-B}.R - I_{\text{Im}-B}.X \quad (4.21)$$

$$V_{\mathrm{Im}-B} = V_{Th-\mathrm{Im}} + I_{\mathrm{Im}-B}.R + I_{\mathrm{Re}-B}.X \quad (4.22)$$

We obtain a system of four equations at two different points in time A and B with four variables: $V_{Th-\mathrm{Re}}$, $V_{Th-\mathrm{Im}}$, R and X to be determined. The measurements of voltages and currents of harmonics at the PCC after the loads have changed are known. By determining, the complex harmonic components of voltage and current at the PCC, the Thevenin equivalent source voltage and impedance for the customer can be determined.

The four variables $V_{Th-\mathrm{Re}}$, $V_{Th-\mathrm{Im}}$, R and X can be determined by solving (4.19) -(4.22) above. To solve these equations, we use Cramer's method.

Equations (4.19) -(4.22) above can be arranged in terms of $V_{Th-\mathrm{Re}}$, $V_{Th-\mathrm{Im}}$, R and X as follows:

$$V_{\mathrm{Re}-A} = 1.V_{Th-\mathrm{Re}} + 0.V_{Th-\mathrm{Im}} + I_{\mathrm{Re}-A}.R - I_{\mathrm{Im}-A}.X \quad (4.23)$$

$$V_{\mathrm{Re}-B} = 1.V_{Th-\mathrm{Re}} + 0.V_{Th-\mathrm{Im}} + I_{\mathrm{Re}-B}.R - I_{\mathrm{Im}-B}.X \quad (4.24)$$

$$V_{\mathrm{Im}-A} = 0.V_{Th-\mathrm{Re}} + 1.V_{Th-\mathrm{Im}} + I_{\mathrm{Im}-A}.R + I_{\mathrm{Re}-A}.X \quad (4.25)$$

$$V_{\mathrm{Im}-B} = 0.V_{Th-\mathrm{Re}} + 1.V_{Th-\mathrm{Im}} + I_{\mathrm{Im}-B}.R + I_{\mathrm{Re}-B}.X \quad (4.26)$$

The following matrix can be deducted from the system of four equations above:

$$A = \begin{pmatrix} 1 & 0 & I_{\mathrm{Re}-A} & -I_{\mathrm{Im}-A} \\ 1 & 0 & I_{\mathrm{Re}-B} & -I_{\mathrm{Im}-B} \\ 0 & 1 & I_{\mathrm{Im}-A} & I_{\mathrm{Re}-A} \\ 0 & 1 & I_{\mathrm{Im}-B} & I_{\mathrm{Re}-B} \end{pmatrix} \qquad y = \begin{pmatrix} V_{Th-\mathrm{Re}} \\ V_{Th-\mathrm{Im}} \\ R \\ X \end{pmatrix} \qquad B = \begin{pmatrix} V_{\mathrm{Re}-A} \\ V_{\mathrm{Re}-B} \\ V_{\mathrm{Im}-A} \\ V_{\mathrm{Im}-B} \end{pmatrix}$$

Where A matrix of coefficients

y Column matrix of unknown variables.

B Column matrix of known quantities.

Any system of equations can be expressed in the form of $A.y = B$

$A.y = B$ yields as follows:

$$\begin{pmatrix} 1 & 0 & I_{\mathrm{Re}-A} & -I_{\mathrm{Im}-A} \\ 1 & 0 & I_{\mathrm{Re}-B} & -I_{\mathrm{Im}-B} \\ 0 & 1 & I_{\mathrm{Im}-A} & I_{\mathrm{Re}-A} \\ 0 & 1 & I_{\mathrm{Im}-B} & I_{\mathrm{Re}-B} \end{pmatrix} \begin{pmatrix} V_{Th-\mathrm{Re}} \\ V_{Th-\mathrm{Im}} \\ R \\ X \end{pmatrix} = \begin{pmatrix} V_{\mathrm{Re}-A} \\ V_{\mathrm{Re}-B} \\ V_{\mathrm{Im}-A} \\ V_{\mathrm{Im}-B} \end{pmatrix}$$

Since the system of these four equations is linear, the Cramer's method can be used to find the unknown variables ($V_{Th-\mathrm{Re}}$, $V_{Th-\mathrm{Im}}$, R and X). This leads to the following results:

$$V_{Th-\mathrm{Re}} = \frac{\left|\begin{pmatrix} V_{\mathrm{Re}-A} & 0 & I_{\mathrm{Re}-A} & -I_{\mathrm{Im}-A} \\ V_{\mathrm{Re}=B} & 0 & I_{\mathrm{Re}-B} & -I_{\mathrm{Im}-B} \\ V_{\mathrm{Im}-A} & 1 & I_{\mathrm{Im}-A} & I_{\mathrm{Re}-A} \\ V_{\mathrm{Im}-B} & 1 & I_{\mathrm{Im}-B} & I_{\mathrm{Re}-B} \end{pmatrix}\right|}{|A|} \qquad V_{Th-\mathrm{Im}} = \frac{\left|\begin{pmatrix} 1 & V_{\mathrm{Re}-A} & I_{\mathrm{Re}-A} & -I_{\mathrm{Im}-A} \\ 1 & V_{\mathrm{Re}-B} & I_{\mathrm{Re}-B} & -I_{\mathrm{Im}-B} \\ 0 & V_{\mathrm{Im}-A} & I_{\mathrm{Im}-A} & I_{\mathrm{Re}-A} \\ 0 & V_{\mathrm{Im}-B} & I_{\mathrm{Im}-B} & I_{\mathrm{Re}-B} \end{pmatrix}\right|}{|A|}$$

$$R = \frac{\left|\begin{pmatrix} 1 & 0 & V_{\mathrm{Re}-A} & -I_{\mathrm{Im}-A} \\ 1 & 0 & V_{\mathrm{Re}-B} & -I_{\mathrm{Im}-B} \\ 0 & 1 & V_{\mathrm{Im}-A} & I_{\mathrm{Re}-A} \\ 0 & 1 & V_{\mathrm{Im}-B} & I_{\mathrm{Re}-B} \end{pmatrix}\right|}{|A|} \qquad X = \frac{\left|\begin{pmatrix} 1 & 0 & I_{\mathrm{Re}-A} & V_{\mathrm{Re}-A} \\ 1 & 0 & I_{\mathrm{Re}-B} & V_{\mathrm{Re}-B} \\ 0 & 1 & I_{\mathrm{Im}-A} & V_{\mathrm{Im}-A} \\ 0 & 1 & I_{\mathrm{Im}-B} & V_{\mathrm{Im}-B} \end{pmatrix}\right|}{|A|} \qquad (4.27)$$

Where $|A|$ represents the determinant of the matrix A. It should be pointed out that the model made above is per harmonic.

From Fig, 4.3, the sign of the quantities in different matrix above can be defined as follows:

$I_{\mathrm{Re}-A} = -\mathrm{Re}(I_{C1-A})$ $\qquad$ $I_{\mathrm{Im}-A} = -\mathrm{Im}(I_{C1-A})$

$I_{\mathrm{Re}-B} = -\mathrm{Re}(I_{C1-B})$ $\qquad$ $I_{\mathrm{Im}-B} = -\mathrm{Im}(I_{C1-B})$

Similarly, voltage components are defined as:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A})$ $\qquad$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A})$

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B})$ $\qquad$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B})$

$\vartheta = a\tan\left(\frac{V_{Th-\mathrm{Im}}}{V_{Th-\mathrm{Re}}}\right)$, phase angle of Thevenin voltage sources

Once the voltage and current at the PCC are measured at two different time instances "A" and "B" (after loads have changed) and the complex harmonic components of the PCC voltage and current have been calculated, (4.27) can determine the Thevenin equivalent circuit parameters of the power system. In other words, once the current components ($I_{\text{Re}-A}$, $I_{\text{Im}-A}$, $I_{\text{Re}-B}$, and $I_{\text{Im}-B}$) and voltage components ($V_{\text{Re}-A}$, $V_{\text{Im}-A}$, $V_{\text{Re}-B}$, and $V_{\text{Im}-B}$) are known, the Thevenin voltage ($V_{Th-\text{Re}}$, $V_{Th-\text{Im}}$) and Thevenin impedance (R, X) of customer 1 can be calculated by (4.27).

b) Customer 2

To determine the Thevenin equivalent voltage ($V_{Th-\text{Re}}$, $V_{Th-\text{Im}}$) and the Thevenin equivalent impedance (R, X) of the customer 2 side, an equivalent process to that of the customer 1 side in Fig. 4.3 is followed. Two time instants "A" and "B" are needed and analysis is performed at customer 2 side. Since customer 2 is connected to the same PCC with customer 1, (19) -(22) remain a valid development applicable to the determination of the Thevenin equivalent circuit of customer 2.

From Fig. 4.3, the harmonic current components are defined (opposite sign to that of the PCC current) as:

$$I_{\text{Re}-A} = -\text{Re}(I_{C2-A}) \qquad I_{\text{Im}-A} = -\text{Im}(I_{C2-A})$$

$$I_{\text{Re}-B} = -\text{Re}(I_{C2-B}) \qquad I_{\text{Im}-B} = -\text{Im}(I_{C2-B})$$

Similarly, voltage components are defined as:

$$V_{\text{Re}-A} = \text{Re}(V_{PCC-A}) \qquad V_{\text{Im}-A} = \text{Im}(V_{PCC-A})$$

$$V_{\text{Re}-B} = \text{Re}(V_{PCC-B}) \qquad V_{\text{Im}-B} = \text{Im}(V_{PCC-B})$$

$\vartheta = a\tan\left(\dfrac{V_{Th-\text{Im}}}{V_{Th-\text{Re}}}\right)$, phase angle of Thevenin voltage sources.

Again, as for Customer 1, once the current components ($I_{\text{Re}-A}$, $I_{\text{Im}-A}$, $I_{\text{Re}-B}$, and $I_{\text{Im}-B}$) and voltage components ($V_{\text{Re}-A}$, $V_{\text{Im}-A}$, $V_{\text{Re}-B}$, and $V_{\text{Im}-B}$) are determined, the Thevenin voltage ($V_{Th-\text{Re}}$, $V_{Th-\text{Im}}$) and Thevenin impedance (R, X) of Customer 2 can be calculated by (4.27) above.

c) The utility

To determine the Thevenin equivalent voltage ($V_{Th-\mathrm{Re}}, V_{Th-\mathrm{Im}}$) and the Thevenin equivalent impedance (R, X) circuit for the utility, an equivalent process to that of the customer 1 and 2 side in Fig. 4.3 is followed. At the utility side, the current from the PCC into the utility is equal to the sum of all customers' currents.

Therefore, the current components ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$, and $I_{\mathrm{Im}-B}$) and voltage components ($V_{\mathrm{Re}-A}, V_{\mathrm{Im}-A}, V_{\mathrm{Re}-B}$, and $V_{\mathrm{Im}-B}$) can be expressed as follows:

$$I_{\mathrm{Re}-A} = \mathrm{Re}(I_{C1-A}) + \mathrm{Re}(I_{C2-A}) \qquad I_{\mathrm{Im}-A} = \mathrm{Im}(I_{C1-A}) + \mathrm{Im}(I_{C2-A})$$

$$I_{\mathrm{Re}-B} = \mathrm{Re}(I_{C1-B}) + \mathrm{Re}(I_{C2-B}) \qquad I_{\mathrm{Im}-B} = \mathrm{Im}(I_{C1-B}) + \mathrm{Im}(I_{C2-B})$$

Similarly, voltage components are defined as:

$$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A}) \qquad V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A})$$

$$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B}) \qquad V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B})$$

$\vartheta = a\tan\left(\dfrac{V_{Th-\mathrm{Im}}}{V_{Th-\mathrm{Re}}}\right)$, phase angle of the Thevenin voltage sources.

The Thevenin voltage ($V_{Th-\mathrm{Re}}, V_{Th-\mathrm{Im}}$) and Thevenin impedance (R, X) of the utility can be calculated by (4.27).

To generalise this approach to harmonic frequencies, The Thevenin voltage ($V_{Th-\mathrm{Re}}, V_{Th-\mathrm{Im}}$) and Thevenin impedance (R, X) of the utility when customers 1 and 2 are connected to the PCC can be calculated at any frequency by (4.27). Therefore, the current components ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$, and $I_{\mathrm{Im}-B}$) and voltage components ($V_{\mathrm{Re}-A}, V_{\mathrm{Im}-A}, V_{\mathrm{Re}-B}$, and $V_{\mathrm{Im}-B}$) at harmonic frequencies will be expressed as follows:

$$I_{\mathrm{Re}-A} = \mathrm{Re}(I_{C1-n-A}) + \mathrm{Re}(I_{C2-n-A}) \qquad I_{\mathrm{Im}-A} = \mathrm{Im}(I_{C1-n-A}) + \mathrm{Im}(I_{C2-n-A})$$

$$I_{\mathrm{Re}-B} = \mathrm{Re}(I_{C1-n-B}) + \mathrm{Re}(I_{C2-n-B}) \qquad I_{\mathrm{Im}-B} = \mathrm{Im}(I_{C1-n-B}) + \mathrm{Im}(I_{C2-n-B})$$

Similarly, voltage components are defined as:

$$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-n-A}) \qquad V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-n-A})$$

$$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-n-B}) \qquad V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-n-B})$$

Where the subscript " n " indicates the harmonic order and $n = 1,...$

$\vartheta = a\tan\left(\frac{V_{Th-\mathrm{Im}}}{V_{Th-\mathrm{Re}}}\right)$, phase angle of the Thevenin voltage sources

4.4. Contribution of Harmonics Current at the PCC

Once the Thevenin equivalent circuits of the power systems of the utility and customers are determined, the contribution of harmonic currents at the PCC can be assessed by using the principle of superposition to Fig.4.3. This theorem states that any linear circuit with two or more independent sources can be separated into a number of single linear circuits based on the statement of the superposition theorem. In Fig. 4.3, we do have voltage independent sources. Therefore, we apply the voltage superposition principle. According to the theorem, in every single linear circuit, an independent source acts alone, and all the other independent sources are replaced by their internal impedance, here equals to zero. The principle applied leads to the Fig. 4.4 below:

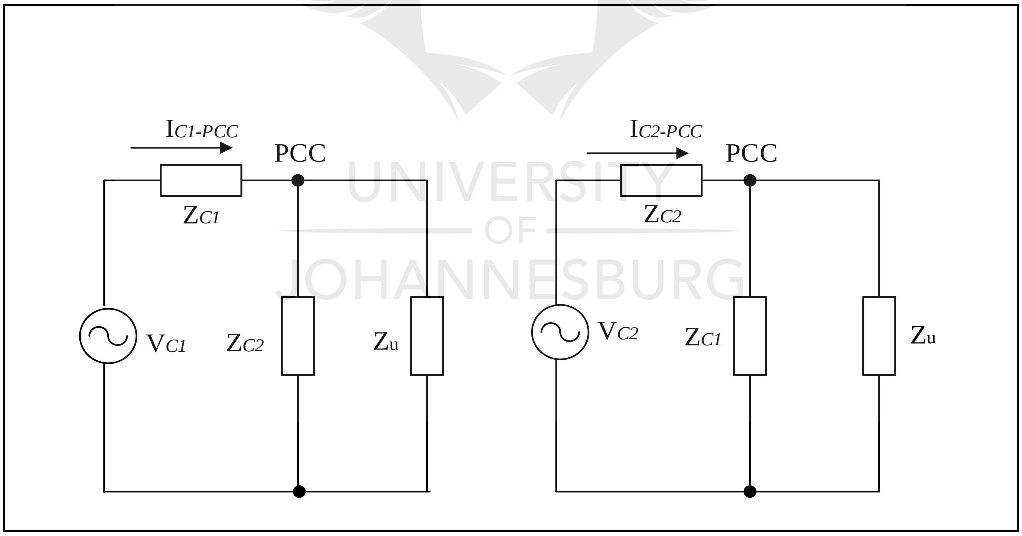


Fig. 4.4: Harmonic contribution of customers for the Thevenin equivalent circuit model

From Fig. 4.4 above, when customer 1 voltage source acts alone, Z_{C2} and Z_u are in parallel and the two parallel impedances are in series with Z_{C1}. When customer 2 source voltage acts alone, Z_{C1} and Z_u are in parallel. The two parallel impedances are in series with Z_{C2}. Using Kirchoff's law, the harmonic contribution of the customers can be calculated as follows in (4.28a) and (4.28b):

$$I_{C1-PCC} = \frac{V_{C1}}{Z_{C1} + \left(\frac{Z_{C2}.Z_u}{Z_{C2} + Z_u} \right)} \quad (4.28a)$$

$$I_{C2-PCC} = \frac{V_{C2}}{Z_{C2} + \left(\frac{Z_{C1}.Z_u}{Z_{C1} + Z_u} \right)} \quad (4.28b)$$

For harmonic contribution of a utility, an equivalent process to that of the customers is applied. An independent utility voltage source acts alone in the one side while in the other side, the customers' independent voltage sources are replaced by their internal impedances. This yields to the Fig. 4.5 below:

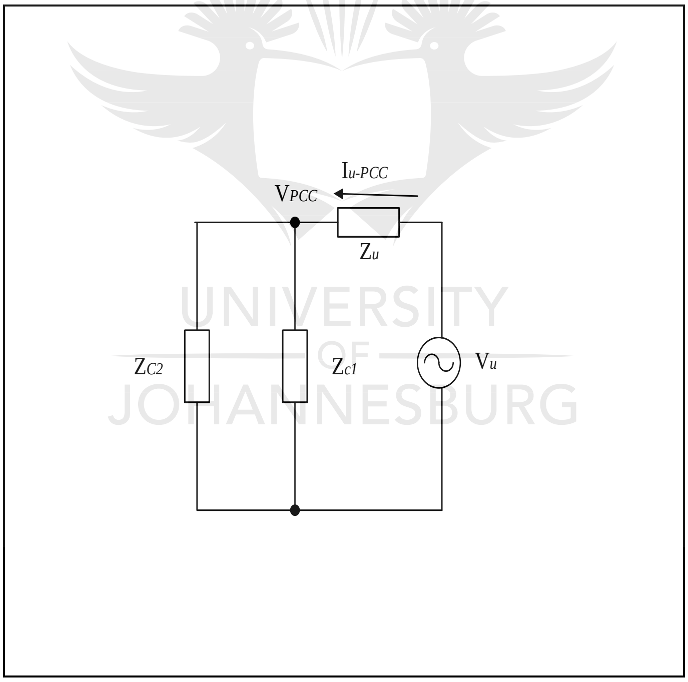


Fig. 4.5: Harmonic contribution of utility for the Thevenin equivalent circuit model

From Fig. 4.5 above, when utility source voltage acts alone, impedances Z_{C1} and Z_{C2} are in parallel and the two parallel impedances are in series with impedance Z_u . Using Kirchoff's law, the harmonic current contribution of a utility at the PCC leads to the following expression:

$$I_{u-PCC} = \frac{V_u}{Z_u + \left(\frac{Z_{C1}.Z_{C2}}{Z_{C1}+Z_{C2}}\right)} \quad (4.28c)$$

The harmonic current at the PCC can be separated into customers and utility parts as follows:

$I_{PCC} = (I_{C1-PCC} + I_{C2-PCC}) - I_{u-PCC}$. This is referred to as the harmonic current contribution of the utility and customers' sides. As stated earlier, the current flowing to the utility from the PCC is equal to the sum of the currents from the customers. The contribution of harmonic current at the PCC depends on the harmonic impedance, which varies over time [28]. According to (4.28 (a), (b), (c)), the more the combined utility and customer equivalent harmonic impedance is larger, the less the contribution of harmonic current at the PCC

4.5. Summary

This chapter introduced a linear model at each harmonic for calculating the Thevenin equivalent impedance and voltage source. This model can be used to assess the contribution of harmonics current at the PCC between the utility and the customers. As IEEE 1459-2010 deals with one measurement slice in time, it cannot provide the Thevenin equivalents necessary to determine harmonic contribution at the PCC. As a result, this chapter focussed on the voltage and current at the PCC at different times A and B. Before establishing the model, this chapter demonstrated that determining V_{Th} by extrapolation and then R_{Th} by the slope of the load line is only valid in a network where the Thevenin equivalent impedance is purely resistive. Unfortunately, this cannot be used in practical installation with reactance, as the Thevenin equivalent impedance of such installation is complex with Thevenin equivalent resistive (R_{Th}) and Thevenin equivalent reactive (X_{Th}) parts. This chapter further provides the theory of determining the complex Thevenin equivalents of the utility and customers from measured values. It also shows that once the Thevenin equivalents are known, the individual harmonic contributions at the PCC can be calculated.

