Allocation of Transmission Losses to Determine Tariff

Thesis by:
Adebayo Adeyinka Victor
Department of Electrical Engineering
University of Cape Town

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Professor C. T. Gaunt

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Declaration

In the preparation of this dissertation, much literature was consulted, lots of caution was taken to properly reference all work used. The rest there with is my work.

The number of words in the main text of the thesis does not exceed 80,000.

Abstract

The recent widespread restructuring and unbundling of the electricity industry has introduced some changes in the organization of the sector, thereby creating a more competitive environment in which each participant must bear its own cost and be responsible for its own contribution to losses in the system. The allocation of transmission losses has become an important issue as this determines how and what to charge each of the participants in the industry. This allocation is best assessed and based on their individual contributions to grid losses.

Earlier methods used in loss allocation include: The Pro rata approach which arbitrarily allocates 50% each to the load and generator; the Marginal procedure allocation, which is either positive or negative; the Proportional sharing method which bases its allocation on the Kirchhoff's current law and allocates no losses to the transmission line and the Equilateral bilateral exchange (EBE) method. Most of the other methods, such as the Game theory method, Circuit theory method, Graph theory method, and Optimization methods are either mathematically complex in operation or time-consuming. And till date, none of these methods could be used to allocate transmission losses with fairness and transparency.

Currently, power loss measurements have been estimated based on ideal conditions in which there exist a balanced load and reactive power, while the inefficiency caused by distortion and the unbalanced load is not usually taken into consideration. This research introduces a novel and a fairer method of determining power losses by using the Thévenin impedance in calculating the line parameters used in the determination of power losses. Since losses associated with a transmission power line depend on the wire resistance and the line current ($I^2 R$), the Thévenin equivalent of the system is calculated from the point of connecting each participant (generator or load), i.e. the point of common coupling, to determine the system losses without prior knowledge of the power system supply quantities.

This thesis identifies the avoidable losses in the system, which participants pay for because of the inadequacy of current methods which use only reactive powers (inductive and capacitive) to determine the power losses in the allocation of losses and in the calculation of the power system tariff. This report elucidates how to estimate the

losses that can be avoided by the participants. This loss is equal to the numerical power difference in the conventional power loss and the new power loss calculation method which utilizes the general power theory where two components that are orthogonal to each other, making non-active power (reactive power and distortion power) are used. This difference, which is an extra loss created by the participants, can be conserved to reduce power generation cost and tariffs. This method which was tested on a standard IEEE test system is transparent, fair and requires a comparatively short time to execute, making it suitable for decision making thus emphasizing the importance of the proposed solution.

List of Abbreviations

CPU	-	Central Processing Unit
DISCOs	-	Distribution Companies
DSP	-	Digital Signal Processor
EPI	-	Electric Power Industry
EBE	-	Equal Bilateral Exchange
GENCOs	-	Generation Companies
GPT	-	General Power Theory
ILFA	-	Incremental Load Flow Approach
IOU	-	Independent Owned Utility
IPP	-	Independent Power Producers
ISO	-	Independent System Operator
ITL	-	Incremental Transmission Loss
KCL	-	Kirchhoff's current Law
KVC	-	Kirchhoff's voltage law
MTLA	-	Marginal Transmission Loss Approach
NUG	-	Non-Utility Generators
PCC	-	Point of Common Coupling
PMU	-	Phasor Monitoring Units
PR	-	Pro-Rata
PS	-	Postage Stamp
PSP	-	Proportional Sharing
PV	-	Photovoltaic
SMPS	-	Switch Mode Power System
SRMC	-	Short-Term Marginal Cost
TPM	-	Transmission Pricing Methodology
TRANSCO	-	Transmission Company
TT	-	Tellegen's Theory

BWLA - Bus Wise Loss Allocation

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CHAPTER ONE
INTRODUCTION

This chapter introduces a recent trend in the power industry, in which vertically-integrated power sectors are restructured, thus altering the marketing pattern of transmitted power with the economic impact of the grid network falling on the system users. The hypothesis on which this thesis is based is stated and this is followed by the research questions and scope, while the objectives and the main contribution of the work are presented. This chapter then concludes with the outline of the thesis.

1.1 Restructuring of the Power Industry

The Electric Power Industry (EPI) is undergoing a significant transformation around the world with the aim of introducing competition, which has the advantage of increasing efficiency and better service in the EPI [3]. Since the start of electricity supply, until relatively recently, vertically integrated utility providers that operate as franchised monopolies supplied a large amount of power to consumers in the United States; they have overseen, controlled and marketed electricity in a vertically integrated monopolistic way [4]. However, with the recent transformation process, called electricity restructuring, open access is introduced in the EPI in such a way that all the three major components of generation, transmission and distribution are separated and handed over to different successor companies; namely, Generation Companies (GENCOs), Transmission Company (TRANSCO) and Distribution Companies (DISCOs).

The power system operation is separated from the transmission sector in some countries as an independent entity to dispatch power and monitor the grids [5]. The ultimate goal in power system restructuring is to reduce the consumer price by means of competition as it is widely believed that a competitive market can guarantee cost minimization and help keep the average energy price held at a minimum level [6], [7]. Different independent power producers (IPPs) generate power by hydro, coal, solar, wind or nuclear technology and sell to the transmission company for power transmission. In addition, multiple companies are involved in the distribution sector, transferring electricity from the transmission end to the consumers and introducing competition in the distribution sector. Because of the difficulty involved in building separate transmission lines for every generation facility, the transmission sector remains a monopolistic market in many countries [8].

While the countries with the old system of a single entity generating, transmitting and distributing electricity are said to operate a regulated system, the countries adopting restructuring with the unbundling of the electric power industry are said to be deregulated [9]. The term ‘market deregulation’ is only to provide a choice of electricity provider to the customer; the system still falls under the regulatory body. As the system of market deregulation is becoming widespread, some countries still maintain a regulated system, as shown in the Figure, 1.1 (that is, vertically integrated monopoly) where the electricity company is usually owned by the government or Independent Owned Utility (IOU). This company owns all the infrastructures (the wires, transformers, poles, generator, and the likes) involved in the generation, transmission and the distribution of electricity. Thus, the major functions performed in the regulated electricity industry are the generation of electricity, transmission, and distribution of the same to the consumers [10]. Thus, the regulated electric industry has various characteristics, which include [11]:

(i) Monopoly franchise; the task to produce, transport and sell the electricity by the utility company.

(ii) The obligation to serve; the electric utility company must provide every service that is related, not just the profitable work.

(iii) Least-cost operation; This means that every utility must minimize their cost from the total overall revenue requirements.

Therefore, in summary, a regulated electricity market is all about the government creating a level of control in the price and quality of electricity, as well as protecting the consumer, thereby taking most of the risk, rather than investors.