Chapter 5: Case study

5.1. Introduction

A case study was conducted at a Metropolitan municipality power utility in Johannesburg to investigate the effectiveness of the developed linear model. It determines the Thevenin equivalent circuit parameters necessary to assess the contribution of harmonic currents at the PCC between the utility and the customers in a distribution electrical network. A numerical analysis of current and voltage harmonics waveforms components was performed in order to complement the practical assessment. This chapter deals with the assessment of the contribution of harmonic current at the PCC between the utility and two customers and the identification of the main contributor of harmonic currents. The study uses the Thevenin equivalent circuits of both the utility and customers connected to the PCC per harmonic identified.

5.2. Power System Analysis and Measurement Set up

5.2.1. Power System Analysis

To assess the contribution of harmonics in a practical electrical network, measurements were carried out in a substation of a power utility in South Africa where one 132/11kV incomer supplies two customers through two single feeders, as shown in Fig. 5.1 below:

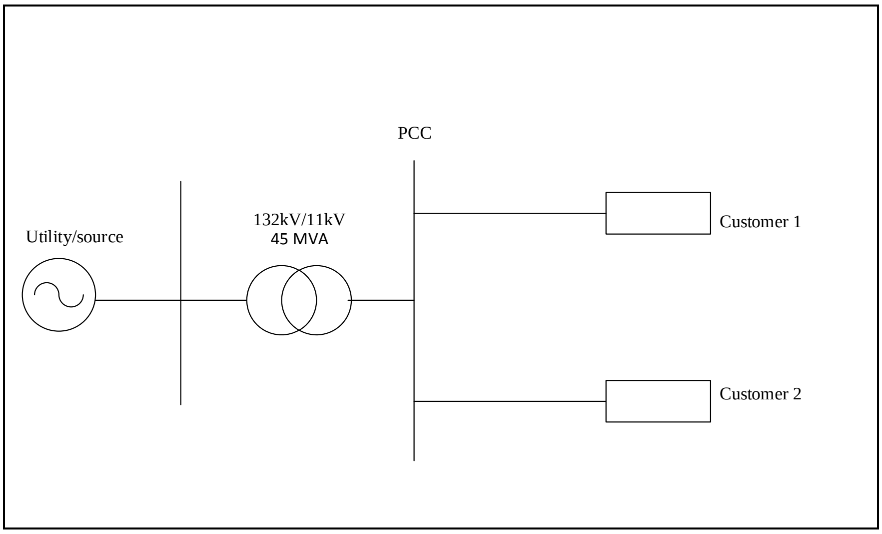


Fig. 5.1: Practical Network for Power Harmonic Assessment

5.2.2. Measurement and Instruments

During the practical experiments, power quality instruments were used to measure the voltage and current at the PCC and at two customers' sides. All the multipoint measurements carried out were synchronised in order to ensure the reliability and accuracy of the data collected. This process was done to ensure that the practical experiment is carried out in the same conditions to facilitate the comparison of the results from the power utility and customers connected to the same PCC.

5.2.2.1. Instrument Specifications

To assess, three groups of power quality meters were installed for measurement. One group was placed in the substation 132kV/11kV and the other two groups were positioned at each line connecting the two local customers. Each group of power quality meters used was designed to measure three-phase voltage and current waveforms sampled over 10 to 12 cycles of the 50 Hz electrical distribution system before averaging. Utility rules and regulations did not allow us to install private current transformers (CTs). Voltage and current waveforms were measured by the power quality meter G4430 installed by the power utility. The power quality PQSCADA software collected the data. The compression on board was done using the power quality PQElspec patented PQZip technology for data analysis.

The Elspec G4400 Power Quality instruments used for the measurements were power quality recorder compliant to the requirements of IEC 61000-4-30 [47] and with the South African standards NRS048-2 [91].

The ELspec G4400 power Quality data center used in this work is an accurate electronic power meter designed to sample voltage and current waveforms, calculate relevant power quality parameters, and compress and store the waveforms using the technology called Elspec patented PQZip for collection by PQSCADA software.

Data from every phase, including current and voltage are saved by the power quality meter at a resolution of up to 1024 samples per cycle.

The Power Quality Data Center is designed with an integral web server. All the equipment in the extensive system forms a package. This includes the power meter for collecting the data, PQSCADA software for collecting and storing the data from the instruments on a system wide server network and the investigator software for analysing the gathered data. Fig.5.2 below represents one of the power quality instruments used in this work.

Fig. 5.2: ELspec G4100 LCD Remote Display (left) and Power Meter G4430 (right)

The system topology is presented as follows: The G4430 Power Quality instrument is connected to the electrical system via current and voltage transformers. These instruments are designed with one purpose; to constanltly record the voltage and current waveforms. The data collected are compressed on board using the Elspec patented PQZip. The PQZip files are transferred to a PNode designed to run on a server managed by the Site Manager. The G4400 series instrument hosts an on-board website and the power meter G4430 used in this work is designed to access to data from any web browser. The configuration of the G4400 series instrument can be fulfilled via the Website or via the G4100 Remote Display Unit shown in Fig.5.2 above.

The Elspec G4400 series power meters available in the market are in three models. These models are designed to offer "cost efficient application" across an electrical distribution system. The selection of power meter Elspec G4430 for this thesis is based on the performance of this meter as indicated in Table 5.1 below:

Table 5.1: Comparison of three power meters' models specifications

Real Time Measurements	**Elspec G4410**	**Elspec G4420**	**Elspec G4430**
Voltage/Current: per phase, average, unbalance	+	+	+
Power: real, reactive, apparent, power factor, frequency	+	+	+
Energy: bi-directional, import, export, net, total	+	+	+
Demand: window, sliding window	+	+	+
Sampling rate: samples/cycle Current	256	512	1024
Harmonic calculations unit	127^{th}	255^{th}	511^{th}
Measurement according to IEC 61000-4-30	+	+	+
Cycle by cycle RMS, frequency and harmonics	-	+	+
Measurement during overloading	X2	X10	X10

5.2.2.2 Instrument Synchronisation

This thesis used the time-setting signals. This method is mostly used over the internet to set the time on computers. The process is fast and easy to implement. The time synchronisation of instrument indicates the quality of the simple network time protocol (SNTP) connection. The connection supplies the instrument with world time either from a reference clock server, or from an Elspec power quality G4400 device serving as the reference clock. The display of the time synchronisation, as shown in Figure 5.3 below, is necessary for the PQZip coherent file generation.

Fig. 5.3: Web based remote display unit

A group of three power quality meters were installed for measurement, and synchronised by time-setting signals.

5.3. Measured Waveforms

To optimise the PQ analysis, IEC 61000-4-30 is used to define measurements. The plots shown in Fig. 5.4, 5.5 and 5.6 represent the measured waveforms of current collected by the power quality PQSCADA software.

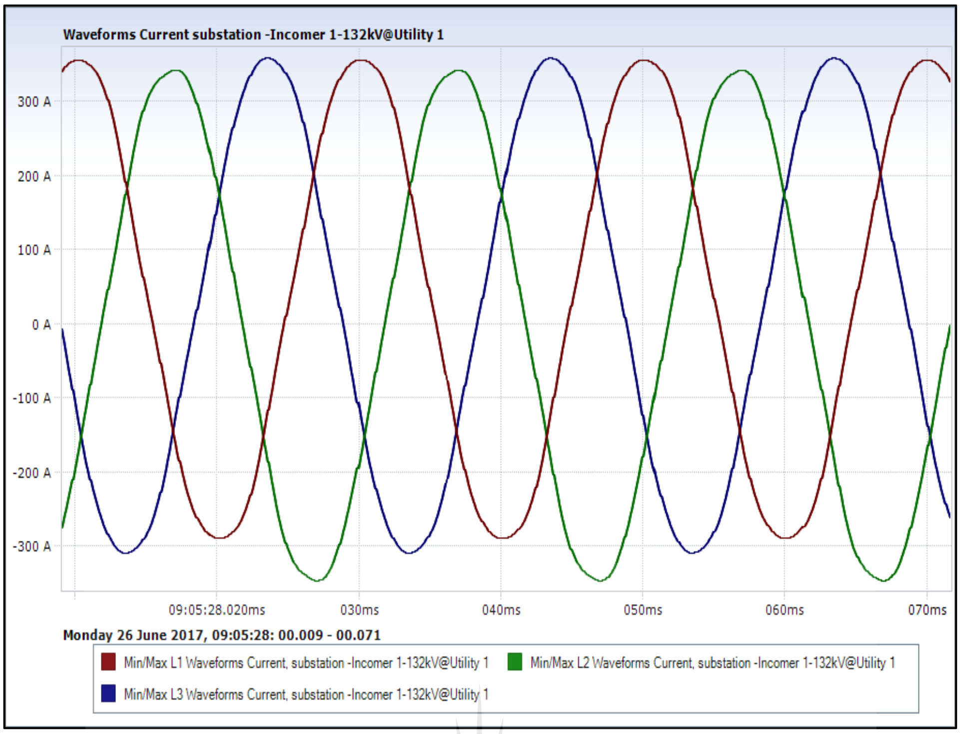


Fig. 5.4: Example of currents flowing in the incomer supplying power to substation bus

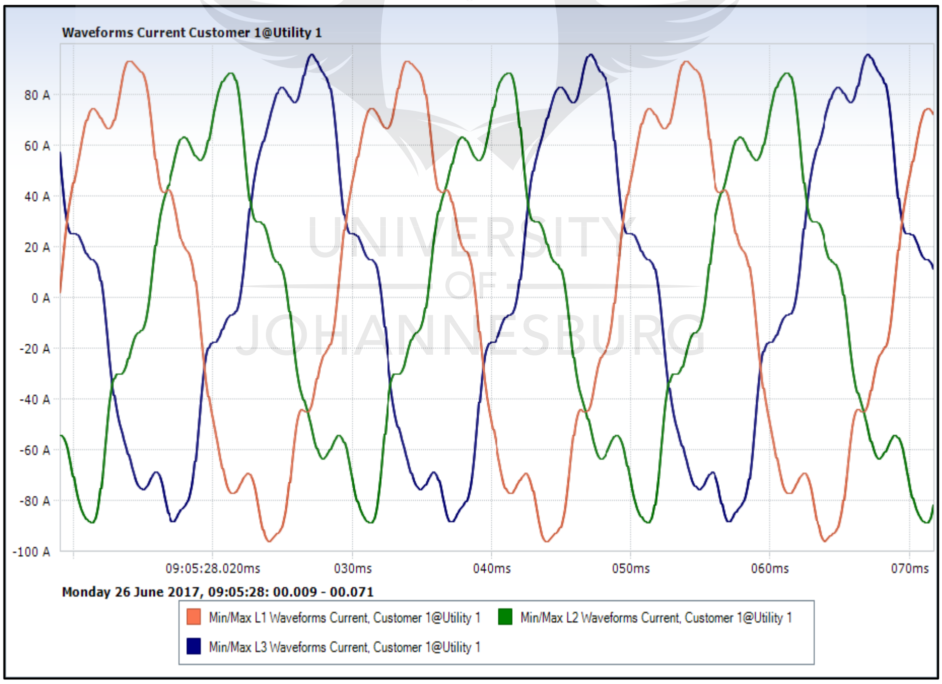


Fig. 5.5: Example of currents drawn by customer 1

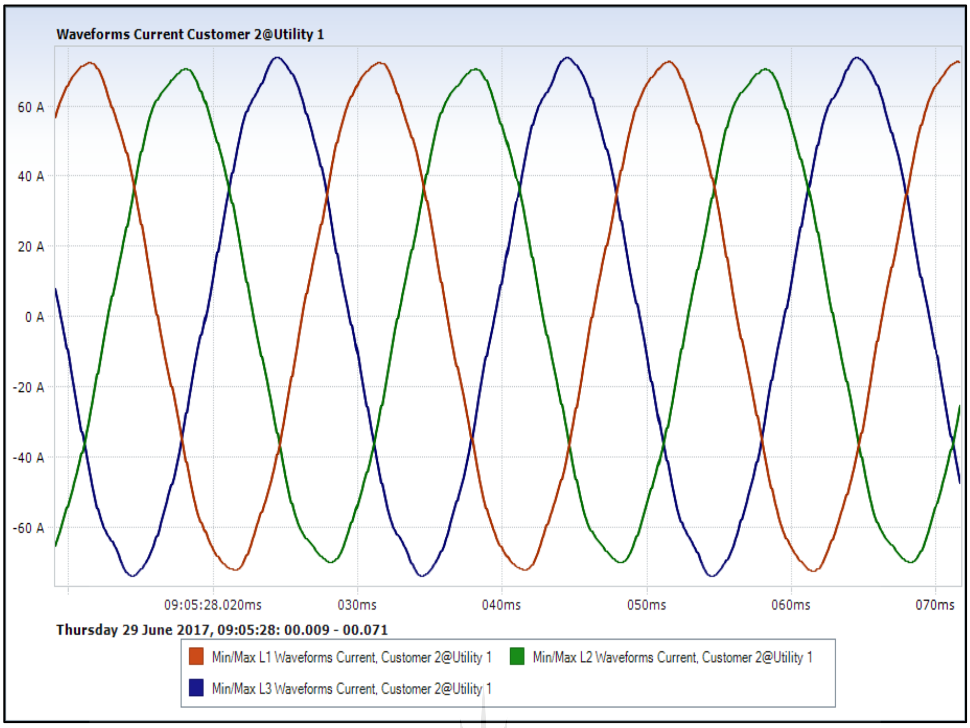


Fig. 5.6: Example of currents drawn by customer 2

5.4. Harmonic current and voltage amplitudes and power components

The magnitude of voltage and current and phase angle of harmonic order (5th, 7th, and 11th), both at the utility side and customer side are assessed by computing (4.6) and (4.7). Fourier coefficients, RMS voltages and currents, phase angle difference as well as IEEE Std 1459-2010, based voltages and current components are calculated using (4.10) -(4.12) and (2.28) - (2.30). Results in the three locations are presented in the appendices 1, 2 and 3. The following Tables 5.2, 5.3, 5.4 and 5.5 summarise the results for a single phase L1.

For the phase L1, Fourier analysis method provides Table 5.2 below:

Table 5.2: Fourier coefficients phase L1: Voltage- incomer/substation

index	a_n	b_n	c_n	α_n
1	108011.960	14855.358	109028.7355	82.1689902
5	-263.009	-980.693	1015.34846	15.0127057
7	-115.349	-133.858	176.7013185	40.75235032
11	-213.510	-90.292	231.8170946	67.07681199

Where a_n and b_n represent the Fourier coefficients;

c_n and α_n represent respectively the amplitude of the Fourier coefficients and phase angle.

The RMS amplitude for the phase L1 is calculated using (4.12) and results are as follows:

$V_1 = 77094.958$ V

$V_5 = 717.959$ V

$V_7 = 124.946$ V

$V_{11} = 163.919$ V

For the phase L1, Fourier analysis provides Table 5.3 below for current incomer supplying power to substation bus:

Table 5.3: Fourier coefficients phase L1: Current- incomer supplying power to substation bus

index	a_n	b_n	c_n	β_n
1	287.655	155.884	327.1776589	61.54615785
3	-2.965	-2.431	3.834186485	50.65171395
7	-1.686	-2.326	2.872781231	35.93646036
11	-10.298	9.496	14.0079556	-47.32020282

The RMS amplitude current for the phase L1 is calculated following (4.12) and results are as follows:

$I_1 = 231.349$ A

$I_5 = 2.711$ A

$I_7 = 2.031$ A

$I_{11} = 9.905$ A

At customer 1 side, Fourier analysis for the phase L1, is as the table 5.4 below:

Table 5.4: Fourier coefficients phase L1: Current-customer 1

index	a_n	b_n	c_n	β_n
1	-0.751	85.889	85.89228325	-0.500972579
5	-7.352	-1.509	7.505263819	78.40111324
7	3.839	-0.507	3.872333922	-82.4767331
11	1.946	-0.133	1.950539669	-86.09018153

The RMS amplitude current for the phase L1 is calculated following (4.12) and results are as follows:

$I_1 = 60.735$ A

$I_5 = 5.307$ A

$I_7 = 2.738$ A

$I_{11} = 1.379$ A

At customer 2 side, Fourier analysis provides for the phase L1 the table 5.5 below:

Table 5.5: Fourier coefficients phase L1: Current-customer 2

index	a_n	b_n	c_n	β_n
1	48.248	52.890	71.59065305	42.37210067
5	0.104	0.054	0.117183617	62.56027205
7	0.553	0.422	0.69562418	52.65237403
11	0.356	-0.658	0.748131005	-28.41486997

The RMS amplitude current for the phase L1 is calculated following (4.12) and results are as follows:

$I_1 = 50.622$ A

$I_5 = 0.082$ A

$I_7 = 0.492$ A

$I_{11} = 0.529\,\text{A}$

5.5. Dominant harmonic voltages and currents

The dominant harmonics were analysed using the frequency spectrums of the voltages and currents measured at the PCC as depicted in the Fig. 5.7 and 5.8 below together with the calculated values. These dominant harmonics have the larger magnitudes that the transducers were able to measure.

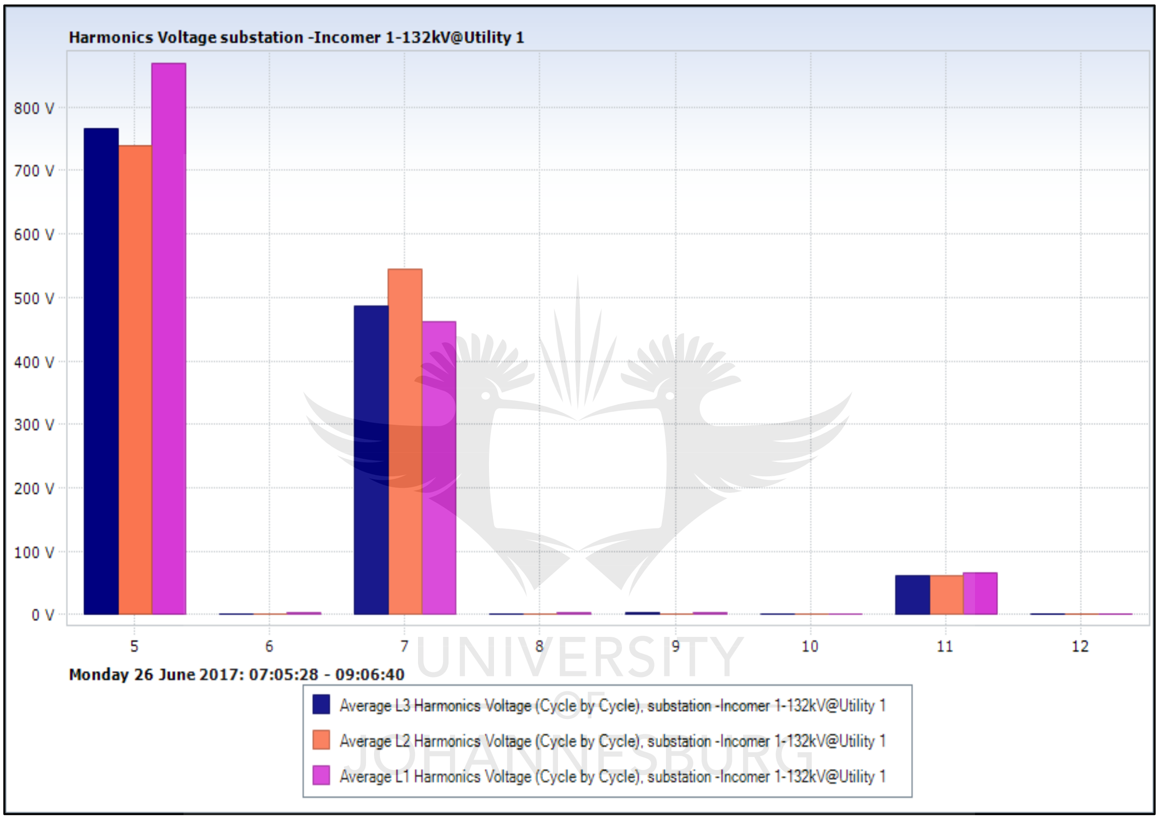


Fig. 5.7: Spectrum of harmonics voltage order at the PCC

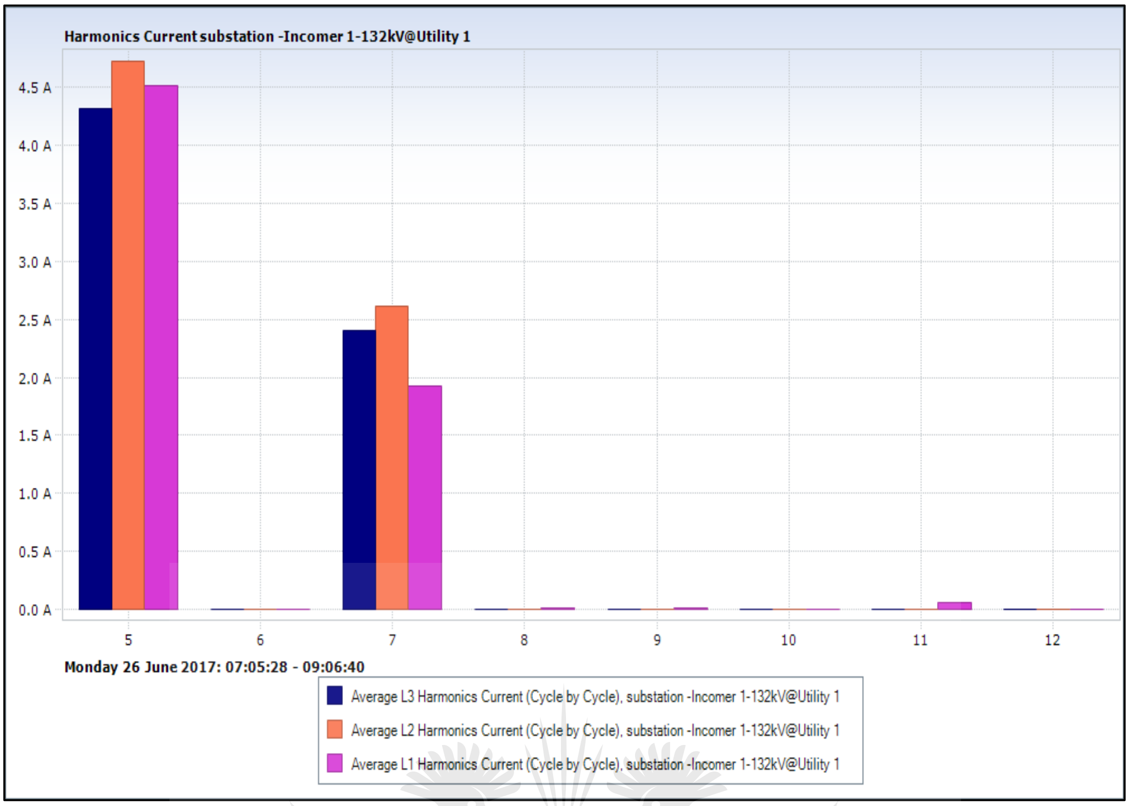


Fig. 5.8: Spectrum of current harmonics order/substation-incomer

An analysis of the frequency spectrum of the voltages and currents of Fig.5.7 and 5.8 above indicates that the 5th, 7th and 11th harmonic order are dominant. The 5th, 7th and 11th current harmonics drawn by the loads flow through impedances in the system and voltage harmonics are seen across the impedances at the PCC. It should be pointed out that other harmonic frequencies have also been found, but not analysed due to their insignificant values.

Therefore, only the dominant characteristic harmonics (5th, 7th and 11th harmonics) are evaluated. The magnitudes of dominant harmonics are calculated using (4.6), (4.7) and (4.12). Eq. (4.10) and (4.11) calculate the phase angle of voltage and current respectively. In the tables 5.6, 5.7, 5.8 and 5.9 below, $\alpha_a(h)$, $\alpha_b(h)$ and $\alpha_c(h)$ are respective voltage phase angles of line a, b and c where h is the harmonic order. $\beta_a(h)$, $\beta_b(h)$ and $\beta_c(h)$ are respective current phase angle of line a, b and c. $V_a(h)$, $V_b(h)$ and $V_c(h)$ are the voltage magnitude of respectively line a, b and c. $I_a(h)$, $I_b(h)$ and $I_c(h)$ are current magnitudes respectively of line a, b and c. h indicates harmonic order. All the results regarding the dominant harmonic components obtained are summarised in the tables 5.6, 5.7, 5.8 and 5.9 below:

Table 5.6: Dominant harmonic voltage magnitudes and phase angle at the PCC

h	$V_a(h)$	$\alpha_a(h)$	$V_b(h)$	$\alpha_b(h)$	$V_c(h)$	$\alpha_c(h)$
1	77094.95	82.169	77490.479	-37.944	77215.339	21.926
5	717.96	15.013	133.830	-68.267	617.924	12.785
7	124.94	40.752	673.035	-72.908	500.394	-50.660
11	163.91	67.077	445.283	-81.559	248.054	-76.825

Table 5.7: Dominant harmonic current magnitudes and phase angles at utility side

h	$I_a(h)$	$\beta_a(h)$	$I_b(h)$	$\beta_b(h)$	$I_c(h)$	$\beta_c(h)$
1	231.350	61.546	244.026	-59.314	233.557	-1.828
5	6.262	-70.213	2.706	-50.068	4.829	35.163
7	2.031	35.936	2.061	35.419	1.653	34.982
11	9.905	-47.320	1.715	-73.516	1.717	-65.788

Table 5.8: Dominant harmonic current magnitudes and phase angles towards customer 1

h	$I_a(h)$	$\beta_a(h)$	$I_b(h)$	$\beta_b(h)$	$I_c(h)$	$\beta_c(h)$
1	60.735	-0.501	53.011	62.680	59.999	-52.813
5	5.307	78.401	5.653	33.247	6.287	-28.892
7	2.738	-82.477	1.373	65.124	0.824	35.601
11	1.380	-86.090	0.587	77.404	0.712	86.757

Table 5.9: Dominant harmonic current magnitudes and phase angles towards customer 2

h	$I_a(h)$	$\beta_a(h)$	$I_b(h)$	$\beta_b(h)$	$I_c(h)$	$\beta_c(h)$
1	50.622	42.372	49.102	-76.818	50.510	-16.000
5	0.083	62.560	0.700	-57.854	1.050	-28.309
7	0.492	52.652	0.243	21.121	0.635	-44.729
11	0.529	-28.415	0.490	-4.062	0.485	10.081

5.6. Evaluation of Currents and Voltages Complex Components

This section evaluates the currents and voltages complex components needed to calculate the Thevenin equivalents impedance and source voltages described in paragraph 4.2. Measurements were carried out at both the utility and the two customers' sides. Appendix 3 shows the customer 1 results for 5th, 7th and 11th harmonic over time. Measurements for both utility and two customers (5th, 7th and 11th) are saved in the Microsoft excel files. To calculate the variables ($I_{\text{Re}-A}$, $I_{\text{Im}-A}$, $I_{\text{Re}-B}$ $I_{\text{Im}-B}, V_{\text{Re}-A}, V_{\text{Im}-A}, V_{\text{Re}-B}, V_{\text{Im}-B}$), we need first to determine the values of the following quantities in time instant A and time instant B:

$\text{Re}(I_{C1-A})$ $\qquad$ $\text{Im}(I_{C1-A})$

$\text{Re}(I_{C1-B})$ $\qquad$ $\text{Im}(I_{C1-B})$

For this exercise, we need to calculate phase angle and since currents, active power and reactive power values are measured, the above quantities can be calculated.

The two points in time instance A and B used are selected based on 10 minutes' data aggregate interval on voltage. This requirement applies to power quality instruments complying with IEC 61000-4-30 [47] as used in this work. The data aggregation interval is defined as "the time period over which the sampled data is combined to produce an average" [19] [47]. The range of aggregation intervals commonly used includes 3 seconds, 10 seconds, 10 minutes, 15 minutes, 1 hour and 2 hours. The non-appropriate selection of data aggregation interval can lead either to the loss of important detail due to the process of averaging of the RMS if this interval is too long or too large amounts of data, which is in reality difficult to assess if this interval is too short. The measurements were recorded at fundamental frequency and harmonic frequencies (5th, 7th and 11th) for every 10 minutes' aggregate interval. The results of this evaluation are developed below for customer 1, customer 2 and utility for single phase:

a) Customer 1:

Fundamental frequency:

At time instance A

The measured RMS active power, reactive power and current at time instance A recorded at 07:30:42.016 are as follows:

$P = 376626.6\,\text{W}$

$Q = -149268.7$ VAR

$I = 63.063$ A

The phase angle between reactive power and active power, $\theta = \tan^{-1}(\frac{Q}{P})$

Thus $\theta = -21.62°$

To determine a real part of a complex current of customer 1 ($\mathrm{Re}(I_{C1-A})$), we use RMS current as follows:

$\mathrm{Re}(I_{C1-A}) = I\cos\vartheta$

$\mathrm{Re}(I_{C1-A}) = 58.63$ A

Similarly, for the imaginary part of the complex current of customer 1 $\mathrm{Im}(I_{C1-A})$, we use RMS current as follows:

$\mathrm{Im}(I_{C1-A}) = I\sin\theta$

$\mathrm{Im}(I_{C1-A}) = -23.24$ A

At time instance B

The measured RMS values of active power, reactive power and current at time instance B recorded at 07:40:39.859 for the fundamental are as follows:

$P = 385001.6$ W

$Q = -146379$ VAR

$I = 63.73$ A

The phase angle between reactive power and active power, $\theta = \tan^{-1}(\frac{Q}{P})$

Thus $\theta = -20.82°$

To determine a current complex current of customer 1 $\mathrm{Re}(I_{C1-B})$, we use RMS current as follows:

$\mathrm{Re}(I_{C1-B}) = I\cos\vartheta$

$\mathrm{Re}(I_{C1-B}) = 59.57$ A

Similarly, for imaginary part of a complex current of Customer 1, $\mathrm{Im}(I_{C1-B})$, we use RMS current as follows:

$$\mathrm{Im}(I_{C1-B}) = I\sin\theta$$

$$\mathrm{Im}(I_{C1-B}) = -22.65 \text{ A}$$

The current complex components of customer 1 (Fig. 4.3) are calculated as:

$I_{\mathrm{Re}-A} = -\mathrm{Re}(I_{C1-A})$ = -58.63A $\qquad$ $I_{\mathrm{Im}-A} = -\mathrm{Im}(I_{C1-A})$ = 23.24A

$I_{\mathrm{Re}-B} = -\mathrm{Re}(I_{C1-B})$ = -59.57A $\qquad$ $I_{\mathrm{Im}-B} = -\mathrm{Im}(I_{C1-B})$ = 22.65A

The process used for current is applied to the measured voltage at the PCC to obtain the following results in time instances A and B:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A})$ = 6114.18V $\qquad$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A})$ = 1933.66V

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B})$ = 6124.46V $\qquad$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B})$ = 2027.49V

As stated earlier, due to a high amount of data, the measurement carried out at different locations of evaluation are computed and saved in the Microsoft excel files. The following results are obtained following the same process as for the fundamental frequency

5th Harmonic

The current complex components of customer 1 (Fig. 4.3) at fifth harmonic are calculated as:

$I_{\mathrm{Re}-A} = -\mathrm{Re}(I_{C1-A})$ = -0.09A $\qquad$ $I_{\mathrm{Im}-A} = -\mathrm{Im}(I_{C1-A})$ = -7.29A

$I_{\mathrm{Re}-B} = -\mathrm{Re}(I_{C1-B})$ = -0.80A $\qquad$ $I_{\mathrm{Im}-B} = -\mathrm{Im}(I_{C1-B})$ = -7.27A

Similarly, voltage complex components are defined as:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A})$ =45.85V $\qquad$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A})$ =57.56V

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B})$ = 64.06V $\qquad$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B})$ = 34.20V

7th Harmonic

The current complex components of customer 1 (Fig. 4.3) at seventh harmonic are calculated as:

$I_{\mathrm{Re}-A} = -\mathrm{Re}(I_{C1-A}) = -1.00\text{A}$ $I_{\mathrm{Im}-A} = -\mathrm{Im}(I_{C1-A}) = 1.51\text{A}$

$I_{\mathrm{Re}-B} = -\mathrm{Re}(I_{C1-B}) = -1.45\text{A}$ $I_{\mathrm{Im}-B} = -\mathrm{Im}(I_{C1-B}) = 1.25\text{A}$

Similarly, voltage complex components are defined as:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A}) = 39.36\text{V}$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A}) = 4.65\text{V}$

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B}) = 37.21\text{V}$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B}) = -9.30\text{V}$

11th Harmonic

The current complex components of customer 1 (Fig. 4.3) at 11th harmonic are calculated as:

$I_{\mathrm{Re}-A} = -\mathrm{Re}(I_{C1-A}) = -1.29\text{A}$ $I_{\mathrm{Im}-A} = -\mathrm{Im}(I_{C1-A}) = -1.96\text{A}$

$I_{\mathrm{Re}-B} = -\mathrm{Re}(I_{C1-B}) = -1.70\text{A}$ $I_{\mathrm{Im}-B} = -\mathrm{Im}(I_{C1-B}) = -1.50\text{A}$

Similarly, voltage components are calculated as:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A}) = 0$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A}) = 1.62\text{V}$

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B}) = 0$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B}) = 0$

b) Customer 2

Fundamental Frequency

The measured RMS active power, reactive power and current at time instance A recorded at 07:30:42.016 for the fundamental are as follows:

$P = 445697.4\,\text{W}$

$Q = 387364\,\text{VAR}$

$I = 54.4634\,\text{A}$

Whereas, the recorded data at 07:40:39.859 at time instance B are:

$P = 443041.6\,\text{W}$

$Q = 400518.9\,\text{VAR}$

$I = 54.93914\,\text{A}$

Similarly, to customer 1, an equivalent process is applied here to find the current components of customer 2.