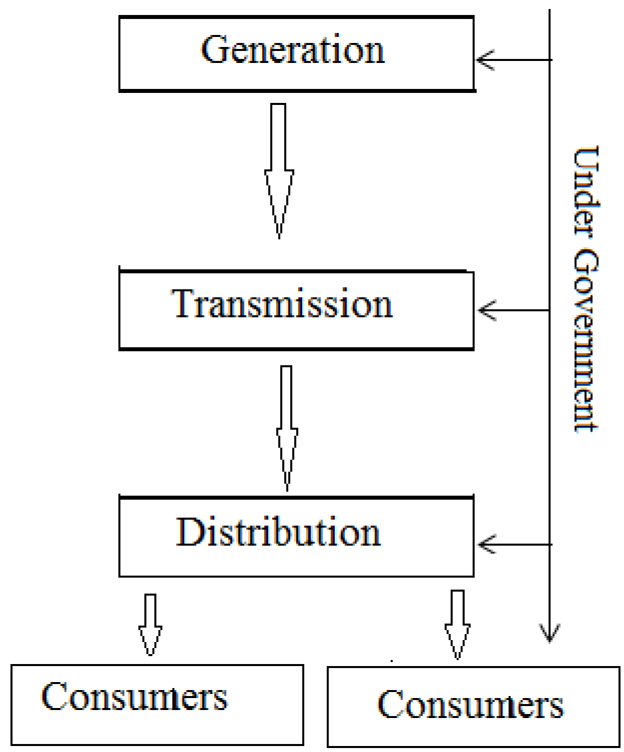


Figure. 1.1 Vertically Integrated Monopoly Company.

In the deregulated environment (Figure 1.2), restructuring of electricity provision does not mean the system is completely open; the regulatory body, which also provides oversight function on the market, monitors adherence to rules and guidelines. In addition, in a restructured power system, some of the infrastructures can still be owned by the government, but, it gives different companies licenses to generate, distribute and sell to the consumers (removing the monopoly from the traditional integrated power system) while the transmission can either be done by the government or also unbundled [10].

Electricity restructuring brings about competition with improved services, competitive pricing and some significant benefits not found in the vertically integrated monopoly company due to the increase in the use of renewable and alternative electricity sources that provide cleaner energy, with increasing grid efficiency by the Independent Power Producers (IPPs) and the Non-Utility Generators (NUG) [12].

Restructuring of the electricity industry has been carried out for many reasons, including, but not limited to; when the reason for regulation has changed and there is a need for privatization; when there is a plan to reduce costs; to provide electricity to all demands that are reasonable; to promote the efficiency and when there is a need for new ideas and improved technology with the aim of encouraging competition in the chain of production, transportation and supply of electricity [11]. [7].

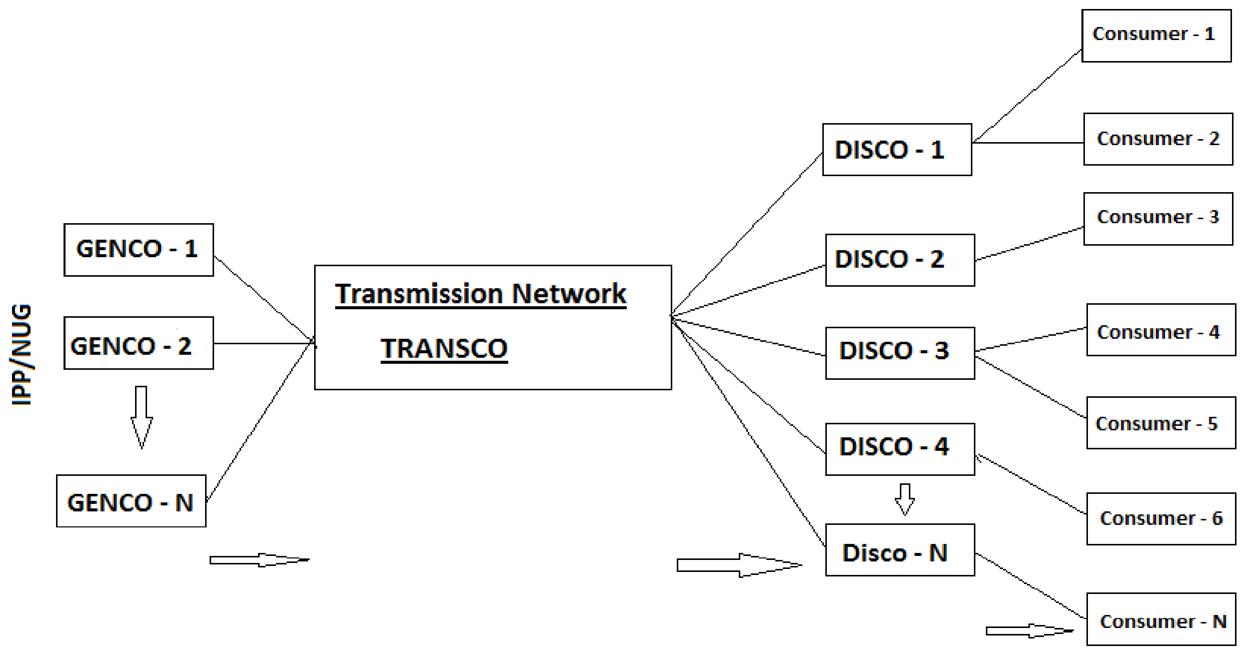


Figure 1.2 Restructured electricity industry.

The implementation of trading in the restructured power market can be separated into power pool and bilateral contracts. A Power pool is a form of simple marketing structure in which both the NUG or the IPP and customers both bid for electricity marketing that is, selling and buying power at the pool; in this system of power marketing, both parties have the same right to information pertaining to the marketing price and the demand. The Power Pool conducts different types of markets, such as the day before market, the hour before market and real-time market operation with the existing economic dispatch procedures. In the marketing of electricity, the meter at the consumer end reads their actual usage, while the meter at the generating side measures the generator actual outputs. The generator output always reads higher than the cumulative meter reading at the customers' end because of the network losses. Therefore, the problem of, "*who should pay for the losses?"* arises and these payments constitute a substantial amount of money [13]. In bilateral contracts, the power generators (Producer) and the customers contact each other for the marketing of power to avoid unpredictable changes; the seller arranges the transportation of the contracted power over the network [14]. Bilateral transactions are usually long-term agreements determined through proper negotiations between the producer and the customer as defined by the price agreed to on a bilateral exchange; this is based on market forces other than under potential system security violations [15]. This type of power marketing allows the consumers to make the best deal in price negotiations due to its less volatile retail price, spot market purchase and ability to obtain more favorable financing terms; it also creates room for choices of supplier's direct contract with the producer [16]. In addition, it allows the producer to have direct dealings with their customers and provides different ways of meeting their needs. However, the impact of individual losses should be well defined, where every user will have its own interaction and no user will be subsidized by another.

1.2 Allocation of Power Losses.

One of the key issues in a restructured environment is the way the power loss on transmission lines is satisfactorily allocated and accounted for among all involved partners. In addition, due to the non-linear nature of power flow [17], it is important to determine the loss on each line accurately since economic theory states that 'goods and services should be charged on the marginal cost basis' [18]. More also, loss allocation should be realistic, fair and transparent.

An appropriate model and algorithm to determine transmission losses accurately is therefore required since power loss in a transmission and distribution network is determined by different factors. Some of the factors are, the placement of generating plants and load connection points with the energy associated with it, the types of connected loads and network configuration, the voltage levels and voltage unbalance, the active factors in relation with the networks (such as Power factor, harmonics and the control of active and reactive power) [10]. Others are, the length of the lines - this is an almost linear relationship with the season and time of the day, the current in the line in relation to a square law relationship where doubling the line current would quadruple the line loss with the types of transformers used; their loadings with the connection, line design, line size and materials [19].

In the allocation of transmission loss, previous works have shown that the Short-term Marginal Cost (SRMC) pricing of transmission service is highly unstable and has not been able to regain the total investment in the system; this has promoted a negative economic signal in the transmission company [18]. The cost incurred on network losses amounts to millions of Rupees yearly in India, or 5–10% of the total power generated by the system [20], while it accounts for 6% of the total power transmitted in the United States grid [21]. Knowing this, an Independent System Operator (ISO) that has the energy capacity and energy bid price of all the generators, can select the most cost-effective generator to supply the consumer and allocate the losses accordingly with little or no cost attached. Since the generation, transmission and distribution of electricity in some countries are now carried out by different companies, the question of '**who**' should pay and '**how**' much should be paid for losses arises and continues to be a vexing question [22]. One approach is the tracing of power. The tracing of losses in a power system was first carried out in New Zealand when it was used as part of the Trans-Power Transmission Pricing Methodology (TPM) in 1993 [23]. Some years after, a paper titled "Tracing the flow of electricity" was published by Bialek, (1996).

Recently, electricity tracing has been proposed, and used, as a resolution for many markets related problems around the globe. These include the allocation of transmission charges in large interconnected networks of multiple countries, congestion management, the decision on generator scheduling, cost assignment to transmission line pricing and loss allocation to each route [24].

1.3 Transmission Tariff.

Transmission loss allocation to determine tariff is a process by which transmission loss is shared between the generation, transmission and distribution companies, as well as the consumers to determine the cost of energy loss. Loss allocation and cost allocation are part of the major issues faced by the electric power industry. Though tracing of power flow can be achieved through the determination of customer power consumption, this means the power contributed by each generator to each consumer can as well give the loss allocation associated to each of the networks [25]. The power grid itself has contributed to the power loss and thus has an important role to play in the determination of electricity tariff. Also, with the advent of renewable energy, renewable energy technologies (like wind turbines, Photovoltaic system, and many others) are now integrated into the transmission and distribution system. Due to this change, transmission losses are getting more relevant, as some renewable energy sources increase losses on the grid due to high penetration [26]. Also, there have been debates about whether to bill the cost of transmission used on the basis of distance; disputing this, a point was raised to show that far distance is not the fault of the customer [27]. Considering the economic parameters and the high associated costs, distance-based billing method encourages the local generation of power, as well as investment in microgrids, as producers are forced to stay close to consumers.

It has been stated by Soonee, et al., (2013) that any pricing model or methodology of transmission tariff must meet the following criteria: cover the total cost of the transmission services; be easy to implement; should be able to differentiate levels of services, and also take the location of the generator and load into consideration [28]. Introducing a fair competition and appropriate pricing in the charges of transmission cost, Figure 1.3 presents the charging strategy for a transmission utility for a fair and equitable balance [29].

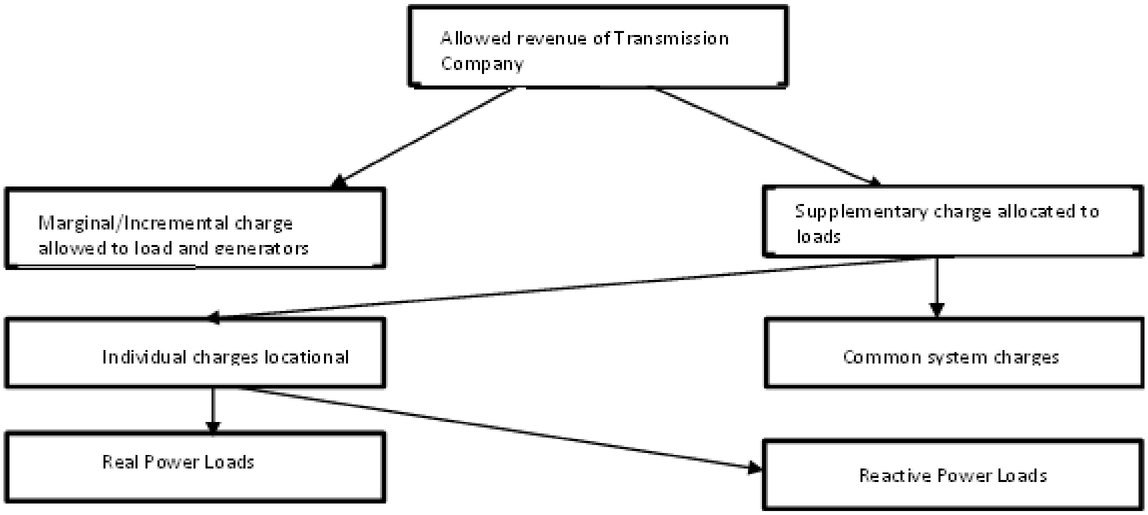


Figure 1.3 Charging Methods

1.4 Inefficiency in Transmission Loss

In the process of transferring power, losses occur due to inefficiency in the power system. This loss is as a result of many factors, such as load balancing, low power factor, phase current, load factor and many more. The understanding of the effects of this loss, coupled with the knowledge of the minimum power required to energize a load, will give a clear direction on how to reduce the transmission losses.

Gaunt and Malengret (2013), show that most measurements in the power system are done under an ideal system called the conventional measurement of power losses (in which the power system operates in a sinusoidal waveform with a balanced supply and measuring the losses on reactive power associated with inductance L and capacitance C). In a non-ideal situation, the power factor representing the efficiency of the power to be transferred reduces further. With the GPT as earlier stated, losses are categorized as reactive power and distortion power. The reactive power is due to the inductive or capacitive reactance while the distortion is due to the unbalanced load and generator with harmonics of the system. More also, the effect of the DC or zero sequence current of the components which require energy storage will make the conventional measurement to give misleading results for transmission power loss allocation. Therefore, the development of General Power Theory (GPT) has shown that minimum possible transmission loss can be achieved; hence the new approach developed by Malengret (2008), will compel a critical look into the literature for ways of addressing non-ideal conditions following the IEEE definition to reduce the system losses [30].