The current complex components of customer 2 (Fig. 4.3) at fundamental frequency is calculated as:

$I_{\text{Re}-A} = -\text{Re}(I_{C1-A})$ = -41.11A $\quad$ $I_{\text{Im}-A} = -\text{Im}(I_{C1-A})$ = -26.97A

$I_{\text{Re}-B} = -\text{Re}(I_{C1-B})$ = -40.75A $\quad$ $I_{\text{Im}-B} = -\text{Im}(I_{C1-B})$ = -36.84A

Similarly, voltage complex components are calculated as:

$V_{\text{Re}-A} = \text{Re}(V_{PCC-A})$ = 6114.18V $\quad$ $V_{\text{Im}-A} = \text{Im}(V_{PCC-A})$ = 1933.66V

$V_{\text{Re}-B} = \text{Re}(V_{PCC-B})$ = 6124.46V $\quad$ $V_{\text{Im}-B} = \text{Im}(V_{PCC-B})$ = 2027.49V

5th Harmonic

The current complex components of customer 2 at fifth harmonic are calculated as:

$I_{\text{Re}-A} = -\text{Re}(I_{C1-A})$ = 0 $\quad$ $I_{\text{Im}-A} = -\text{Im}(I_{C1-A})$ = 0

$I_{\text{Re}-B} = -\text{Re}(I_{C1-B})$ = -0.06A $\quad$ $I_{\text{Im}-B} = -\text{Im}(I_{C1-B})$ = -0.10A

Similarly, to customer 1 an equivalent process is applied to fifth harmonic to determine the voltage complex components as follows:

$V_{\text{Re}-A} = \text{Re}(V_{PCC-A})$ = 45.85V $\quad$ $V_{\text{Im}-A} = \text{Im}(V_{PCC-A})$ = 57.56V

$V_{\text{Re}-B} = \text{Re}(V_{PCC-B})$ = 64.06V $\quad$ $V_{\text{Im}-B} = \text{Im}(V_{PCC-B})$ = 34.20V

7th Harmonic

The current complex components of customer 2 at seventh harmonic is calculated as:

$I_{\text{Re}-A} = -\text{Re}(I_{C1-A})$ = -0.50A $\quad$ $I_{\text{Im}-A} = -\text{Im}(I_{C1-A})$ = 0.82A

$I_{\text{Re}-B} = -\text{Re}(I_{C1-B})$ = -0.48A $\quad$ $I_{\text{Im}-B} = -\text{Im}(I_{C1-B})$ = 0.79A

Similarly, to customer 1 an equivalent process is applied to seventh harmonic to determine the voltage complex components as follows:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A})$ = 39.36V $\qquad V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A})$ = 4.65V

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B})$ = 37.21V $\qquad V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B})$ = -9.30V

11th Harmonic

The current complex components of customer 2 at 11th harmonic are calculated as:

$I_{\mathrm{Re}-A} = -\mathrm{Re}(I_{C1-A})$ = -0.02A $\qquad I_{\mathrm{Im}-A} = -\mathrm{Im}(I_{C1-A})$ = 0.19A

$I_{\mathrm{Re}-B} = -\mathrm{Re}(I_{C1-B})$ = 0 $\qquad I_{\mathrm{Im}-B} = -\mathrm{Im}(I_{C1-B})$ =0

Similarly, to customer 1 an equivalent process is applied to11th harmonic to determine the voltage complex components as follows:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A})$ =0 $\qquad V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A})$ = 1.62V

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B})$ =0 $\qquad V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B})$ = 0

c) Utility

The process of determining the Thevenin equivalent circuit parameters of utility has been explained in detail in chapter 4. This section calculates the values of the Thevenin equivalent impedances and sources voltage for the fundamental frequency and harmonic order (5th, 7th, 11th)

Fundamental Frequency

Taking into account the measurements of active power, reactive power and current at time instances A and B performed, the current complex components at utility side (Fig. 4.3) for fundamental frequency is calculated as:

$\mathrm{Re}(V_{PCC-A}) =$ 6114.18V

$\mathrm{Im}(V_{PCC-A}) =$ 1933.66V

$\mathrm{Re}(V_{PCC-B}) =$ 6124.46V

$\mathrm{Im}(V_{PCC-B}) = 2027.49\text{V}$

At the utility side, the current from the PCC to the utility is equal to the sum of customers' currents.

Therefore, the current components ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$, and $I_{\mathrm{Im}-B}$) and voltage components ($V_{\mathrm{Re}-A}$, $V_{\mathrm{Im}-A}$, $V_{\mathrm{Re}-B}$, and $V_{\mathrm{Im}-B}$) can be expressed as follows:

$I_{\mathrm{Re}-A} = \mathrm{Re}(I_{C1-A}) + \mathrm{Re}(I_{C2-A}) = 99.74\text{A}$ $I_{\mathrm{Im}-A} = \mathrm{Im}(I_{C1-A}) + \mathrm{Im}(I_{C2-A}) = 3.73\text{A}$

$I_{\mathrm{Re}-B} = \mathrm{Re}(I_{C1-B}) + \mathrm{Re}(I_{C2-B}) = 100.32\text{A}$ $I_{\mathrm{Im}-B} = \mathrm{Im}(I_{C1-B}) + \mathrm{Im}(I_{C2-B}) = 14.19\text{A}$

Similarly, voltage complex components are calculated as:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A}) = 6114.18\text{V}$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A}) = 1933.66\text{V}$

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B}) = 6124.46\text{V}$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B}) = 2027.49\text{V}$

5th Harmonic

The current components at the utility for fifth harmonic are given by:

$\mathrm{Re}(V_{PCC-A}) = 45.85\text{V}$

$\mathrm{Im}(V_{PCC-A}) = 57.56\text{V}$

$\mathrm{Re}(V_{PCC-B}) = 64.06\text{V}$

$\mathrm{Im}(V_{PCC-B}) = 34.20\text{V}$

Similarly, as for the fundamental frequency, the current from the PCC to the utility is equal to the sum of customers' currents.

Therefore, the current components ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$, and $I_{\mathrm{Im}-B}$) and voltage components ($V_{\mathrm{Re}-A}$, $V_{\mathrm{Im}-A}$, $V_{\mathrm{Re}-B}$, and $V_{\mathrm{Im}-B}$) can be expressed as follows:

$I_{\mathrm{Re}-A} = \mathrm{Re}(I_{C1-A}) + \mathrm{Re}(I_{C2-A}) = 0.09\text{A}$ $I_{\mathrm{Im}-A} = \mathrm{Im}(I_{C1-A}) + \mathrm{Im}(I_{C2-A}) = 7.29\text{A}$

$I_{\mathrm{Re}-B} = \mathrm{Re}(I_{C1-B}) + \mathrm{Re}(I_{C2-B}) = 0.86\text{A}$ $I_{\mathrm{Im}-B} = \mathrm{Im}(I_{C1-B}) + \mathrm{Im}(I_{C2-B}) = 7.37\text{A}$

Similarly, to the fundamental frequency an equivalent process is applied to fifth harmonic to determine the voltage complex components as follows:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A}) = 45.85\text{V}$ $\quad$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A}) = 57.56\text{V}$

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B}) = 64.06\text{V}$ $\quad$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B}) = 34.20\text{V}$

7th Harmonic

The current complex components at the utility for seventh harmonic are given by:

$\mathrm{Re}(V_{PCC-A}) = 39.36\text{V}$

$\mathrm{Im}(V_{PCC-A}) = 4.65\text{V}$

$\mathrm{Re}(V_{PCC-B}) = 37.21\text{V}$

$\mathrm{Im}(V_{PCC-B}) = -9.30\text{V}$

Similarly, the current from the PCC into utility is equal to the sum of customers' currents.

Therefore, the current components ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$, and $I_{\mathrm{Im}-B}$) and voltage components ($V_{\mathrm{Re}-A}$, $V_{\mathrm{Im}-A}$, $V_{\mathrm{Re}-B}$, and $V_{\mathrm{Im}-B}$) can be expressed as follows:

$I_{\mathrm{Re}-A} = \mathrm{Re}(I_{C1-A}) + \mathrm{Re}(I_{C2-A}) = 1.50\text{A}$ $\quad$ $I_{\mathrm{Im}-A} = \mathrm{Im}(I_{C1-A}) + \mathrm{Im}(I_{C2-A}) = -2.33\text{A}$

$I_{\mathrm{Re}-B} = \mathrm{Re}(I_{C1-B}) + \mathrm{Re}(I_{C2-B}) = 1.93\text{A}$ $\quad$ $I_{\mathrm{Im}-B} = \mathrm{Im}(I_{C1-B}) + \mathrm{Im}(I_{C2-B}) = -2.04\text{A}$

Similarly, to the fifth harmonic an equivalent process is applied to the seventh harmonic to determine the voltage complex components as follows:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A}) = 39.36\text{V}$ $\quad$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A}) = 4.65\text{V}$

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B}) = 37.21\text{V}$ $\quad$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B}) = -9.30\text{V}$

11th Harmonic

The current complex components at the utility side for 11th harmonic are given by:

$\mathrm{Re}(V_{PCC-A}) = 0$

$\mathrm{Im}(V_{PCC-A}) = 1.62\mathrm{V}$

$\mathrm{Re}(V_{PCC-B}) = 0$

$\mathrm{Im}(V_{PCC-B}) = 0$

Similarly, the current from the PCC to the utility is equal to the sum of customers' currents.

Therefore, the current components ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$, and $I_{\mathrm{Im}-B}$) and voltage components ($V_{\mathrm{Re}-A}$, $V_{\mathrm{Im}-A}$, $V_{\mathrm{Re}-B}$, and $V_{\mathrm{Im}-B}$) can be expressed as follows:

$I_{\mathrm{Re}-A} = \mathrm{Re}(I_{C1-A}) + \mathrm{Re}(I_{C2-A}) = 1.31\mathrm{A}$ $\qquad$ $I_{\mathrm{Im}-A} = \mathrm{Im}(I_{C1-A}) + \mathrm{Im}(I_{C2-A}) = 1.77\mathrm{A}$

$I_{\mathrm{Re}-B} = \mathrm{Re}(I_{C1-B}) + \mathrm{Re}(I_{C2-B}) = 1.70\mathrm{A}$ $\qquad$ $I_{\mathrm{Im}-B} = \mathrm{Im}(I_{C1-B}) + \mathrm{Im}(I_{C2-B}) = 1.50\mathrm{A}$

Similarly, to seventh harmonic an equivalent process is applied to 11th harmonic to determine the voltage complex components as follows:

$V_{\mathrm{Re}-A} = \mathrm{Re}(V_{PCC-A}) = 0$ $\qquad$ $V_{\mathrm{Im}-A} = \mathrm{Im}(V_{PCC-A}) = 1.62\mathrm{V}$

$V_{\mathrm{Re}-B} = \mathrm{Re}(V_{PCC-B}) = 0$ $\qquad$ $V_{\mathrm{Im}-B} = \mathrm{Im}(V_{PCC-B}) = 0$

5.7. Evaluation of Thevenin Equivalents Parameters

The Thevenin equivalent impedances and source voltages are evaluated on the basis of the variables ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$ $I_{\mathrm{Im}-B}, V_{\mathrm{Re}-A}, V_{\mathrm{Im}-A}, V_{\mathrm{Re}-B}, V_{\mathrm{Im}-B}$) developed in the paragraph 4.2 using (4.27). This section determines the values of the Thevenin equivalent circuits of the customers and utility

a) Customer 1

Fundamental frequency

The values of current complex components ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$ and $I_{\mathrm{Im}-B}$) of customer 1 at fundamental frequency and voltage complex components at the PCC ($V_{\mathrm{Re}-A}$, $V_{\mathrm{Im}-A}$, $V_{\mathrm{Re}-B}$ and $V_{\mathrm{Im}-B}$) in two times instances A and B are evaluated in the section 5.6 above. Using (4.27), the Thevenin equivalent circuit parameters can be expressed as follows:

$$V_{Th-\text{Re}} = \frac{\begin{vmatrix}\begin{pmatrix}6114.18 & 0 & -58.63 & -23.24\\ 6124.46 & 0 & -59.57 & -22.65\\ 1933.66 & 1 & 23.24 & -58.63\\ 2027.49 & 1 & 22.65 & -59.57\end{pmatrix}\end{vmatrix}}{|A|} \quad V_{Th-\text{Im}} = \frac{\begin{vmatrix}\begin{pmatrix}1 & 6114.18 & -58.63 & -23.24\\ 1 & 6124.46 & -59.57 & -22.65\\ 0 & 1933.66 & 23.24 & -58.63\\ 0 & 2027.49 & 22.65 & -59.57\end{pmatrix}\end{vmatrix}}{|A|}$$

$$R = \frac{\begin{vmatrix}\begin{pmatrix}1 & 0 & 6114.18 & -23.24\\ 1 & 0 & 6124.46 & -22.65\\ 0 & 1 & 1933.66 & -58.63\\ 0 & 1 & 2027.49 & -59.57\end{pmatrix}\end{vmatrix}}{|A|} \quad X = \frac{\begin{vmatrix}\begin{pmatrix}1 & 0 & -58.63 & 6114.18\\ 1 & 0 & -59.57 & 6124.46\\ 0 & 1 & 23.24 & 1933.66\\ 0 & 1 & 22.65 & 2027.49\end{pmatrix}\end{vmatrix}}{|A|}$$

Where:

R , represents the Thevenin equivalent resistance at fundamental frequency.

X The Thevenin equivalent reactance at fundamental frequency.

$|A|$, represents the determinant of the matrix A at fundamental frequency below:

$$A = \begin{pmatrix}1 & 0 & -58.63 & -23.24\\ 1 & 0 & -59.57 & -22.65\\ 0 & 1 & 23.24 & -58.63\\ 0 & 1 & 22.65 & -59.57\end{pmatrix}$$

$$|A| = -1.23$$

5th Harmonic

The Thevenin equivalent circuit parameters at 5th harmonic follow an equivalent process to that applied for the fundamental frequency with the values related to 5th harmonic calculated in the section 5.6 above as follows:

$$V_{Th-\text{Re}} = \frac{\begin{vmatrix}\begin{pmatrix}45.85 & 0 & -0.09 & 7.29\\ 64.06 & 0 & -0.80 & 7.27\\ 57.56 & 1 & -7.29 & -0.09\\ 34.20 & 1 & -7.27 & -0.80\end{pmatrix}\end{vmatrix}}{|A|} \quad V_{Th-\text{Im}} = \frac{\begin{vmatrix}\begin{pmatrix}1 & 45.85 & -0.09 & 7.29\\ 1 & 64.06 & -0.80 & 7.27\\ 0 & 57.56 & -7.29 & -0.09\\ 0 & 34.20 & -7.27 & -0.80\end{pmatrix}\end{vmatrix}}{|A|}$$

$$R=\frac{\left|\begin{pmatrix}1 & 0 & 45.85 & 7.29\\ 1 & 0 & 64.06 & 7.27\\ 0 & 1 & 57.56 & -0.09\\ 0 & 1 & 34.20 & -0.80\end{pmatrix}\right|}{|A|} \qquad X=\frac{\left|\begin{pmatrix}1 & 0 & -0.09 & 45.85\\ 1 & 0 & -0.80 & 64.06\\ 0 & 1 & -7.29 & 57.56\\ 0 & 1 & -7.27 & 34.20\end{pmatrix}\right|}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at the fifth harmonic.

The matrix A at fifth harmonic is given by:

$$A=\begin{pmatrix}1 & 0 & -0.09 & 7.29\\ 1 & 0 & -0.80 & 7.27\\ 0 & 1 & -7.29 & -0.09\\ 0 & 1 & -7.27 & -0.80\end{pmatrix}$$

$$|A| = -0.50$$

7th Harmonic

Similarly, to fifth harmonic, an equivalent process is applied to seventh harmonic. The Thevenin equivalent circuit parameters can be expressed using (4.27) as follows:

$$V_{Th-\mathrm{Re}}=\frac{\left|\begin{pmatrix}39.36 & 0 & -1.00 & -1.51\\ 37.21 & 0 & -1.45 & -1.25\\ 4.65 & 1 & 1.51 & -1.00\\ -9.30 & 1 & 1.25 & -1.45\end{pmatrix}\right|}{|A|} \qquad V_{Th-\mathrm{Im}}=\frac{\left|\begin{pmatrix}1 & 39.36 & -1.00 & -1.51\\ 1 & 37.21 & -1.45 & -1.25\\ 0 & 4.65 & 1.51 & -1.00\\ 0 & -9.30 & 1.25 & -1.45\end{pmatrix}\right|}{|A|}$$

$$R=\frac{\left|\begin{pmatrix}1 & 0 & 39.36 & -1.51\\ 1 & 0 & 37.21 & -1.25\\ 0 & 1 & 4.65 & -1.00\\ 0 & 1 & -9.30 & -1.45\end{pmatrix}\right|}{|A|} \qquad X=\frac{\left|\begin{pmatrix}1 & 0 & -1.00 & 39.36\\ 1 & 0 & -1.45 & 37.21\\ 0 & 1 & 1.51 & 4.65\\ 0 & 1 & 1.25 & -9.30\end{pmatrix}\right|}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at the seventh harmonic.

The matrix A at seventh harmonic is given by:

$$A = \begin{pmatrix} 1 & 0 & -1.00 & -1.51 \\ 1 & 0 & -1.45 & -1.25 \\ 0 & 1 & 1.51 & -1.00 \\ 0 & 1 & 1.25 & -1.45 \end{pmatrix}$$

$$|A| = -0.19$$

11th Harmonic

The Thevenin equivalent circuit parameters at 11th harmonic can be expressed using (4.27). The values related to 11th harmonic are calculated in the section 5.6 above.

$$V_{Th-\mathrm{Re}} = \frac{\left|\begin{pmatrix} 0 & 0 & -1.29 & 1.96 \\ 0 & 0 & -1.70 & 1.50 \\ 1.62 & 1 & -1.96 & -1.29 \\ 0 & 1 & -1.50 & -1.70 \end{pmatrix}\right|}{|A|} \qquad V_{Th-\mathrm{Im}} = \frac{\left|\begin{pmatrix} 1 & 0 & -1.29 & 1.96 \\ 1 & 0 & -1.70 & 1.50 \\ 0 & 1.62 & -1.96 & -1.29 \\ 0 & 0 & -1.50 & -1.70 \end{pmatrix}\right|}{|A|}$$

$$R = \frac{\left|\begin{pmatrix} 1 & 0 & 0 & 1.96 \\ 1 & 0 & 0 & 1.50 \\ 0 & 1 & 1.62 & -1.29 \\ 0 & 1 & 0 & -1.70 \end{pmatrix}\right|}{|A|} \qquad X = \frac{\left|\begin{pmatrix} 1 & 0 & -1.29 & 0 \\ 1 & 0 & -1.70 & 0 \\ 0 & 1 & -1.96 & 1.62 \\ 0 & 1 & -1.50 & 0 \end{pmatrix}\right|}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at 11th harmonic.

The matrix A at 11th harmonic is given by:

$$A = \begin{pmatrix} 1 & 0 & -1.29 & 1.96 \\ 1 & 0 & -1.70 & 1.50 \\ 0 & 1 & -1.96 & -1.29 \\ 0 & 1 & -1.50 & -1.70 \end{pmatrix}$$

$$|A| = -0.38$$

b) Customer 2

Customer 2 and customer 1 have the same components of the voltage at the PCC ($V_{\mathrm{Re}-A}$, $V_{\mathrm{Im}-A}$, $V_{\mathrm{Re}-B}$ and $V_{\mathrm{Im}-B}$) per harmonic since both are connected to the same PCC, but not the same current complex components ($I_{\mathrm{Re}-A}$, $I_{\mathrm{Im}-A}$, $I_{\mathrm{Re}-B}$ and $I_{\mathrm{Im}-B}$).

Fundamental frequency

The Thevenin equivalent circuit parameters at fundamental frequency can be expressed using (4.27) as follows:

$$V_{Th-\mathrm{Re}} = \frac{\left|\begin{pmatrix} 6114.18 & 0 & -41.11 & 26.97 \\ 6124.46 & 0 & -40.75 & 36.84 \\ 1933.66 & 1 & -26.97 & -41.11 \\ 2027.49 & 1 & -36.84 & -40.75 \end{pmatrix}\right|}{|A|}$$

$$V_{Th-\mathrm{Im}} = \frac{\left|\begin{pmatrix} 1 & 6114.18 & -41.11 & 26.97 \\ 1 & 6124.46 & -40.75 & 36.84 \\ 0 & 1933.66 & -26.97 & -41.11 \\ 0 & 2027.49 & -36.84 & -40.75 \end{pmatrix}\right|}{|A|}$$

$$R = \frac{\left|\begin{pmatrix} 1 & 0 & 6114.18 & 26.97 \\ 1 & 0 & 6124.46 & 36.84 \\ 0 & 1 & 1933.66 & -41.11 \\ 0 & 1 & 2027.49 & -40.75 \end{pmatrix}\right|}{|A|} \qquad X = \frac{\left|\begin{pmatrix} 1 & 0 & -41.11 & 6114.18 \\ 1 & 0 & -40.75 & 6124.46 \\ 0 & 1 & -26.97 & 1933.66 \\ 0 & 1 & -36.84 & 2027.49 \end{pmatrix}\right|}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at fundamental frequency.

The matrix A at fundamental frequency at customer 2 side is given by:

$$A = \begin{pmatrix} 1 & 0 & -41.11 & 36.97 \\ 1 & 0 & -40.75 & 36.84 \\ 0 & 1 & -26.97 & -41.11 \\ 0 & 1 & -36.84 & -40.75 \end{pmatrix}$$

$$|A| = 1.15$$

5th Harmonic

At fifth harmonic, the Thevenin equivalent circuit parameters of customer 2 can be expressed using (4.27) as follows:

$$V_{Th-\mathrm{Re}} = \frac{\left|\begin{pmatrix} 45.85 & 0 & 0 & 0 \\ 64.06 & 0 & -0.06 & 0.10 \\ 57.56 & 1 & 0 & 0 \\ 34.20 & 1 & -0.10 & -0.06 \end{pmatrix}\right|}{|A|} \qquad V_{Th-\mathrm{Im}} = \frac{\left|\begin{pmatrix} 1 & 45.85 & 0 & 0 \\ 1 & 64.06 & -0.06 & 0.10 \\ 0 & 57.56 & 0 & 0 \\ 0 & 34.20 & -0.10 & -0.06 \end{pmatrix}\right|}{|A|}$$

$$R = \frac{\left|\begin{pmatrix} 1 & 0 & 45.85 & 0 \\ 1 & 0 & 64.06 & 0.10 \\ 0 & 1 & 57.56 & 0 \\ 0 & 1 & 34.20 & -0.06 \end{pmatrix}\right|}{|A|} \qquad X = \frac{\left|\begin{pmatrix} 1 & 0 & 0 & 45.85 \\ 1 & 0 & -0.06 & 64.06 \\ 0 & 1 & 0 & 57.56 \\ 0 & 1 & -0.10 & 34.20 \end{pmatrix}\right|}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at fifth harmonic.

The matrix A at fifth harmonic at customer 2 is given by:

$$A = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & -0.06 & 0.10 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & -0.10 & -0.06 \end{pmatrix}$$

$$|A| = -0.01$$

7th Harmonic

At seventh harmonic, the Thevenin equivalent circuit parameters of customer 2 can be expressed using (4.27) as follows:

$$V_{Th-\mathrm{Re}} = \frac{\left|\begin{pmatrix} 39.36 & 0 & -0.50 & -0.82 \\ 37.21 & 0 & -0.48 & -0.79 \\ 4.65 & 1 & 0.82 & -0.50 \\ -9.30 & 1 & 0.79 & -0.48 \end{pmatrix}\right|}{|A|} \qquad V_{Th-\mathrm{Im}} = \frac{\left|\begin{pmatrix} 1 & 39.36 & -0.50 & -0.82 \\ 1 & 37.21 & -0.48 & -0.79 \\ 0 & 4.65 & 0.82 & -0.50 \\ 0 & -9.30 & 0.79 & -0.48 \end{pmatrix}\right|}{|A|}$$

$$R = \frac{\left|\begin{pmatrix} 1 & 0 & 39.36 & -0.82 \\ 1 & 0 & 37.21 & -0.79 \\ 0 & 1 & 4.65 & -0.50 \\ 0 & 1 & -9.30 & -0.48 \end{pmatrix}\right|}{|A|} \qquad X = \frac{\left|\begin{pmatrix} 1 & 0 & -0.50 & 39.36 \\ 1 & 0 & -0.48 & 37.21 \\ 0 & 1 & 0.82 & 4.65 \\ 0 & 1 & 0.79 & -9.30 \end{pmatrix}\right|}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at seventh harmonic.

The matrix A at seventh harmonic is given by:

$$A = \begin{pmatrix} 1 & 0 & -0.50 & -0.82 \\ 1 & 0 & -0.48 & -0.79 \\ 0 & 1 & 0.82 & -0.50 \\ 0 & 1 & 0.79 & -0.48 \end{pmatrix}$$

$$|A| = -0.0013$$

11th Harmonic

The Thevenin equivalent circuit parameters of customer 2 at fundamental frequency is expressed using (4.27) as follows:

$$V_{Th-\mathrm{Re}} = \frac{\left|\begin{pmatrix} 0 & 0 & -0.02 & -0.19 \\ 0 & 0 & 0 & 0 \\ 1.62 & 1 & 0.19 & -0.02 \\ 0 & 1 & 0 & 0 \end{pmatrix}\right|}{|A|} \qquad V_{Th-\mathrm{Im}} = \frac{\left|\begin{pmatrix} 1 & 0 & -0.02 & -0.19 \\ 1 & 0 & 0 & 0 \\ 0 & 1.62 & 0.19 & -0.02 \\ 0 & 0 & 0 & 0 \end{pmatrix}\right|}{|A|}$$

$$R = \frac{\left|\begin{pmatrix} 1 & 0 & 0 & -0.19 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1.62 & -0.02 \\ 0 & 1 & 0 & 0 \end{pmatrix}\right|}{|A|} \qquad X = \frac{\left|\begin{pmatrix} 1 & 0 & -0.02 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0.19 & 1.62 \\ 0 & 1 & 0 & 0 \end{pmatrix}\right|}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at 11^{th} harmonic at customer 2 side.

The matrix A at 11^{th} harmonic following the values of the currents complex components of customer 2 in two time instances A and B is as follows:

$$A = \begin{pmatrix} 1 & 0 & -0.02 & -0.19 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0.19 & -0.02 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

$$|A| = -0.036$$

c) Utility

The utility Thevenin equivalent circuit representation follows an equivalent process to that applied for customer 1 and customer 2.

Fundamental frequency

The Thevenin equivalent circuit parameters of the utility at fundamental frequency is expressed using (4.27) with the related values calculated in the section 5.6 above:

$$V_{Th-\mathrm{Re}} = \frac{\begin{vmatrix} \begin{pmatrix} 6114.18 & 0 & 99.74 & -3.73 \\ 6124.46 & 0 & 100.32 & -14.19 \\ 1933.66 & 1 & 3.73 & 99.74 \\ 2027.49 & 1 & 14.19 & 100.32 \end{pmatrix} \end{vmatrix}}{|A|}$$

$$V_{Th-\mathrm{Im}} = \frac{\begin{vmatrix} \begin{pmatrix} 1 & 6114.18 & 99.74 & -3.74 \\ 1 & 6124.46 & 100.32 & -14.19 \\ 0 & 1933.66 & 3.73 & 99.74 \\ 0 & 2027.49 & 14.19 & 100.32 \end{pmatrix} \end{vmatrix}}{|A|}$$

$$R = \frac{\begin{vmatrix} \begin{pmatrix} 1 & 0 & 6114.18 & -3.73 \\ 1 & 0 & 6124.46 & -14.19 \\ 0 & 1 & 1933.66 & 99.74 \\ 0 & 1 & 2027.49 & 100.32 \end{pmatrix} \end{vmatrix}}{|A|} \qquad X = \frac{\begin{vmatrix} \begin{pmatrix} 1 & 0 & 99.74 & 6114.18 \\ 1 & 0 & 100.32 & 6124.46 \\ 0 & 1 & 3.74 & 1933.66 \\ 0 & 1 & 14.19 & 2027.49 \end{pmatrix} \end{vmatrix}}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at fundamental frequency at utility side.

The matrix A at fundamental frequency following the values of the currents complex components of utility is as follows:

$$A = \begin{pmatrix} 1 & 0 & 99.74 & -3.73 \\ 1 & 0 & 100.32 & -14.19 \\ 0 & 1 & 3.73 & 99.74 \\ 0 & 1 & 14.19 & 100.32 \end{pmatrix}$$

$$|A| = -109.75$$

5th Harmonic

At the fifth harmonic, the Thevenin equivalent circuit parameters of the utility is expressed using (4.27). The values of complex components of current and voltage related to fifth harmonic are calcultated in the section 5.6 above.

$$V_{Th-\mathrm{Re}} = \frac{\begin{vmatrix} 45.85 & 0 & 0.09 & -7.29 \\ 64.06 & 0 & 0.86 & -7.37 \\ 57.56 & 1 & 7.29 & 0.09 \\ 34.20 & 1 & 7.37 & 0.86 \end{vmatrix}}{|A|} \qquad V_{Th-\mathrm{Im}} = \frac{\begin{vmatrix} 1 & 45.85 & 0.09 & -7.29 \\ 1 & 64.06 & 0.86 & -7.37 \\ 0 & 57.56 & 7.29 & 0.09 \\ 0 & 34.20 & 7.37 & 0.86 \end{vmatrix}}{|A|}$$

$$R = \frac{\begin{vmatrix} 1 & 0 & 45.85 & -7.29 \\ 1 & 0 & 64.06 & -7.37 \\ 0 & 1 & 57.56 & 0.09 \\ 0 & 1 & 34.20 & 0.86 \end{vmatrix}}{|A|} \qquad X = \frac{\begin{vmatrix} 1 & 0 & 0.09 & 45.85 \\ 1 & 0 & 0.86 & 64.06 \\ 0 & 1 & 7.29 & 57.56 \\ 0 & 1 & 7.37 & 34.20 \end{vmatrix}}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at fifth harmonic.

The matrix A at fifth harmonic following the values of the currents complex components of the utility is as follows:

$$A = \begin{pmatrix} 1 & 0 & 0.09 & -7.29 \\ 1 & 0 & 0.86 & -7.37 \\ 0 & 1 & 7.29 & 0.09 \\ 0 & 1 & 7.37 & 0.86 \end{pmatrix}$$

$$|A| = -0.60$$

7th Harmonic

The Thevenin equivalent circuit parameters of the utility at the seventh is expressed using (4.27). An equivalent process to fifth harmonic is applied. The complex components of current and voltage related to the seventh harmonic are calculated in the section 5.6 above.

$$V_{Th-\mathrm{Re}} = \frac{\left|\begin{pmatrix} 39.36 & 0 & 1.50 & 2.33 \\ 37.21 & 0 & 1.93 & 2.04 \\ 4.65 & 1 & -2.33 & 1.50 \\ -9.30 & 1 & -2.04 & 1.93 \end{pmatrix}\right|}{|A|} \qquad V_{Th-\mathrm{Im}} = \frac{\left|\begin{pmatrix} 1 & 39.36 & 1.50 & 2.33 \\ 1 & 37.21 & 1.93 & 2.04 \\ 0 & 4.65 & -2.33 & 1.50 \\ 0 & -9.30 & -2.04 & 1.93 \end{pmatrix}\right|}{|A|}$$

$$R = \frac{\left|\begin{pmatrix} 1 & 0 & 39.36 & 2.33 \\ 1 & 0 & 37.21 & 2.04 \\ 0 & 1 & 4.65 & 1.50 \\ 0 & 1 & -9.30 & 1.93 \end{pmatrix}\right|}{|A|} \qquad X = \frac{\left|\begin{pmatrix} 1 & 0 & 1.50 & 39.36 \\ 1 & 0 & 1.93 & 37.21 \\ 0 & 1 & -2.33 & 4.65 \\ 0 & 1 & -2.04 & -9.30 \end{pmatrix}\right|}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at the seventh harmonic.

The matrix A at seventh harmonic following the values of the currents components of the utility is as follows:

$$A = \begin{pmatrix} 1 & 0 & 1.50 & 2.33 \\ 1 & 0 & 1.93 & 2.01 \\ 0 & 1 & -2.33 & 1.50 \\ 0 & 1 & -2.04 & 1.93 \end{pmatrix}$$

$$|A| = -0.28$$

11th Harmonic

At the 11th harmonic, the Thevenin equivalent circuit parameters of the utility is expressed using (4.27). The values of complex components of current and voltage at the 11th harmonic are calculated in the section 5.6 above. This gives the following result:

$$V_{Th-\mathrm{Re}} = \frac{\left|\begin{pmatrix} 0 & 0 & 1.31 & -1.77 \\ 0 & 0 & 1.70 & -1.50 \\ 1.62 & 1 & 1.77 & 1.31 \\ 0 & 1 & 1.50 & 1.70 \end{pmatrix}\right|}{|A|} \qquad V_{Th-\mathrm{Im}} = \frac{\left|\begin{pmatrix} 1 & 0 & 1.31 & -1.77 \\ 1 & 0 & 1.70 & -1.50 \\ 0 & 1.62 & 1.77 & 1.31 \\ 0 & 0 & 1.50 & 1.70 \end{pmatrix}\right|}{|A|}$$

$$R = \frac{\begin{vmatrix}\begin{pmatrix}1 & 0 & 0 & -1.77\\ 1 & 0 & 0 & -1.50\\ 0 & 1 & 1.62 & 1.31\\ 0 & 1 & 0 & 1.70\end{pmatrix}\end{vmatrix}}{|A|} \qquad X = \frac{\begin{vmatrix}\begin{pmatrix}1 & 0 & 1.31 & 0\\ 1 & 0 & 1.70 & 0\\ 0 & 1 & 1.77 & 1.62\\ 0 & 1 & 1.50 & 0\end{pmatrix}\end{vmatrix}}{|A|}$$

Where $|A|$ represents the determinant of the matrix A at 11th harmonic.

The matrix A at 11th harmonic for utility is as follows:

$$A = \begin{pmatrix}1 & 0 & 1.31 & -1.77\\ 1 & 0 & 1.70 & -1.50\\ 0 & 1 & 1.77 & 1.31\\ 0 & 1 & 1.50 & 1.70\end{pmatrix}$$

$$|A| = -0.23$$

The results of the above calculations are summarised in the Tables 5.10 and 5.11 below.

Table 5.10: Thevenin equivalent impedances

Harmonic order	1st	5th	7th	11th
Utility	8.99-j0.483	20.25-j32.40	-17.75-j19.19	1.90-j2.74
Customer 1	-52.86-j66.77	-26.79+j32.44	24.18+j30.09	-1.96+j1.74
Customer 2	802.08-j117.60	124.34+j322.26	288.84-j264.23	8.55-j0.9

Table 5.11: Thevenin equivalent voltages sources

Harmonic order	1st	5th	7th	11th
Utility	5214.9+j1948.32	-192.27-j87.24	109.166-j8.09	-7.353+j1.81
Customer 1	1471.32-j750.20	-192.65-j134.32	125.582+j0.19	-5.956+j0.03
Customer 2	-4824.7-j1472.2	62.35+j78.28	-32.88-j364.31	0.007+j0.003

5.8. Evaluation of Contribution of Harmonic Current at the PCC

This section evaluates the contribution of harmonic current at the PCC between customers and the utility as described in section 4.3.

To generalise this evaluation to harmonic frequencies, the contribution of harmonic current at the PCC described in section 4.3 between the utility and customers can be calculated at any frequency by the following equations (5.1a), (5.1b) and (5.1c):

$$I_{C1-n-PCC} = \frac{V_{C1-n}}{Z_{C1-n} + \left(\frac{Z_{C2-n}.Z_{u-n}}{Z_{C2-n} + Z_{u-n}} \right)} \quad (5.1a)$$

$$I_{C2-n-PCC} = \frac{V_{C2-n}}{Z_{C2-n} + \left(\frac{Z_{C1-n}.Z_{u-n}}{Z_{C1-n} + Z_{u-n}} \right)} \quad (5.1b)$$

$$I_{u-n-PCC} = \frac{V_{u-n}}{Z_{u-n} + \left(\frac{Z_{C1-n}.Z_{C2-n}}{Z_{C1-n} + Z_{C2-n}} \right)} \quad (5.1c)$$

Where the subscripts,

$c_1 - n$ Denotes the Thevenin voltage and impedance of customer 1 at n_{th} harmonic order.

$c_1 - n - pcc$ Denotes the contribution of the customer 1 at the PCC at n_{th} harmonic order.

$c_2 - n$ Denotes the Thevenin voltage and impedance of customer 2 at n_{th} harmonic order.

$c_2 - n - pcc$ Denotes the contribution of the customer 2 at the PCC at n_{th} harmonic order.