1.5 Transmission Capacity Usage.

There should be transparency in line usage when dealing with allocation of transmission losses in a restructured power system. A critical look must be given to the capacity of the network used by individual power generator and the power consumed by each load that is connected to the transmission network since they all share the same network [31]. In the allocation of transmission losses, the extent of use of the transmission line must be considered separately for each participant since the network configuration, the generating capacity and the load consumption for each participant may be different. These factors all affect the Thévenin parameters of the system [32]. Although in a multi-wire transmission network, the supply voltage to the network is equal, both in magnitude and phase at the point of common connection, the change in connecting load and the power delivered by each generator affects all the Thévenin parameters of the network as they change with time [33]. Therefore, due to the negative and the zero sequence components, it may be difficult to achieve a balance current in the multi-wire system, so the Thévenin parameters of the system must be determined from the point of connecting each load and generator for the capacity usage transparency.

1.6 Hypothesis Statement

A more accurate and indisputable estimation of power loss allocation can thus be achieved by determining the Thévenin impedance of the system and utilizing the general power theory to unmask the avoidable losses on the network for tariff reduction.

To examine the validity of the hypothesis, it will be necessary to investigate the following research questions:

- What are the demerits of conventional methods currently in use to determine transmission losses?
- How does using the conventional methods (based on reactive power) differ from using the general power theory in the determination of power losses?
- What is the impact of the Thévenin impedance estimation on loss allocation using non-active power?
- How do we determine avoidable losses on transmission lines using the non-active power?
- How does this method change the cost/ tariffs?

1.7 Scope

The increase in the requirements for honest and transparent power allocation in the competitive environment, as well as the complexity introduced by unbundling the service point, is of great importance in the power sector. Therefore, the scope of this work is to critically analyze the relationship between the two different causes of loss of efficiency in the power system and allocate the losses using Thévenin theorem to individual participants (loads and generators). The work will differentiate between the losses due to reactive power and the losses due to distortion power as stipulated in section 1.4.

In the end, this thesis is expected to contribute to a critical evaluation of the various methods used in loss allocation in power systems, provide an extensive overview of the use of Thévenin theorem in the determination of line impedance and contribute a clear account of the present method to the literature. Also, in the process, new methods for estimating grid impedance and avoidable losses in the power system, as well as a method for transmission loss allocation will be developed. At the end of this research, the unnecessary loss (avoidable loss) in the transmission system will be determined to account for the non-unity power factor.

1.8 The Thesis Outline

Chapter One of the eight chapters of this thesis deals with the basic concepts and the introduction of a power system in a restructured environment. It also describes the evolution of power systems from vertically regulated monopoly to a restructured system. The chapter discusses the transmission loss, the theory which the research is based on, the research questions, the scope, and the research objectives.

Chapter Two of this thesis dwells on the review of the current methods of transmission loss allocation and line impedance measurement. The current methods used in allocating the losses, the merit and demerit in the ways transmission losses are allocated in solving the dispute between the generators and consumers in the electricity industry and the usefulness of Thévenin's theorem in resolving large power network system in the determination of equivalent circuit to be used in analyzing critical problems on the line.

Chapter Three discusses the effect of power losses due to an unbalanced load, the impact of harmonics on transmission losses, and the effect of neutral current on a power system. The chapter also differentiates between the conventional power triangle and the general power triangle which is the key part used in differentiating the conventional power loss and the new loss allocation proposed.

Chapter Four explains the theory development which is in two forms; for the determination of the Thévenin's equivalent component of the network from the PCC; Switching between two parallel loads to determine the change in current and voltage with time and the current injection method; this technique injects double harmonics current at different frequencies to the system to determine the equivalent parameters of the system. The two methods were simulated using MATLAB/Simulink.

Chapter five of this thesis discusses the laboratory implementation of the method of finding the Thévenin parameters of a power system, where a laboratory bench work was performed to verify the two methods of grid impedance determination.

Chapter Six shows both the results of the simulation with the laboratory bench work results with some mathematical calculations for the validation of the results.

Chapter Seven demonstrates the effects of the non-active power, the orthogonal current vector and loss allocation of some IEEE test systems. The chapter also breaks down the non-active current into its various orthogonal components which can be useful to design active and passive filters and is significant in power factor correction for both compensating and non-compensating losses.

Chapter Eight, the conclusion addresses each of the research questions, states the contributions of the research to knowledge and concludes by summarizing the work with a suggestion for possible improvement.

CHAPTER TWO
LITERATURE REVIEW

This chapter reviews the several methods that have been used in solving the problem of transmission loss allocation, for a more equitable share of the associated costs between electricity sellers and buyers. The chapter also discusses the need to reduce a large, complicated circuit into its equivalent smaller circuit, states the Thévenin theorem and its advantages, as well as where it has been used to solve power system problems. Finally, the chapter introduces the general power theory as a means of achieving minimum losses in the power system.

2.1 Review of Previous Methods

Several questions have been asked about the contribution of losses by individual generators and loads [34]. However, different procedures and techniques for loss allocation in the power system are presented in the technical literature to answer this question. Since there is no unique method for loss allocation due to the inseparable nature of electrical power loss and the real power. Any algorithm to be used should have most of the desirable properties stated below [35] [36].

- Agree with the measure of energy either produced or consumed (Kirchhoff's law).
- Should be based on the relative positioning on the grid network.
- Avoid volatility and be able to recover the total amount of losses.
- Provide appropriate economic marginal signals and avoid undue subsidization between participants.
- Agree with the result of power flow and be applicable to a different situation such as a change in generation and load patterns.
- Be easy to understand and should be based on the data gathered from that network.

- Be technically simple and transparent for implementation.
- Provide correct signals concerning the size and location of the network.

Pro Rata (PR) method can be termed the simplest and the most frequently used loss allocation method [37]. The method neglects the relative location of the system participants on the network and favours the remotely located load and generator making it inconsistent with the system power flow [38]. In another method called Marginal procedure, losses are assigned to generators and demands with the process of incremental transmission loss (ITL) coefficients, the method allocates negative losses due to its volatile nature [39] [37].

Proportional Sharing Procedure (PSP) sometimes called flow-tracing scheme, satisfies Kirchhoff's current law; it makes use of the results of a converged power flow, plus a linear proportional sharing principle to show that the network node is a perfect mix of incoming flows [40] [41]. This method does not provide efficient economic signals, and it is not based on any fairness criteria; hence, it has some degree of arbitrariness [42]. Wen-Chen, et al. (2004), proposed Circuit-based loss allocation method, in which system Z-bus matrix was used, and the Y-bus matrix was reconstructed without stating any assumptions. The Z-bus procedure gives a negative allocation to compensate those participants who contribute to reducing network losses due to their strategically well-positioned locations within the network [43].

The basic postage stamp method (PS), also known as the rolled-in method, consists of three components; the method which is commonly used in India ignores the actual system operation and is likely to send incorrect economic signals to the users [44]. Also, this method is not distance and direction sensitive; hence, it only depends on the amount of transacting power [29]. The primary advantage of the Relative electrical distance method lies in its applicability to multiple contracts/transactions simultaneously, but it is highly volatile and not economically marginal [45] [46].