$u - n$ Denotes the Thevenin voltage and impedance of utility at n_{th} harmonic order.

$u - n - pcc$ Denotes the harmonic current contribution of the utility at n_{th} harmonic order.

$n = 1,...$

Therefore, the contribution of harmonic current components will be expressed as follows:

5th Harmonic

The harmonic current contribution at the PCC of both customers and the utility at 5th, 7th and 11th harmonic can be expressed by using $n = 5$, $n = 7$ and $n = 11$ in (5.1a), (5.1b) and (5.1c) respectively.

Tables 5.10 and 5.11 are used to assess (5.1a) - (5.1c). Calculations made and saved in Microsoft excel files give the following results.

5th Harmonic

The harmonic current contribution at the PCC of customers 1 and 2 at the fifth harmonic gives:

$$I_{C1-5-PCC} = 137.92\angle 39.68°\ \text{A}$$

$$I_{C2-5-PCC} = 0.05\angle 48.18°\ \text{A}$$

The harmonic current contribution of the utility at the PCC leads to the following result:

$$I_{u-5-PCC} = 2.86\angle 36.48°\ \text{A}$$

7th Harmonic

The harmonic current contribution at the PCC of customers 1 and 2 at the seventh harmonic gives:

$$I_{C1-7-PCC} = 10.04\angle -51.46°\ \text{A}$$

$$I_{C2-7-PCC} = 0.84\angle -29.48°\ \text{A}$$

The harmonic current contribution of the utility at the PCC leads to the following result:

$$I_{u-7-PCC} = 2.09\angle -48.64°\ \text{A}$$

11th Harmonic

The harmonic current contribution at the PCC of customers 1 and 2 at the 11th harmonic gives:

$$I_{C1-11-PCC} = 164.94\angle 14.42°\ \text{A}$$

$$I_{C2-11-PCC} = 0$$

The harmonic current contribution of the utility at the PCC leads to the following result:

$$I_{u-11-PCC} = 0.99\angle 48.95^{\circ}\,\text{A}$$

The results of contribution of harmonic current at the PCC between the utility and two customers are summarised in Fig.5.9 below:

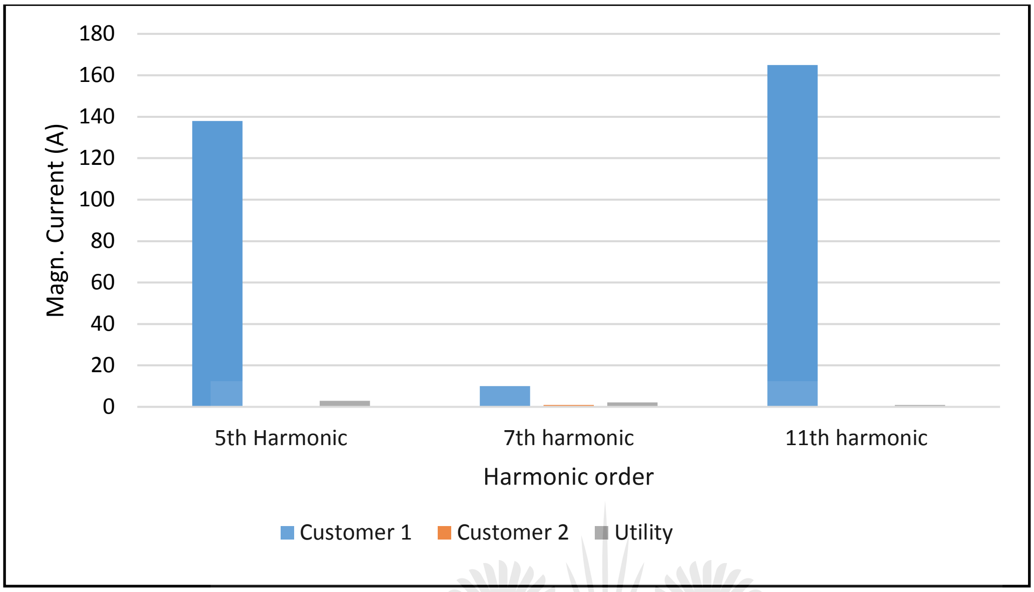


Fig. 5.9: Individual harmonic current contribution at the PCC

An analysis of the results obtained in Fig.5.8 above indicates that customer 1 is the main contributor. This outcome corroborates the results obtained from the measurements. In Fig. 5.5, the customer 1 current is considerably distorted while customer 2's current appears more sinusoidal.

5.9. Summary

A case study was carried out in this chapter to demonstrate the effectiveness of the proposed methodology for calculating the Thevenin equivalent impedance and sources voltages using two different times instances. The data analysis of measurements was conducted as well as numerical analysis. The numerical analysis was based on the current and voltage waveforms using IEEE 1459-2010 to determine the harmonic content. Based on the target harmonic order (5^{th}, 7^{th} and 11^{th}), the Thevenin equivalent impedances and source voltages for both the utility and two customers connected to the PCC was calculated. The Thevenin equivalent circuit parameters were calculated in two different points in time A and B selected based on 10 minutes' data aggregate interval on voltage. An assessment of the contribution of harmonic currents at the PCC between the utility and customers was also carried out in this chapter. The assessment per harmonic was conducted by applying the principle of superposition to the Thevenin equivalent circuit of both the utility and customers. The identification of the main contributor was achieved using the value of harmonic current contribution at the PCC between the utility and the two customers. The study found that customer 1 was the main contributor of harmonics at the PCC for the 5th, 7th and 11th harmonic. The next chapter is an analysis and interpretation of the results obtained in this chapter.

Chapter 6: Discussion of Results and Conclusion

6.1. Introduction

This chapter analyses and interprets the results obtained in chapter 5. It also discusses the usefulness of the dominant harmonic order analysis and the Thevenin harmonic impedances and sources voltages characteristics, as well as the contributions of harmonic currents. Additionally, it discusses the strengths of the proposed methodology.

6.2. Discussion of Results

6.2.1 Instrument setup

The instruments were setup according to the recommendations of IEC 61000-4-30 [47] and NRS 048-2 [49], time synchronised and connected to the network. The PQ instruments in differents points of measurement were synchronized in order to compare the measured data in real time. During the measurements, the time was set via the internet. The implementation is simple and requires only a dedicated software and internet connection. The process was achieved via the power quality PQCADA and PQElspec software.

6.2.2. Dominant Harmonic Order

Prior to the evaluation of the Thevenin equivalent impedances and sources voltages, the dominant harmonics were investigated based on the magnitudes of harmonics currents. Analysis of the spectrums of voltages and currents measured in Fig. 5.6 and Fig. 5.7 as well as the calculated values indicated the presence of the dominant harmonic orders, the 5^{th}, 7^{th} and 11^{th} at the PCC. These harmonics represent currents with higher frequency components that the transducers could measure with high accuracy level. The currents and voltage transformers used are manufactured primarily for the fundamental frequency. According to the literature, a lower accuracy level should be expected at higher frequencies with smaller harmonic magnitudes [33] [110]. Therefore, only dominants harmonics order with the larger magnitudes were investigated in order to obtain a good result with negligible error. The harmonics found at the PCC are the result of currents drawn by the loads and flowing through impedances in the system. Other harmonics were also found, but their magnitudes were smaller and therefore negligible.

6.2.3. Aggregate data interval and measurement accuracy

The two points in time "A" and "B" were selected based on a 10 minutes' data aggregate interval on voltage. Among the ranges of aggregation intervals commonly used are, 3 seconds, 19 seconds, 10 minutes, 15 minutes, 1 hour and 2 hours [19] [47]. Appropriate data aggregation interval plays a key function in data measurements. Due to the process of averaging the RMS values, a long interval can lead to the loss of an important detail of current and voltage measurement, whereas a considerably short aggregation data interval can lead to excessive amounts of measurement data, which might be difficult to assess. The 10 minutes of aggregation interval were enough for the reliability and accuracy of the data assessment. The analysis of data recorded by the PQElspec meters showed that beyond 10 minutes' period interval, the recorded RMS values was either too close and making tough the process of data assessment or subjected in losing an important detail of RMS averaging [19].

6.2.4. Load line between two different points in time of a real power system

Before establishing the linear model of the Thevenin equivalent circuit parameters, this study demonstrated that determining V_{Th} by extrapolation and then R_{Th} by the slope of the load line is valid in a network where the Thevenin equivalent impedance is purely resistive. It illustrates the concept of having two work points ("A" and "B"). It cannot be used in a practical installation with reactance. Traditionally, a load connected to a circuit has a Thevenin equivalent determined by its open circuit voltage and its short circuit. However, this is difficult in practical installations. This thesis found that between two different points in time A and B, for a power system with reactance, a load might vary during a normal operation. Therefore, the Thevenin equivalent circuit parameters can be determined by using a load operating at time instance A and waiting for the load to change at time instance B to obtain voltages and currents.

6.2.5. Contribution of Harmonic Currents at the PCC

Prior to the evaluation of the contribution of harmonics at the PCC, this thesis assessed the Thevenin equivalent impedances and source voltages of customers and utility. The load of customer 1 consisted of several fluorescent lamps, which might have influenced the characteristics of harmonic impedances evaluated.

The contribution of harmonic current at the PCC depends on the harmonic impedance, which varies over the time. In practice a certain range of the total utility and customer equivalent harmonic impedance needs to be considered. This study found that the harmonic current contribution at the PCC depends on the equivalent harmonic impedance of customers and utility as well as the range of harmonic voltage associated for each harmonic value considered. Therefore, the larger the combined utility and customer equivalent harmonic impedance, the less the contribution of harmonic current at the PCC. Analysis of the individual harmonic current (5^{th}, 7^{th} and 11^{th}) indicated that customer 1 is the main contributor at the PCC. This latter result is qualitatively confirmed by the current drawn by customer 1 in Fig. 5.5, as it shows more distortion than that of customer 2.

6.2.6. Usefulness of the Proposed Methodology

The proposed methodology provides a useful evaluation of the Thevenin equivalent impedance and source voltages by the measurement of harmonic voltage, harmonic current without using the harmonic current injection processes.

6.2.7. Summary

The determination of the Thevenin equivalent impedance and source voltages of customers and utility were assessed using two operating points in time called "time A" and "time B". Instead of injecting currents, measurements were taken after waiting for the loads to change. Instruments were setup according to IEC 61000-4-30 and NRS 048-12, timed synchronised and connected to the network. The selection of the two points in time A and B was based on 10 minutes' data aggregate interval on voltage and current. This time interval was enough to handle the reliability and the accuracy of the data measurement. Prior to the evaluation of the Thevenin equivalent parameters, the dominant harmonic order was assessed. It was found that the 5^{th}, 7^{th}, and 11^{th} injected at the PCC were significant, while other harmonics magnitudes were found to be smaller and negligible. The analysis of the 5^{th}, 7^{th} and 11^{th} harmonic order indicated that customer 1 was the main contributor of harmonics at the PCC.

6.3 Conclusion and Future Work

6.3.1. Conclusion

This study sought to determine the respective contributions of harmonics at the PCC between the utility and end users. It proceeded by developing a methodology for determining the parameters of the Thevenin equivalent circuits at different points in time "A" and "B". IEEE 1459-2010 deals with one measurement slice in time, and cannot provide the Thevenin equivalents necessary to determine harmonic contribution at the PCC. Hence, the study rather looked at the voltage and current at the PCC at different times. Before establishing this model, this thesis demonstrated that determining V_{Th} by extrapolation and then R_{Th} by the slope of the load line is only valid in the network where the Thevenin equivalent impedance is purely resistive and cannot unfortunately be used in practical installation with reactance. The methodology proposed in this thesis is as follows:

a. Determine the dominant harmonics at the PCC by selecting the larger magnitudes of high frequency components that the transducers could measure with accuracy. Better results were obtained with harmonics having larger magnitudes at lower frequencies since the transducers are mostly manufactured to measure the fundamental frequency.
b. Determine the Thevenin equivalent circuit per dominant harmonic by selecting two operating points in time (i.e time A and time B) for both the utility and customers when loads change.
c. Determine the main contributor of harmonics at the PCC per harmonic number by applying the principle of superposition to the Thevenin equivalents.

The analysis conducted in the network involved two customers, a sport stadium and Johannesburg metropolitan company connected to the utility. It was shown that the 5^{th}, 7^{th} and 11^{th} harmonic order were injected to the PCC from customers to the utility. In the case study, the corresponding Thevenin equivalent circuits showed that the sport stadium was the main contributor of harmonics at the PCC.

The study supported its findings using the concepts of power theories definitions, harmonics identification methods based on power flow and on voltage-current used in power systems, measurement techniques and instruments, as discussed in chapter 2. Harmonics in power systems, their associated problems, effects and standards dealing with harmonic distortion were presented in chapter 3. Chapter 4 dealt with the design process of the model for determining the Thevenin equivalent circuit impedance and voltage sources, and described the important steps and different points in time. Chapter 5 proposed a practical case of real installation to demonstrate the application of the model used. A discussion of results obtained were presented in chapter 6, as well as the conclusion about this study and the recommendation for the future research.

6.3.2. Future Work

- The measurements in this study focused on single-phase analysis even if the PQSCADA instruments carried out measurements both in single and three phases. The proposed methodology however can be extended to three-phase systems. This might allow for different results in the behaviour of the Thevenin equivalent circuit impedance and voltage sources.

- In general, the currents drawn by non-linear loads might not be in phase with each other. These harmonic currents can possibly interact in a different manner, which causes the harmonic impedance of the power system to vary in time. As observed in this study, the resistive part of the impedance can vary up to the negative value for some harmonic frequencies. Therefore, a complete evaluation of the characteristics of these non-linear loads might be required in the future.
- The contribution of harmonic currents at the PCC has always been attributed to the end users, and not to the power utility. Heavy harmonic current interaction between two or more end users make the assessment of the main contributor more complicated in power systems. An accurate measurement of harmonic current using the method of this study can shed light on the contribution of harmonic currents at the PCC between two or more end users with interacting loads currents.

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APPENDICES

Appendix 1

Substation 132 kV/11 kV- Incomer: Harmonic analysis

a) Voltage measurement

Incomer

Harmonic analysis gives the following results in the table below for harmonic voltage components:

Phase a (L1): Voltage

index	a_n	b_n	c_n	α_n	V_{rms}
1	108011.960	14855.358	109028.7355	82.1689902	77094.95822
5	-263.009	-980.693	1015.34846	15.0127057	717.959781
7	-115.349	-133.858	176.7013185	40.75235032	124.9467006
11	-213.510	-90.292	231.8170946	67.07681199	163.9194396

Phase b (L2): Voltage

index	a_n	b_n	c_n	α_n	V_{rms}
1	-67384.820	86422.420	109588.0862	-37.94406162	77490.47892
5	-175.812	70.080	189.2645391	-68.26739803	133.830239
7	909.776	-279.748	951.8147476	-72.90780425	673.0346624
11	622.904	-92.435	629.7250372	-81.55926718	445.2828441

Phase c (L3): Voltage

index	a_n	b_n	c_n	α_n	V_{rms}
1	-40775.830	-101300.290	109198.9792	21.9259842	77215.33872
5	193.389	852.209	873.8761268	12.78541405	617.9237352
7	-547.300	448.609	707.663285	-50.65932889	500.3935076
11	-341.569	79.954	350.8019725	-76.82548746	248.0544536

b) Current measurement:

Harmonic analysis gives the following results in the table below:

Phase a-L1: Current

index	a_n	b_n	c_n	α_n	I_{rms}
1	287.655	155.884	327.1776589	61.54615785	231.3495413
5	8.333	-2.998	8.855895946	-70.21256785	6.262064077
7	-1.686	-2.326	2.872781231	35.93646036	2.031363089
11	-10.298	9.496	14.0079556	-47.32020282	9.905120393

Phase b-L2: Current

Index	a_n	b_n	c_n	α_n	I_{rms}
1	-296.783	176.117	345.1048345	-59.31425423	244.0259687
5	2.934	-2.456	3.826263451	-50.06788911	2.705576833
7	1.689	2.375	2.914334572	35.4188355	2.060745739
11	2.325	-0.688	2.424658533	-73.51577803	1.714492491

Phase c-L3: Current

Index	a_n	b_n	c_n	α_n	I_{rms}
1	10.537	-330.132	330.3001147	-1.828119489	233.557451
5	3.933	5.583	6.829229678	35.16316266	4.828994616
7	1.340	1.915	2.337268705	34.98197888	1.652698551
11	-2.215	0.996	2.428629449	-65.7883901	1.717300352

The following harmonic voltages and currents were obtained with harmonic analysis method of Fourier series coefficients: The rms amplitude voltage, current and phase angle is calculated following (4.12) and results are as follows:

a) For Voltage

Va_1 = 77094.95822 Vb_1 = 77490.47892 Vc_1 = 77215.33872

Va_5 = 717.959781 Vb_5 = 133.830239 Vc_5 = 617.9237352

Va_7 = 124.9467006 Vb_7 = 673.0346624 Vc_7 = 500.3935076

Va_{11} = 163.9194396 Vb_{11} = 445.2828441 Vc_{11} = 248.0544536

θaV_1 = 82.1689902 θbV_1 = -37.94406162 θcV_1 = 21.9259842

θaV_5 = 15.0127057 θbV_5 = -68.26739803 θcV_5 = 12.78541405

θaV_7 = 40.75235032

θbV_7 = -72.90780425

θcV_7 = -50.65932889

θaV_{11} = 67.07681199

θbV_{11} = -81.55926718

θcV_{11} = -76.82548746

b) For current

Ia_1 = 231.3495413

Ib_1 = 244.0259687

Ic_1 = 233.557451

Ia_5 = 6.262064077

Ib_5 = 2.705576833

Ic_5 = 4.828994616

Ia_7 = 2.031363089

Ib_7 = 2.060745739

Ic_7 = 1.652698551

Ia_{11} = 9.905120393

Ib_{11} = 1.714492491

Ic_{11} = 1.717300352

θaI_1 = 61.54615785

θbI_1 = -59.31425423

θcI_1 = -1.828119489

θaI_5 = -70.21256785

θbI_5 = -50.06788911

θcI_5 = 35.16316266

θaI_7 = 35.93646036

θbI_7 = 35.4188355

θcI_7 = 34.98197888

θaI_{11} = -47.32020282

θbI_{11} = -73.51577803

θcI_{11} = -65.7883901

c) Phase angle

Phase a	Phase b	Phase c
θa_1 = 20.6228323	θb_1 = 21.37019261	θc_1 = 23.75410369
θa_5 = 85.225273	θb_5 = -18.19950892	θc_5 = -22.37774861
θa_7 = 4.81588996	θb_7 = -108.3266398	θc_7 = -85.64130777
θa_{11} = 114.3970148	θb_{11} = -8.04348915	θc_{11} = -11.03709736