MVA- MILE method considers the used and the unused (spare) network capacity; the real power loads pay for a locational charge proportional to its demand, and the reactive load is charged by the demand satisfied by the generators [18]. This method did not take into consideration the slack bus; it does not consider the unbalanced nature of the system, and hence, it is not economically marginal. Game theory-based methods are based on maximizing the benefit of each participant [47]. The method is suitable for a competitive scenario but seems cumbersome for a real system. It gives a rational decision that involves a conflicting solution and it is applicable to a limited large power system. The popular game theoretic approaches used in power engineering problems are Nucleolus methods, Shapley values, Aumann- Shapley value and the like [48]. The nucleolus is another loss allocation method introduced by Schmeidler in 1969; this involves two important characters which are (a) every game has one and only one nucleolus, and (b) unless the core is empty, the nucleolus is in the core [51]. This method is fair and impartial in its loss allocation, but it involves a lot of mathematical calculations, and it is time-consuming.

The independence of the slack bus is an advantage when using the Equilateral Bilateral Exchange method (EBE), but it is a purely mathematical concept which does not exist. However, in this way, all the different configurations of the generator demand become observable [45] [49]. Conejo, et al., (2003) came up with a method where the radial equivalent network was used to apportion the monetary value of losses, where modification was made to the work done by Rau in 2001. This method allocates the cost of losses in a straightforward manner, but it does not make an economic difference [50].

Daniel, et al 2005 [52] proposed a modified Y bus method which requires a single state-steady power flow solution with moderate computational effort, but it requires some mathematical matrix solution and does not take the unbalanced nature of the system into consideration.

The method for transmission loss allocation proposed by Kazemi and Andami [53] allocates transmission system losses to the participants, without considering any bus or buses as a loss compensator of the total system losses but based its judgment on each participant's share of total system losses. The method provides the possibility of power loss, self-compensating for all multilateral transactions and makes them completely independent of the market pool. The Incremental Transmission Loss method (ITL) is highly volatile and also allocates negative losses. The procedure creates an imbalance between generation and demand, thereby allocating higher loss to generators compared to the load losses [20].

$$ITL_{(k)} = \frac{\partial Losses}{\partial (Pog - Pd)} \quad 2.1$$

Where *Pog* is the power output at the bus (k) and *Pd* is the power demand at the bus (k).

Two procedures proposed by Ebrahimi, et al were based on the current projection and transmission function decomposition; this method provides a fair loss allocation but may give negative loss allocation [54]. Loop frame used in [55] follows the load flow solution to allocate the system losses, this method has the limitation of multiple loops and equally valid loops which may give a complicated result. The superposition theorem method of loss allocation proposed by Mustafa and Sulaiman (2008) was based on circuit theories which include KVC, KCL, and superposition law; the generator bus was treated as equivalent current injection and load bus as equivalent impedance; all the generators in the system were allocated with losses whether generator were active or not [56].

Mishra and Das [57] proposed an active method for an unbalanced system; the merit of this method is that it allocates the total active loss of the system to various buses, but the method allocates an excessive active loss to some consumers. Direct evaluation of loss allocation was carried out by Goswami and Basu in [58] where it is difficult to number the used buses and the system branches; this method can only solve a maximum of three nodes or branches. The method proposed by Gundugallu, et al [59] was used for radial distribution systems; it was effective for the lateral and the sub-laterals; it uses a simple equation, but it is only suitable for the radial system. In the method suggested by Fang and David [60], loss allocation is established along the sequence of the used generator; its outcome is highly volatile in nature.

Bhuiya and Chowdhury [61] suggested two methods of transmission loss allocation, the incremental load flow approach, and marginal transmission loss approach. ILFA requires long computational time due to the numbers of iterations, while MTLA which is based on the modification of

Kron's loss formula calls for a complex analysis of mathematical operations. The optimization method is good and suitable for large power systems due to the good objective function formulated; the method is complex and requires a long execution time [62].

A review of transmission power loss allocation and the suitability of each with its practicability has been presented in this section, Table 2.1 provides a summary comparison of the critical assessment of the different allocation methods discussed.

Table 2.1 A qualitative and quantitative comparison of various power loss allocating methods analysed.

Method / Characteristic	Proportional Sharing [42]	Game Theory [29]	Graph Theory [63]	Pro Rata [35]	Equilateral Bilateral Exchange (EBE) [45]	Incremental Transmission Loss [20] (ITL)	MW-Mile [64]	Optimization Method [62]	Relative Electrical Distance [29]
Quantity Dependent	✓	✓	✓	✓	✓	✓	✓	✓	✓
Network-Dependent	○	○	○	○	✓	✓	✓	○	○
Slack Bus Dependant	○	○	○	○	○	○	○	✓	○
Kirchhoff law	✓	✓	✓	○	○	○	✓	✓	○
Volatility	○	○	○	○	○	✓	○	○	○
Easily Understood	✓	✓	✓	✓	○	✓	✓	○	✓
Simple	✓	✓	✓	✓	✓	✓	✓	✓	✓
Economic difference	○	○	○	○	○	○	○	○	○

The section and the table have shown that each of the methods depends on the study objectives and the structure of the market in which it is to be used without considering a case of multiple wires with different line parameters and generators (unbalanced). However, there is still no consensus on the choice of algorithms to be used in the transmission loss allocation up to date. Thus, allocation of transmission loss and its cost is a complex problem; it involves the recovery of the embedded or fixed cost of transmission system losses from multiple network load and generators, from many agents with free access to transmission networks. But it was discovered that none of the models used, gives account for the total inefficiency nor separates the losses into its components being aware that the inductive or the capacitive reactance is not the only cause of inefficiency in the delivery of power that leads to transmission losses. *Unbalanced loads across the three phases result in an out-of-phase balance voltage drop, which makes the resultant current return to the source through the fourth wire called the neutral, which leads to increase in total loss* [65].

2.2 System Equivalent Circuit

The equivalent circuit simplifies calculation of complex circuits and brings to fore the ideas of the input and output impedance, it makes a complicated functional circuit easy to work on, hence simplifying a complex circuit at any point of view as if it consists of only one source and a single line impedance [66]. It makes simulation faster and required less storage with less up-to-date data requirement; in view of this finding, the Thévenin equivalent circuit of a system from the point of common coupling will reduce the system to an appreciable equivalent in the allocation of power loss to the individual participant. Moreover, it is easier to resolve a complex system with multiple generators, loads, and wires when the Thévenin equivalent of the system is determined [67].

An equivalent circuit is a simpler form of a complicated network as shown in Figure 2.1. The two predominantly used equivalent circuits are the Norton's and the Thévenin's theories, which only differ by their source, that is, current and voltage source respectively as shown in Figure 2.2. The equivalent circuit impedance (Z_{eq}) is the same in both theorems, and the source value is related by equation 2.2.

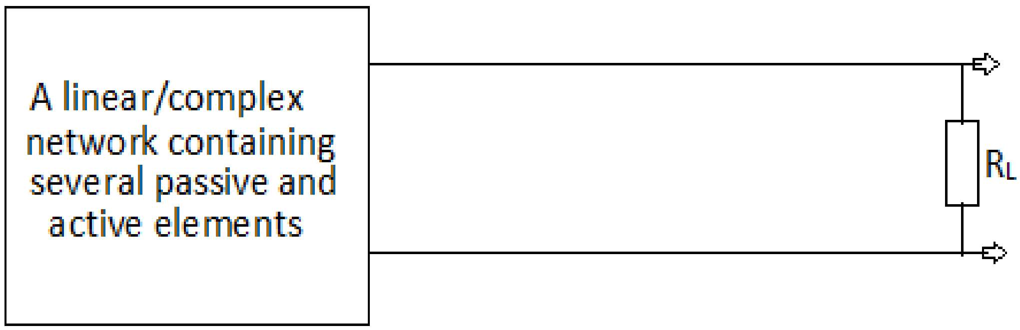
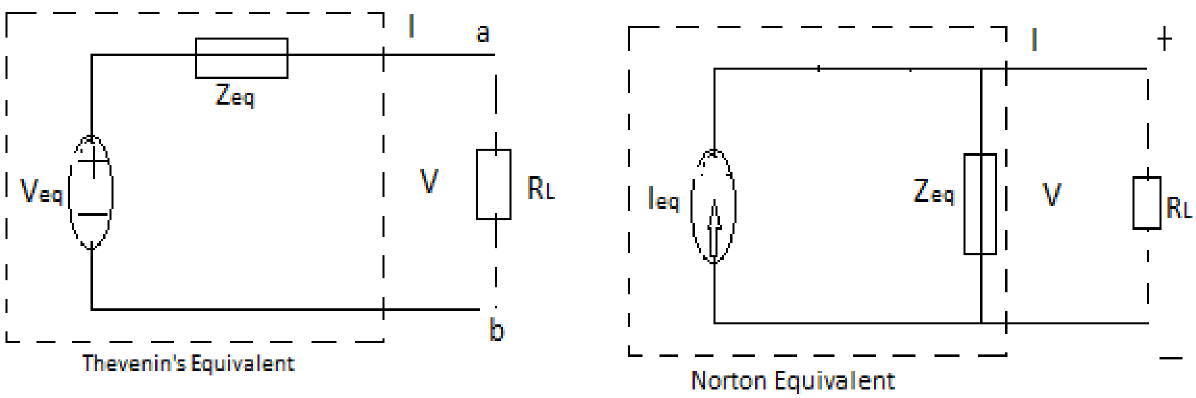


Figure 2.1 Power Network with the different subsystems.



(a) (b)

Figure 2.2 Equivalent circuits: (a) Thévenin's (b) Norton's

2.3 Thévenin's Theorem.

The Thévenin theory states that in a linear circuit with two ends a and b that contains many voltage source generators can always be replaced with a single voltage generator V_{Th} that will be in series with the line impedance Z_{Th} connected across the two points [68]. With the increasing number of photovoltaic and wind farms being connected to the grid, the easiest way of having good information of the power grid is by using Thévenin's theorem in the determination of the equivalent circuit of the network. The theorem can be defined mathematically as the 'systematic elimination of circuit voltages and currents in the linear equations expressing Kirchhoff's and Ohm's law [69]. Due to the usefulness of Thévenin theory, it has found its way in different applications for solving different problems in electrical and electronic networks.

With the theorem of Thévenin, we can substitute the whole system with its equivalent circuit that takes only an independent generator (voltage) source in series with the entire impedance (resistor), such that the relationship between the current-voltage with the load still maintains. Also, Thévenin's theory can be used to incrementally simplify circuits into stages; this theorem has been used to solved problems such as, power fault detection, power fault location, Load matching for maximum power transfer, state of charge estimation for battery bank, simultaneous estimation of Thévenin equivalent of multiple source, load management, voltage stability margin adjustment, investigation of power system behavior, study of renewable energy penetration to the grid and many others [70]. Thévenin's theory can also be used to analyze the features of a complex power network of a country where the whole system can be simplified to its Thévenin equivalent circuit as one single finite-bus system for simplicity.

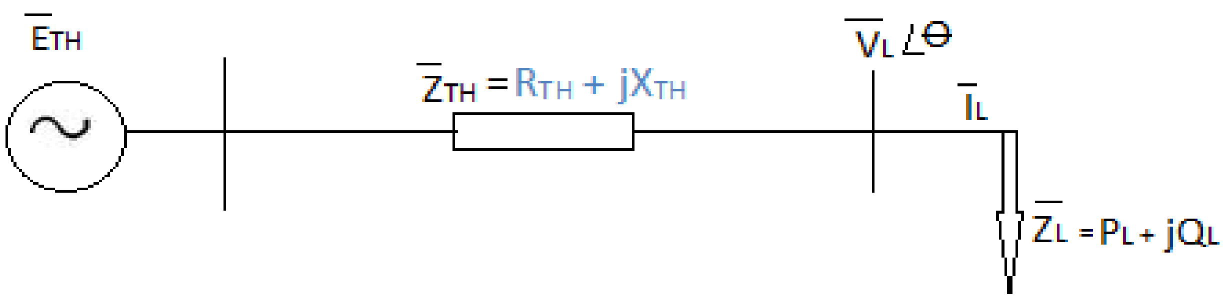


Figure 2.3 A simple 2 bus Thévenin equivalent circuit.

Looking at the single line diagram of the electrical circuit in Figure. 2.3, the Thévenin equivalent of the circuit parameters is calculated using Kirchhoff's law, by taking the current $\vec{I}_L$ and voltage $\vec{V}_L$ as seen from the point of common coupling of the load. Hence, this can be achieved by equation 2.2.

$$\vec{V}_{\mathrm{L}} = \vec{E}_{\mathrm{Th}} - \bar{Z}_{\mathrm{Th}}\, \vec{I}_{\mathrm{Th}} \qquad 2.2$$

and

$$\bar{Z}_{\mathrm{Th}} = \mathrm{R}_{\mathrm{TH}} + \mathrm{jX}_{\mathrm{TH}} \qquad 2.3$$

In solving many problems in power systems, Thévenin's equivalent has been crucial in the measurement of the line parameters. Different methods have been proposed for the identification of Thévenin's equivalent of power networks, but most of the methods have not been compared explicitly with each other in solving network problems; moreover, some of these methods are tested on false measurements of power flow result [71].

The Tellegen based Theory (TT) '*is based on Kirchhoff's current and Kirchhoff's voltage law and the topology of the network either linear or nonlinear, time- invariant or time variant reciprocal or non-reciprocal, hysteretic or non-hysteretic'* [72]. The procedure is based on the change in current (ΔI) and change in voltage (ΔV) phasor in the branches of two networks, the incremental and the adjoint networks which must be identical. The authenticity of this method is confirmed by the installation of phasor monitoring units (PMUs) at the bus [71].