IEEE 1459-2010: Voltage and Current indices

The following rms voltages and currents were obtained for each phase
Phase a (L1):

$$V_a = \sqrt{(Va_1^{\,2} + Va_5^{\,5} + Va_7^{\,2} + Va_{11}^{\,2})}$$

Va = 77098.93687

$$Ia = \sqrt{(Ia_1^{\,2} + Ia_5^{\,2} + Ia_7^{\,2} + Ia_{11}^{\,2})}$$

Ia = 231.6709132

Phase b (L2):

$$Vb = \sqrt{(Vb_1{}^2 + Vb_5{}^2 + Vb_7{}^2 + Vb_{11}{}^2)}$$

$$Vb = 77504.09967$$

$$Ib = \sqrt{(Ib_1{}^2 + Ib_5{}^2 + Ib_7{}^2 + Ib_{11}{}^2)}$$

$$Ib = 244.072213$$

Phase c (L3):

$$Vc = \sqrt{(Vc_1{}^2 + Vc_5{}^2 + Vc_7{}^7 + Vc_{11}{}^2)}$$

$$Vc = 77228.63692$$

$$Ic = \sqrt{(Ic_1{}^2 + Ic_5{}^2 + Ic_7{}^2 + Ic_{11}{}^2)}$$

$$Ic = 233.6397767$$

Appendix 2

Customer 1: Harmonic analysis

a) Voltage measurement

Harmonic analysis gives the following results in the table below for harmonic voltage components:

Phase a: Voltage-customer 1

index	a_n	b_n	c_n	α_n	V_{rms}
1	-3359.281	8340.694	8991.770973	-21.93750407	6358.14223
5	47.926	-9.416	48.84222079	-78.88469841	34.53666553
7	48.555	-56.419	74.43582193	-40.71575865	52.63407445
11	36.278	35.819	50.98131074	45.36476424	36.04923054

Phase b-L2: Voltage-customer 1

index	a_n	b_n	c_n	α_n	V_{rms}
1	-5584.078	-7121.402	9049.657096	38.10092454	6399.0739
5	13.085	0.543	13.09626183	87.62370899	9.26045555
7	-11.669	32.358	34.39775756	-19.83040884	24.32288763
11	-42.614	-8.612	43.47550506	78.57479482	30.74182444

Phase c-L3: Voltage

index	a_n	b_n	c_n	α_n	V_{rms}
1	8917.948	-1234.241	9002.952148	-82.12033921	6366.048514
5	-80.554	-15.795	82.0879342	78.90620984	58.04493493
7	-2.593	24.890	25.02470278	-5.947527251	17.69513703
11	8.357	-7.952	11.53575975	-46.42252882	8.157013945

a) Current measurement

Harmonic analysis gives the following results in the table below for harmonic current components:

Phase a-L1: Current

index	a_n	b_n	c_n	α_n	I_{rms}
1	-0.751	85.889	85.89228325	-0.500972579	60.73501594
5	-7.352	-1.509	7.505263819	78.40111324	5.307022941
7	3.839	-0.507	3.872333922	-82.4767331	2.738153575
11	1.946	-0.133	1.950539669	-86.09018153	1.379239827

Phase b-L2: Current

Index	a_n	b_n	c_n	α_n	I_{rms}
1	-66.607	-34.408	74.96934649	62.67992233	53.01133328
5	4.383	6.686	7.994578475	33.24680136	5.653020653
7	-1.762	-0.817	1.942197982	65.12389962	1.373341363
11	0.810	0.181	0.829976506	77.40380314	0.586882015

Phase c-L3: Current

Index	a_n	b_n	c_n	α_n	I_{rms}
1	67.598	-51.286	84.8513017	-52.81273357	59.99893082
5	4.296	-7.785	8.891672565	-28.89125102	6.287361967
7	0.678	0.947	1.164685795	35.6005836	0.823557223
11	-1.006	-0.057	1.007613517	86.7570862	0.712490351

The following harmonic voltages and currents were obtained with harmonic analysis method of Fourier series coefficients:

d) For Voltage

$Va_1 =$ 6358.14223
$Vb_1 =$ 6399.0739
$Vc_1 =$ 6366.048514

$Va_5 =$ 34.53666553
$Vb_5 =$ 9.26045555
$Vc_5 =$ 58.04493493

$Va_7 =$ 52.63407445
$Vb_7 =$ 24.32288763
$Vc_7 =$ 17.69513703

$Va_{11} =$ 36.04923054
$Vb_{11} =$ 30.74182444
$Vc_{11} =$ 8.157013945

$\theta aV_1 =$ -21.93750407
$\theta bV_1 =$ 38.10092454
$\theta cV_1 =$ -82.12033921

$\theta aV_5 =$ -78.88469841
$\theta bV_5 =$ 87.62370899
$\theta cV_5 =$ 78.90620984

θaV_7 = -40.71575865 θbV_7 = -19.83040884 θcV_7 = -5.947527251

θaV_{11} = 45.36476424 θbV_{11} = 78.57479482 θcV_{11} = -46.42252882

e) For current

Ia_1 = 60.73501594 Ib_1 = 53.01133328 Ic_1 = 59.99893082

Ia_5 = 5.307022941 Ib_5 = 5.653020653 Ic_5 = 6.287361967

Ia_7 = 2.738153575 Ib_7 = 1.373341363 Ic_7 = 0.823557223

Ia_{11} = 1.379239827 Ib_{11} = 0.586882015 Ic_{11} = 0.712490351

θaI_1 = -0.500972579 θbI_1 = 62.67992233 θcI_1 = -52.81273357

θaI_5 = 78.40111324 θbI_5 = 33.24680136 θcI_5 = -28.89125102

θaI_7 = -82.4767331 θbI_7 = 65.12389962 θcI_7 = 35.6005836

θaI_{11} = -86.09018153 θbI_{11} = 77.40380314 θcI_{11} = 86.7570862

f) Phase angle

Phase a	Phase b	Phase c
θa_1 = -21.43653149	θb_1 = -24.57899779	θc_1 = -29.30760564
θa_5 = -157.2858117	θb_5 = 54.37690763	θc_5 = 107.7974609
θa_7 = 41.76097445	θb_7 = -84.95430846	θc_7 = -41.54811085
θa_{11} = 131.4549458	θb_{11} = 1.17099168	θc_{11} = -133.179615

IEEE 1459-2010 Voltage and Current indices

The following RMS voltages and currents were obtained for each phase
Phase a:

$$V_a = \sqrt{(Va_1{}^2 + Va_5{}^5 + Va_7{}^2 + Va_{11}{}^2)}$$
$$Va = 6359.155968$$

$$Ia = \sqrt{(Ia_1{}^2 + Ia_5{}^2 + Ia_7{}^2 + Ia_{11}{}^2)}$$

$$Ia = 61.05034467$$

Appendix 3

Customer 2: Harmonic analysis

a) Voltage measurement

Harmonic analysis gives the following results in the table below for harmonic voltage components:

Phase a-L1: Voltage-customer 2

index	a_n	b_n	c_n	α_n	V_{rms}
1	15236.498	1309.376	15292.6563	85.0882512	10813.54097
5	8.630	47.019	47.80442721	10.40046995	33.80283465
7	37.318	-21.637	43.13690871	-59.89481512	30.50240067
11	41.861	-132.591	139.0421397	-17.52170094	98.31763983

Phase b-L2: Voltage-customer 2

index	a_n	b_n	c_n	α_n	V_{rms}
1	-14.258	31.538	34.61121217	-24.32722833	24.47382283
5	4.223	-0.404	4.242280637	-84.53533882	2.999745406
7	7.343	1.684	7.533624957	77.08347931	5.327077294
11	-7.765	-26.364	27.48373557	16.41130509	19.4339358

Phase c-L3: Voltage-customer 2

index	a_n	b_n	c_n	α_n	V_{rms}
1	8621.757	-12200.025	14939.05297	-35.24884672	10563.50566
5	-148.316	234.573	277.5286079	-32.30438095	196.2423606
7	24.198	147.445	149.4174395	9.320039381	105.6540847
11	-54.277	-137.182	147.5292983	21.58656863	104.3189672

b) Current measurement

Harmonic analysis gives the following results in the table below for harmonic current components:

Phase a-L1: Current

index	a_n	b_n	c_n	α_n	I_{rms}
1	48.248	52.890	71.59065305	42.37210067	50.62223624
5	0.104	0.054	0.117183617	62.56027205	0.08286133
7	0.553	0.422	0.69562418	52.65237403	0.491880575
11	0.356	-0.658	0.748131005	-28.41486997	0.529008507

Phase b-L2: Current

Index	a_n	b_n	c_n	α_n	I_{rms}
1	-67.611	15.836	69.44081089	-76.81768621	49.10206827
5	-0.802	0.504	0.947216976	-57.85355764	0.669783547
7	-0.124	-0.321	0.344117712	21.12118934	0.243327968
11	0.049	-0.690	0.691737667	-4.062011557	0.489132395

Phase c-L3: Current

Index	a_n	b_n	c_n	α_n	I_{rms}
1	19.690	-68.665	71.43233389	-16.00048427	50.51028769
5	-0.704	1.307	1.484542017	-28.3085977	1.049729727
7	-0.632	0.638	0.898035634	-44.72931329	0.635007087
11	-0.120	-0.675	0.685583693	10.08059799	0.484780878

The following harmonic voltages and currents were obtained with harmonic analysis method of Fourier series coefficients:

a) For Voltage

Va_1 = 10813.54097 Vb_1 = 24.47382283 Vc_1 = 10563.50566

Va_5 = 33.80283465 Vb_5 = 2.999745406 Vc_5 = 196.2423606

Va_7 = 30.50240067 Vb_7 = 5.327077294 Vc_7 = 105.6540847

Va_{11} = 98.31763983 Vb_{11} = 19.4339358 Vc_{11} = 104.3189672

θaV_1 = 85.0882512 θbV_1 = -24.32722833 θcV_1 = -35.24884672

θaV_5 = 10.40046995 θbV_5 = -84.53533882 θcV_5 = -32.30438095

θaV_7 = -59.89481512 θbV_7 = 77.08347931 θcV_7 = 9.320039381

θaV_{11} = -17.52170094 θbV_{11} = 16.41130509 θcV_{11} = 21.58656863

b) For current

Ia_1 = 50.62223624 Ib_1 = 49.10206827 Ic_1 = 50.51028769

Ia_5 = 0.08286133 Ib_5 = 0.669783547 Ic_5 = 1.049729727

Ia_7 = 0.491880575 Ib_7 = 0.243327968 Ic_7 = 0.635007087

Ia_{11} = 0.529008507 Ib_{11} = 0.489132395 Ic_{11} = 0.484780878

θaI_1 = 42.37210067 θbI_1 = -76.81768621 θcI_1 = -16.00048427

θaI_5 = 62.56027205 θbI_5 = -57.85355764 θcI_5 = -28.3085977

θaI_7 = 52.65237403 θbI_7 = 21.12118934 θcI_7 = -44.72931329

θaI_{11} = -28.41486997 θbI_{11} = -4.062011557 θcI_{11} = 10.08059799

c) Phase angle

Phase a	Phase b	Phase c
θa_1 = 42.71615053	θb_1 = 52.49045788	θc_1 = -19.24836245
θa_5 = -52.1598021	θb_5 = -26.68178118	θc_5 = -3.99578325
θa_7 = -112.5471892	θb_7 = 55.96228997	θc_7 = 54.04935267
θa_{11} = 10.89316903	θb_{11} = 20.47331665	θc_{11} = 11.50597064

IEEE 1459-2010 Voltage and Current indices

The following RMS voltages and currents were obtained for each phase
Phase a:

$$V_a = \sqrt{(Va_1^{\ 2} + Va_5^{\ 5} + Va_7^{\ 2} + Va_{11}^{\ 2})}$$

$$Va = 10814.21693$$

$$Ia = \sqrt{(Ia_1^{\ 2} + Ia_5^{\ 2} + Ia_7^{\ 2} + Ia_{11}^{\ 2})}$$

$$Ia = 50.62817242$$

Phase b:

$$Vb = \sqrt{(Vb_1^{\ 2} + Vb_5^{\ 2} + Vb_7^{\ 2} + Vb_{11}^{\ 2})}$$

$$Vb = 32.22987748$$

$$Ib = \sqrt{(Ib_1^{\ 2} + Ib_5^{\ 2} + Ib_7^{\ 2} + Ib_{11}^{\ 2})}$$

$$Ib = 49.11536371$$

Phase c:

$$Vc = \sqrt{(Vc_1^{\ 2} + Vc_5^{\ 2} + Vc_7^{\ 7} + Vc_{11}^{\ 2})}$$

$$Vc = 10567.77108$$

$$Ic = \sqrt{(Ic_1^{\ 2} + Ic_5^{\ 2} + Ic_7^{\ 2} + Ic_{11}^{\ 2})}$$

Appendix 4

Customer 1: 5th statistical data of voltage, current, active power and reactive power

Period Start	Period End	H5, L1 Active Power Harmonics (Cycle by Cycle), Customer 1@Utility 1 Average	H5, L1 Reactive Power Harmonics (Cycle by Cycle), Customer 1@Utility 1 Average	H5, L1 Harmonics Current (Cycle by Cycle), Customer 1@Utility 1 Average	H5, L1 Harmonics Voltage (Cycle by Cycle), Customer 1@Utility 1 Average
26/06/2017 07:30:37.776	26/06/2017 07:30:41.961	1.436789	112.4072	7.294281	15.50502
26/06/2017 07:30:41.961	26/06/2017 07:30:46.147	-16.7522	99.94878	6.849981	15.50502
26/06/2017 07:30:46.147	26/06/2017 07:30:50.332	27.56916	105.9616	7.190777	15.50502
26/06/2017 07:30:50.332	26/06/2017 07:30:54.518	-14.207	116.4398	7.473725	15.93391
26/06/2017 07:30:54.518	26/06/2017 07:30:58.703	13.13525	163.7291	7.615393	21.70703
26/06/2017 07:30:58.703	26/06/2017 07:31:02.888	-14.2518	162.4156	7.68649	21.43272
26/06/2017 07:31:02.888	26/06/2017 07:31:07.073	-0.32865	161.44	7.71746	21.49773
26/06/2017 07:31:07.073	26/06/2017 07:31:11.259	7.1793	180.3742	7.785334	23.41635
26/06/2017 07:31:11.259	26/06/2017 07:31:15.444	-4.41136	172.2145	7.972906	21.70703
26/06/2017 07:31:15.444	26/06/2017 07:31:19.630	-9.72074	163.2758	7.771985	21.3306
26/06/2017 07:31:19.630	26/06/2017 07:31:23.815	4.620683	157.9663	7.659163	20.80217
26/06/2017 07:31:23.815	26/06/2017 07:31:28.000	7.186779	165.4692	7.858083	21.98332
26/06/2017 07:31:28.000	26/06/2017 07:31:32.185	13.32463	178.0655	7.909554	22.57565
26/06/2017 07:31:32.185	26/06/2017 07:31:36.371	-12.1703	173.9666	7.760967	22.53404
26/06/2017 07:31:36.371	26/06/2017 07:31:40.556	-4.23965	165.3465	7.619691	21.70703
26/06/2017 07:31:40.556	26/06/2017 07:31:44.742	-33.0888	165.3465	7.78816	21.70703
26/06/2017 07:31:44.742	26/06/2017 07:31:48.927	-50.7047	151.6086	7.804233	20.96953

26/06/2017 07:31:48.927	26/06/2017 07:31:53.112	-8.17848	130.3474	7.506554	17.54193
26/06/2017 07:31:53.112	26/06/2017 07:31:57.297	-13.2062	134.5882	7.496624	18.21742
26/06/2017 07:31:57.297	26/06/2017 07:32:01.483	-11.0888	148.7829	7.673014	19.61247
26/06/2017 07:32:01.483	26/06/2017 07:32:05.668	-18.0643	165.9889	7.847135	21.72747
26/06/2017 07:32:05.668	26/06/2017 07:32:09.854	-2.34581	169.7635	7.796205	22.14073
26/06/2017 07:32:09.854	26/06/2017 07:32:14.039	-10.8732	171.5224	7.901133	21.92741
26/06/2017 07:32:14.039	26/06/2017 07:32:18.224	-42.1041	167.6647	7.950029	21.92741
26/06/2017 07:32:18.224	26/06/2017 07:32:22.409	-10.7976	191.169	7.927172	24.58935
26/06/2017 07:32:22.409	26/06/2017 07:32:26.595	-1.23952	185.5053	7.902915	23.669
26/06/2017 07:32:26.595	26/06/2017 07:32:30.780	-5.31313	179.702	7.999543	22.93633
26/06/2017 07:32:30.780	26/06/2017 07:32:34.966	-9.23679	172.4159	7.913967	22.15885
26/06/2017 07:32:34.966	26/06/2017 07:32:39.151	18.82203	167.1557	7.771448	21.70703
26/06/2017 07:32:39.151	26/06/2017 07:32:43.337	-15.8471	166.2384	7.708215	21.70703
26/06/2017 07:32:43.337	26/06/2017 07:32:47.521	14.66435	158.9891	7.662896	20.93529
26/06/2017 07:32:47.521	26/06/2017 07:32:51.707	15.46405	167.3552	7.967019	21.93111
26/06/2017 07:32:51.707	26/06/2017 07:32:55.892	38.18835	191.2715	7.9008	25.00109
26/06/2017 07:32:55.892	26/06/2017 07:33:00.078	-13.0289	197.3847	7.928219	25.00109
26/06/2017 07:33:00.078	26/06/2017 07:33:04.263	32.77654	164.2925	7.778122	21.77664
26/06/2017 07:33:04.263	26/06/2017 07:33:08.449	22.90307	183.0042	7.90227	23.57863
26/06/2017 07:33:08.449	26/06/2017 07:33:12.634	-12.0818	186.9615	8.414803	22.77542
26/06/2017 07:33:12.634	26/06/2017 07:33:16.819	-8.00409	172.4842	8.394467	20.80217
26/06/2017 07:33:16.819	26/06/2017 07:33:21.004	-27.4156	180.6508	8.42498	21.959
26/06/2017 07:33:21.004	26/06/2017 07:33:25.190	-17.9994	192.1599	8.010593	24.48173
26/06/2017 07:33:25.190	26/06/2017 07:33:29.375	-0.6245	151.6833	7.717711	19.85611