The Adaptive method (AD), as proposed by Corsi and Taranto [73], takes the assumption of the Thévenin Resistance $R_{Th} \approx 0$. This was based on the inference that in high voltage, R_{Th} can be negligible since the Thévenin Inductance is usually greater and of high value. The success of identification is based on the tuning parameters of the system, but the method involves many processes. The Least Square method (LS) is used to determine the Thévenin equivalent by the installation of PMUs in all the load buses, and the computational time is relative to the size of the window which is the measuring time per second. The method is often used to determine Thévenin equivalent, but it shows that a single measurement cannot give a good equivalent estimation due to many unknown variables involved with just two equations.

The Couple Single Port circuit (CP) method shows that '*when dealing with multi-load systems, the power system load is nonlinear and dynamic and that, they cannot be easily equivalent to Thévenin's* *impedance'* [74]. This method proposed a single port circuit where all the loads are out of the equivalent circuit; hence, the loads can be extensively dealt with. It recommended three different models to represent the load coupling effect where the virtual impedance model is taken to be most suitable. The couple single port circuit can be obtained through the phasor measurement of the targeted generator bus and the load bus from PMUs. This method is faster in running the system power flow and it also recognizes critical buses without using nodal analysis, but with this method, PMUs must be installed at every generator and load buses. The extended Thévenin method is seen as an extension of the real Thévenin's theorem, which was stated as, '*the ideal method comes from the fact that, the computational complexity is reduced significantly if the network is divided into sub-network to be solved separately'* [75]. The method which is computationally complex is suitable for large optimization problems that involve a huge number of calculations, and a complex circuit with more than two terminals is split into the following four stages,

(i) Splitting the circuit into sub- systems

(ii) Getting the equivalent of each of the sub-systems

(iii) Combining the solved sub-systems together

(iv) Getting the equivalent circuit of the sub- systems of interest.

Thévenin method used as a guide in the Gauss-Newton Algorithm was successfully achieved by the model, the line parameter used gives an appreciable percentage of error in both the simulation and the laboratory experiment [76]. The method does not take into cognizance the harmonics in the system when a non-linear load is connected to the system. Asiminoaei, et al [77] also developed a faster way in grid impedance estimation which can be suitable with the required standard when combining it with DSP that is being controlled by a PV converter. This technique is free of additional hardware when in use with PV inverter, CPU and the sensor. It also requires the injection of non-characteristic harmonic current while taking the response from the grid voltage in evaluating the grid impedance. The method is economical and simple in implementation but has the drawback of post-processing the result to eradicate random errors and A/D flickering [77].

2.4 Determination of Thévenin's Impedance.

In power loss allocation, it will be easier and more effective to transmit power when the current and the voltage are in phase using two wires and a single generator, but the situation differs when dealing with a larger power system with multiple wires and different line of Thévenin parameters [33]. Effective transmission and distribution of power requires adequate security margin because *the line impedance always continuously changes with loads, network element, and system conditions* [78] [79]. To achieve a smooth power flow, the maximum allowable load needs to be estimated. The effective system perturbation is made in the determination of the Thévenin impedance. The Thévenin Impedance represents a lot of equipment gathered together with a single value Z_{Th} which characterizes the resistance, the reactance and the voltage of each wire, and all these are time dependent on the changes in load and the generator factors [80]. Hence, all these pieces of equipment can be added together as a single entity when working to solve problems such as power loss, fault allocation and many others in power system. The Thévenin impedance at the bus in a power system is a simple and accurate reduction of a larger power system as seen from that bus which enables the complete assessment, control, and monitoring of the whole system to be implemented easily [81].

2.5 The General Power Theory

The General Power Theory has redefined the separation of non-active power as two orthogonal components that reduce the efficiency of power delivery to the load as, components that can be compensated within the lines without the requirement of energy storage and the components that require energy storage, [82], [83], [84]. These two components are also orthogonal to the real power P delivered to the load [65]. The losses caused by the effect of inductive and the capacitive reactance (Reactive Power) can be reduced by power factor correction using banks of capacitor close to the load. The unbalance and any effect of distortion on the power system (distortion power) can be resolved through compensation locally to increase the power factor of the system (avoidable loss).

When referring to the efficiency of the power delivered to the load, the resistance of the wire used in transferring the power is an important issue either in an ideal condition with resistive load or in a non-ideal condition of a complex load. With the general power theory, the current in the neutral must be taken into account when dealing with the efficiency of the power delivered to the load, likewise, a suitable voltage reference point must be used (virtual null point) for the system voltage [65].

Malengret and Gaunt, in [84], show a simplified derivation of the algebraic calculation of a general instantaneous active current of a system with a different resistance of m wire. This approach shows the minimum losses that can be achieved when energizing a load for energy conservation and tariff reduction.

2.6 Summary

After critically reviewing the various methods that have been used in the literature for loss allocation in power systems, the chapter analyses the different methods used and how this loss is allocated to the system participants, as well as the deficiency in some of the methods with respect to their characteristics such as network dependency, volatility and economic advantage. The chapter also discusses the relevance and aim of using the Thévenin equivalent from the point of connecting the load/generator in the allocation of transmission losses. The chapter points out the importance of finding the Thévenin equivalent of the network, which scales down the complexity of the network and takes into consideration multiple lines with different line parameters.

A review of the methods used in impedance measurement was also carried out, and this revealed that most of the methods either inject a disturbance into the network or require initial information for the impedance estimation. The Tellegen’s theorem, though not new, can be suitable for the passive method when modified because it obeys Kirchhoff’s laws; it is applicable to multiple networks and provides a simple tool for network analysis. The modification can be done on it to avoid the need of PMUs. The major disadvantage of these methods is that they failed to realize that the inductive and capacitive reactance of the load are not the only causes of inefficiency in power delivery. Thus, none of the methods show the procedure for reducing the losses by raising the power factor, whereby compensation can be done locally for Q to achieve a reduction in delivery loss for minimum active power (P). Furthermore, the current in the neutral is not being accounted for; hence, the apparent power in the conventional power allocation is not properly defined.

The chapter has established the critical review of the merits and demerits experienced in the current method of loss allocation to answer one of the research questions developed in Chapter One; (**What are the demerits of conventional methods currently in use to determine transmission losses?**). In validating the Hypothesis, a novel method of determining the line impedance is considered using Thévenin theorem without the requirement of the system initial information and PMUs, that will combine most of the advantages of the method in literature as described in Chapter Three.

CHAPTER THREE

TRANSMISSION LOSSES, AND POWER TRIANGLE

This chapter discusses power loss due to an unbalanced load, harmonics, impacts on transmission losses, the current in the fourth wire and how they all affect the system efficiency in delivering power. It also points out the effects of the types of the load connected on power delivery and generated power taking to account the losses that may arise due to the connected load power factor, remembering that the higher the power factor, the lower the system losses. The conventional power measurement is also differentiated from the general power theory as highlighted through the power triangle.