26/06/2017 07:33:29.375	26/06/2017 07:33:33.561	14.93744	121.0889	7.552392	16.75039
26/06/2017 07:33:33.561	26/06/2017 07:33:37.746	6.355286	134.7513	7.444074	18.52948
26/06/2017 07:33:37.746	26/06/2017 07:33:41.931	15.52184	171.8692	7.666799	22.57565
26/06/2017 07:33:41.931	26/06/2017 07:33:46.116	-2.00504	172.975	7.688635	22.57565
26/06/2017 07:33:46.116	26/06/2017 07:33:50.302	-38.1569	171.4031	7.778245	22.57565
26/06/2017 07:33:50.302	26/06/2017 07:33:54.487	-3.34726	173.2502	7.776007	23.16045
26/06/2017 07:33:54.487	26/06/2017 07:33:58.673	-4.21777	186.8389	7.768633	24.21961
26/06/2017 07:33:58.673	26/06/2017 07:34:02.858	-26.6493	187.1504	7.805172	24.21961
26/06/2017 07:34:02.858	26/06/2017 07:34:07.043	-37.3345	182.3007	7.83732	23.96138
26/06/2017 07:34:07.043	26/06/2017 07:34:11.228	-36.5687	181.8465	7.88209	23.61654
26/06/2017 07:34:11.228	26/06/2017 07:34:15.414	-37.923	164.5584	7.68905	22.2168
26/06/2017 07:34:15.414	26/06/2017 07:34:19.599	-18.1999	172.9498	7.836505	23.26385
26/06/2017 07:34:19.599	26/06/2017 07:34:23.785	-23.9944	189.7397	7.955479	24.21961
26/06/2017 07:34:23.785	26/06/2017 07:34:27.970	-8.92526	177.6075	7.817854	23.21358
26/06/2017 07:34:27.970	26/06/2017 07:34:32.155	18.77561	175.0371	7.797838	22.57565
26/06/2017 07:34:32.155	26/06/2017 07:34:36.340	-6.74947	171.5337	7.622028	22.57565
26/06/2017 07:34:36.340	26/06/2017 07:34:40.526	-31.0073	166.9467	7.604234	22.50909
26/06/2017 07:34:40.526	26/06/2017 07:34:44.711	2.468849	147.0404	7.553558	19.61247

Customer 1: 7th statistical data of voltage, current, active power and reactive power

Period Start	Period End	H7, L1 Active Power Harmonics (Cycle by Cycle), Customer 1@Utility 1 Average	H7, L1 Reactive Power Harmonics (Cycle by Cycle), Customer 1@Utility 1 Average	H7, L1 Harmonics Current (Cycle by Cycle), Customer 1@Utility 1 Average	H7, L1 Harmonics Voltage (Cycle by Cycle), Customer 1@Utility 1 Average
26/06/2017 07:30:37,776	26/06/2017 07:30:41,928	-42,3517	64,14121	1,810451	43,76902
26/06/2017 07:30:41,928	26/06/2017 07:30:46,079	-60,8258	69,54006	2,039122	45,62111
26/06/2017 07:30:46,079	26/06/2017 07:30:50,230	-60,913	58,80696	1,935732	46,74164
26/06/2017 07:30:50,230	26/06/2017 07:30:54,381	-46,2297	63,07796	1,852897	42,71288
26/06/2017 07:30:54,381	26/06/2017 07:30:58,533	-56,5856	33,71662	1,578461	42,54673
26/06/2017 07:30:58,533	26/06/2017 07:31:02,684	-40,1792	51,54301	1,57466	43,07795
26/06/2017 07:31:02,684	26/06/2017 07:31:06,835	-51,2875	36,86525	1,57466	40,84739
26/06/2017 07:31:06,835	26/06/2017 07:31:10,986	-55,5852	11,80812	1,49774	40,3143
26/06/2017 07:31:10,986	26/06/2017 07:31:15,138	-48,0329	29,39328	1,487456	37,95354
26/06/2017 07:31:15,138	26/06/2017 07:31:19,289	-45,9254	25,54632	1,487456	37,83722
26/06/2017 07:31:19,289	26/06/2017 07:31:23,440	-51,3805	26,86266	1,487456	39,6382
26/06/2017 07:31:23,440	26/06/2017 07:31:27,591	-33,3157	39,84379	1,501982	37,8884
26/06/2017 07:31:27,591	26/06/2017 07:31:31,743	-56,413	16,85324	1,57466	37,46501
26/06/2017 07:31:31,743	26/06/2017 07:31:35,894	-48,8095	30,71967	1,57466	37,38985
26/06/2017 07:31:35,894	26/06/2017 07:31:40,045	-39,3624	42,95214	1,57466	37,38788
26/06/2017 07:31:40,045	26/06/2017 07:31:44,196	-45,6841	19,59721	1,523304	37,46957
26/06/2017 07:31:44,196	26/06/2017 07:31:48,348	-52,9284	12,05442	1,487456	37,32135
26/06/2017 07:31:48,348	26/06/2017 07:31:52,499	-33,6774	41,35099	1,487456	36,80481

26/06/2017 07:31:52,499	26/06/2017 07:31:56,651	-50,2799	23,84303	1,559952	37,73644
26/06/2017 07:31:56,651	26/06/2017 07:32:00,802	-48,0366	37,20103	1,57466	39,25191
26/06/2017 07:32:00,802	26/06/2017 07:32:04,953	-33,6974	48,12986	1,582068	40,35426
26/06/2017 07:32:04,953	26/06/2017 07:32:09,105	-50,816	29,83183	1,610588	37,73212
26/06/2017 07:32:09,105	26/06/2017 07:32:13,256	-38,1844	44,74266	1,595532	37,46957
26/06/2017 07:32:13,256	26/06/2017 07:32:17,407	-49,0589	8,614188	1,310196	38,60447
26/06/2017 07:32:17,407	26/06/2017 07:32:21,558	-39,386	29,90431	1,321933	40,6022
26/06/2017 07:32:21,558	26/06/2017 07:32:25,710	-54,5098	14,8404	1,381068	41,34943
26/06/2017 07:32:25,710	26/06/2017 07:32:29,861	-44,8259	33,3436	1,381068	41,0713
26/06/2017 07:32:29,861	26/06/2017 07:32:34,012	-41,4289	26,70185	1,450325	40,00773
26/06/2017 07:32:34,012	26/06/2017 07:32:38,163	-56,675	19,32439	1,525439	39,98005
26/06/2017 07:32:38,163	26/06/2017 07:32:42,315	-46,2919	39,71187	1,525439	40,39814
26/06/2017 07:32:42,315	26/06/2017 07:32:46,466	-51,3316	28,64967	1,543436	40,64682
26/06/2017 07:32:46,466	26/06/2017 07:32:50,617	-62,8023	9,970838	1,5625	40,72594
26/06/2017 07:32:50,617	26/06/2017 07:32:54,768	-48,7072	31,11361	1,5625	38,19217
26/06/2017 07:32:54,768	26/06/2017 07:32:58,920	-50,7936	15,30446	1,450141	40,38552
26/06/2017 07:32:58,920	26/06/2017 07:33:03,071	-52,7346	19,04711	1,408418	40,23895
26/06/2017 07:33:03,071	26/06/2017 07:33:07,222	-35,4731	45,89711	1,408418	42,14369
26/06/2017 07:33:07,222	26/06/2017 07:33:11,373	-66,3443	28,75675	1,839374	40,04521
26/06/2017 07:33:11,373	26/06/2017 07:33:15,525	-74,7094	25,20088	1,973884	41,38433
26/06/2017 07:33:15,525	26/06/2017 07:33:19,676	-68,9589	33,62455	1,919131	41,2235
26/06/2017 07:33:19,676	26/06/2017 07:33:23,827	-61,2494	24,71064	1,746928	38,74515
26/06/2017 07:33:23,827	26/06/2017 07:33:27,978	-42,826	43,41639	1,687507	39,87022
26/06/2017 07:33:27,978	26/06/2017 07:33:32,130	-51,863	36,78825	1,5625	41,23025

26/06/2017 07:33:32,130	26/06/2017 07:33:36,281	-57,2286	31,98541	1,630572	43,464
26/06/2017 07:33:36,281	26/06/2017 07:33:40,432	-63,1148	35,91027	1,668751	43,61043
26/06/2017 07:33:40,432	26/06/2017 07:33:44,583	-49,0589	46,03053	1,668751	40,31305
26/06/2017 07:33:44,583	26/06/2017 07:33:48,735	-58,8224	4,147186	1,495121	40,20525
26/06/2017 07:33:48,735	26/06/2017 07:33:52,886	-54,5098	21,80393	1,487456	39,46934
26/06/2017 07:33:52,886	26/06/2017 07:33:57,037	-43,9119	34,32877	1,487456	38,88365
26/06/2017 07:33:57,037	26/06/2017 07:34:01,188	-43,0617	36,33669	1,530743	39,25637
26/06/2017 07:34:01,188	26/06/2017 07:34:05,340	-62,865	16,24375	1,610588	40,34969
26/06/2017 07:34:05,340	26/06/2017 07:34:09,491	-59,3552	30,28324	1,610588	41,37255
26/06/2017 07:34:09,491	26/06/2017 07:34:13,643	-44,3794	43,89755	1,610588	40,31409
26/06/2017 07:34:13,643	26/06/2017 07:34:17,794	-60,0598	14,78644	1,574935	40,2875
26/06/2017 07:34:17,794	26/06/2017 07:34:21,945	-52,4158	30,66979	1,57466	38,71966
26/06/2017 07:34:21,945	26/06/2017 07:34:26,096	-43,7422	44,23432	1,580098	41,2267
26/06/2017 07:34:26,096	26/06/2017 07:34:30,248	-66,6231	19,38128	1,610588	43,08052
26/06/2017 07:34:30,248	26/06/2017 07:34:34,399	-58,1296	39,55337	1,610588	43,95209
26/06/2017 07:34:34,399	26/06/2017 07:34:38,550	-54,6238	44,70526	1,610588	44,19569
26/06/2017 07:34:38,550	26/06/2017 07:34:42,701	-42,3127	57,31361	1,627833	46,07331

Customer 1: 11th statistical data of voltage, current, active power and reactive power

Period Start	Period End	H11, L1 Active Power Harmonics (Cycle by Cycle), Customer 1@Utility 1 Average	H11, L1 Reactive Power Harmonics (Cycle by Cycle), Customer 1@Utility 1 Average	H11, L1 Harmonics Current (Cycle by Cycle), Customer 1@Utility 1 Average	H11, L1 Harmonics Voltage (Cycle by Cycle), Customer 1@Utility 1 Average
26/06/2017 07:30:37,776	26/06/2017 07:30:41,952	-23,7612	-35,9299	2,346347	18,69578
26/06/2017 07:30:41,952	26/06/2017 07:30:46,127	-39,4995	-30,483	2,351874	21,5397
26/06/2017 07:30:46,127	26/06/2017 07:30:50,303	-31,0039	-32,3813	2,346728	20,18587
26/06/2017 07:30:50,303	26/06/2017 07:30:54,479	-24,4305	-34,4464	2,350579	18,60602
26/06/2017 07:30:54,479	26/06/2017 07:30:58,654	-15,8991	-30,3868	2,348102	15,68031
26/06/2017 07:30:58,654	26/06/2017 07:31:02,830	-24,0832	-24,5068	2,349563	14,91718
26/06/2017 07:31:02,830	26/06/2017 07:31:07,005	-14,7302	-23,5304	2,277959	13,01279
26/06/2017 07:31:07,005	26/06/2017 07:31:11,181	-18,3236	-20,0688	2,31344	13,19668
26/06/2017 07:31:11,181	26/06/2017 07:31:15,356	-17,2065	-21,6111	2,226905	13,13982
26/06/2017 07:31:15,356	26/06/2017 07:31:19,532	-19,6028	-23,0938	2,310599	13,84057
26/06/2017 07:31:19,532	26/06/2017 07:31:23,707	-23,9415	-22,9841	2,309516	15,11784
26/06/2017 07:31:23,707	26/06/2017 07:31:27,883	-24,552	-20,2881	2,304933	14,45816
26/06/2017 07:31:27,883	26/06/2017 07:31:32,059	-22,3456	-28,5481	2,278209	16,69942
26/06/2017 07:31:32,059	26/06/2017 07:31:36,234	-24,6177	-23,8355	2,209709	16,08919
26/06/2017 07:31:36,234	26/06/2017 07:31:40,410	-24,882	-25,8755	2,2812	16,4099
26/06/2017 07:31:40,410	26/06/2017 07:31:44,585	-29,0719	-29,0719	2,34375	17,54193
26/06/2017 07:31:44,585	26/06/2017 07:31:48,761	-21,9301	-27,5153	2,24349	16,33082
26/06/2017 07:31:48,761	26/06/2017 07:31:52,936	-23,1569	-19,7322	2,327355	14,39217

26/06/2017 07:31:52,936	26/06/2017 07:31:57,112	-26,9484	-18,0849	2,297483	14,41717
26/06/2017 07:31:57,112	26/06/2017 07:32:01,287	-27,6513	-15,152	2,228999	15,50502
26/06/2017 07:32:01,287	26/06/2017 07:32:05,463	-24,8486	-25,2698	2,301246	15,50502
26/06/2017 07:32:05,463	26/06/2017 07:32:09,638	-26,712	-21,1387	2,297939	15,50502
26/06/2017 07:32:09,638	26/06/2017 07:32:13,814	-27,2549	-24,2266	2,351874	15,50502
26/06/2017 07:32:13,814	26/06/2017 07:32:17,990	-21,491	-27,9021	2,240325	16,96437
26/06/2017 07:32:17,990	26/06/2017 07:32:22,165	-29,283	-34,6496	2,357172	20,19345
26/06/2017 07:32:22,165	26/06/2017 07:32:26,341	-36,5427	-34,61	2,374837	22,09
26/06/2017 07:32:26,341	26/06/2017 07:32:30,516	-29,3997	-34,0685	2,306035	20,76361
26/06/2017 07:32:30,516	26/06/2017 07:32:34,692	-33,3504	-26,2118	2,300734	18,85876
26/06/2017 07:32:34,692	26/06/2017 07:32:38,867	-34,0102	-16,6768	2,340795	16,9069
26/06/2017 07:32:38,867	26/06/2017 07:32:43,043	-21,1983	-27,2549	2,226905	15,50502
26/06/2017 07:32:43,043	26/06/2017 07:32:47,218	-27,3008	-19,1279	2,271631	15,50502
26/06/2017 07:32:47,218	26/06/2017 07:32:51,394	-21,8039	-29,0719	2,34375	15,50502
26/06/2017 07:32:51,394	26/06/2017 07:32:55,570	-9,00029	-28,4403	2,253951	15,83509
26/06/2017 07:32:55,570	26/06/2017 07:32:59,745	-16,1374	-34,7385	2,333339	16,69942
26/06/2017 07:32:59,745	26/06/2017 07:33:03,921	-17,8718	-33,7997	2,292182	17,58535
26/06/2017 07:33:03,921	26/06/2017 07:33:08,096	-21,0139	-27,4095	2,288454	16,38875
26/06/2017 07:33:08,096	26/06/2017 07:33:12,272	-18,9795	-33,0211	2,233549	18,23472
26/06/2017 07:33:12,272	26/06/2017 07:33:16,447	-28,3064	-28,5154	2,321267	18,41183
26/06/2017 07:33:16,447	26/06/2017 07:33:20,623	-15,4315	-39,0066	2,351874	18,15182
26/06/2017 07:33:20,623	26/06/2017 07:33:24,798	-22,2512	-32,9731	2,347195	18,18596
26/06/2017 07:33:24,798	26/06/2017 07:33:28,974	-14,9922	-31,9738	2,351874	16,05168
26/06/2017 07:33:28,974	26/06/2017 07:33:33,149	-18,9201	-30,7082	2,328426	15,56883

26/06/2017 07:33:33,149	26/06/2017 07:33:37,325	-28,5541	-14,8451	2,280584	15,55277
26/06/2017 07:33:37,325	26/06/2017 07:33:41,501	-23,9924	-27,227	2,351874	15,62684
26/06/2017 07:33:41,501	26/06/2017 07:33:45,676	-18,7756	-32,1002	2,351874	15,81208
26/06/2017 07:33:45,676	26/06/2017 07:33:49,852	-18,7756	-32,1002	2,351874	15,81208
26/06/2017 07:33:49,852	26/06/2017 07:33:54,027	-27,0343	-24,9235	2,349044	16,6511
26/06/2017 07:33:54,027	26/06/2017 07:33:58,203	-20,7218	-27,6543	2,272053	16,07856
26/06/2017 07:33:58,203	26/06/2017 07:34:02,378	-19,3813	-29,0719	2,209709	15,81208
26/06/2017 07:34:02,378	26/06/2017 07:34:06,554	-25,2029	-23,4439	2,220716	16,26803
26/06/2017 07:34:06,554	26/06/2017 07:34:10,729	-32,2582	-31,9093	2,34375	20,33956
26/06/2017 07:34:10,729	26/06/2017 07:34:14,905	-37,802	-29,0379	2,149999	23,50564
26/06/2017 07:34:14,905	26/06/2017 07:34:19,081	-36,1777	-27,7718	2,283178	21,72826
26/06/2017 07:34:19,081	26/06/2017 07:34:23,256	-28,6207	-30,9417	2,306949	19,61247
26/06/2017 07:34:23,256	26/06/2017 07:34:27,432	-31,5334	-19,4988	2,226905	16,80132
26/06/2017 07:34:27,432	26/06/2017 07:34:31,607	-23,1493	-27,7266	2,287197	16,69942
26/06/2017 07:34:31,607	26/06/2017 07:34:35,783	-25,121	-25,7549	2,34375	15,83858
26/06/2017 07:34:35,783	26/06/2017 07:34:39,958	-16,9252	-27,8773	2,277531	15,50502
26/06/2017 07:34:39,958	26/06/2017 07:34:44,134	-17,1086	-27,6053	2,254481	15,6974