3.1 Power Loss in line

According to Michelle (2010) [85], approximately $20e^9$ kWh of electrical energy was lost in the power system comprising of the transmission and the distribution lines in California in the year 2008. This is equivalent to about 6.9% of the energy consumed in the state of California for the same year. This loss is amounting to, 2.4 billion dollars in estimation at the rate of $0.1248/kWh in California; these losses are due to the resistive and the coronal loss without the inclusion of the inefficiency introduced by unbalance in three-phase system which reduces the efficiency of the power transfer or the power factor that returns current through the fourth wire.

Unbalanced load in the power system is a major disturbance of the line current and the voltage of the system from achieving the pure sinusoidal waveform. The effect, leads to the increase in the power loss and energy tariff due to the heating it causes on the power line. The increase in the harmonics in a power system due to unbalanced load should always be avoided, not only for the economic reason but also for the technical reason.

Non-linear load on power system results in the flow of current in the neutral line of three phase four wire system which results in the losses in both the phase conductor and the neutral conductor of a power system.

If the power loss in the Red, Yellow, and Blue phases that is the three phases of the system is.

$$P_{LP} = (I^2_R + I^2_Y + I^2_B)\ R_P \qquad 3.1$$

And the power loss in the neutral conductor of the system is,

$$P_{NC} = I^2_N\ R_N \qquad 3.2$$

Hence the total power loss P_{Loss} is,

$$P_{Loss} = P_{LP} + P_{NC} \qquad 3.3$$

Taking R_P as the resistance of the neutral conductor with I_N the RMS value of the neutral current. $I_{R,}$ I_Y, and I_B are the RMS values of the currents in the red, yellow and the blue line of the phases.

3.2 Harmonics Impact on Transmission losses.

Today's electrical loads are of a variety of semiconductor devices and motors which make harmonics become a major issue in power system quality. Anne, et al. (2011) define harmonic distortions as a form of disturbance in the power system that can cause problems if the amount of the harmonic current increases above certain limits [86]. It was defined by Celal, et al. (2013) as components with periodic waveforms having multiple of the fundamental frequency [87]. Harmonics arise due to the generation of non-sinusoidal current or voltage in the power system; the current harmonics are the effect of the drive construction which may be from an unbalanced load while voltage harmonics, are the effects of the current distortion and the line impedance of the system. Harmonic effects can be majorly divided into four major parts which are,

(a) Effect on the system Tariff

(b) Effect on other connected loads

(c) Effect on the system power line

(d) Effect on the communication circuit

Moreover, with a high order of harmonic components in a power system, the inductance and the resistance of the transmission line develops some effects [88].

(a) Distortion of the main voltage and current.

(b) Source over-sizing and apparent power increase, leading to overloading

(c) Capacitor Damage due to increase in current across the dielectric material of the capacitor

(d) Harmonic resonance due to high voltage, leading to high heat in the transformer system

(e) Overloading of the neutral conductor and transformer due to the high phase current

(f) Conductivity loss due to skin effect in the system caused by high resistance

(g) Power system losses due to the effect of the reactive components and high current returning, through the neutral wire in three phase four wire system.

In the determination of the total harmonic distortion of a system, the square root of the sum of the square of the harmonics in the system voltage divided by the fundamental voltage of the system is useful as it also applies to the current which is as shown in equations 3.4 and 3.5

$$THD_v = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \qquad 3.4$$

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \qquad 3.5$$

From the equation, Vn and In are the RMS voltage and current of the n^{th} harmonics respectively whlie V_1 I_1 are the RMS voltage and current at the fundamental frequency respectively, in relation to a particular load. The total demand distortion, also known as the total current distortion, at the PCC where the maximum current demand by the load is I_L, is taken to be,

$$TDD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L} \qquad 3.6$$

3.3 Neutral Current

In a power system that comprises a star connection of four wires, the current in the neutral wire is the vectorial sum of the three lines. This is usually zero in a three-phase system with a balanced load. In this case, the load is linear, and the system sine wave in each phase is 120 electrical degrees from the others as described in Figure 3.1

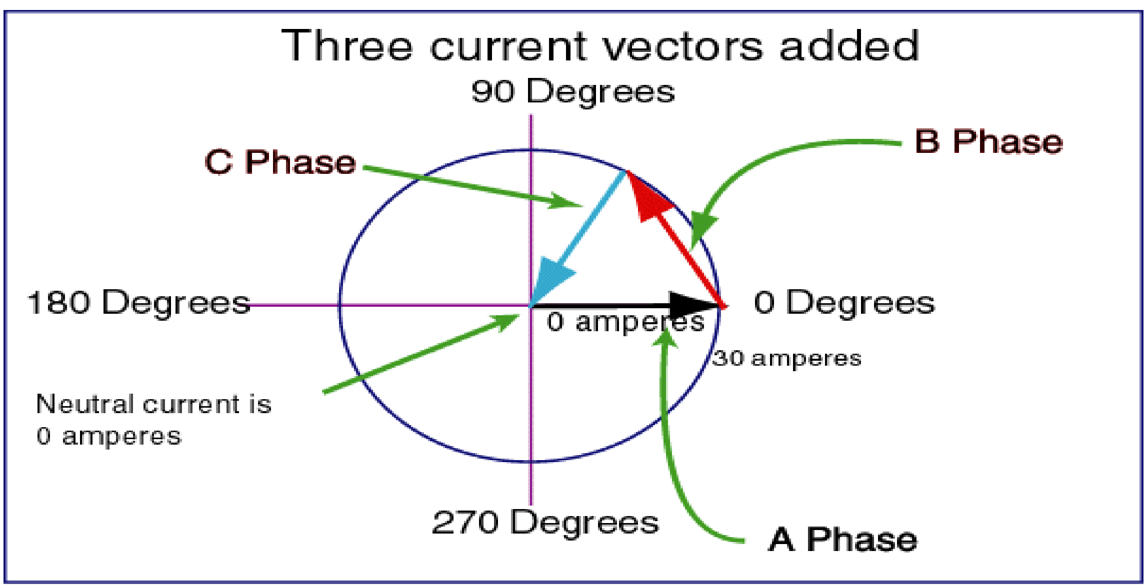


Figure 3.1 A balanced linear 3-phase system with zero current in the neutral [1].

Although in some instances, there are some cases where three perfectly balanced single-phase loads result in a significant neutral current, these are the result of nonlinear loads, load changing, load shift, and/or load diversity due to switching and rectifiers which produce a non-sinusoidal waveform. The vector sum of such is not necessarily equal to zero even if it is three phase balanced system; since it is non-sinusoidal for instance, a balanced square wave current will result in a significant neutral current [89]. Most pieces of equipment with switching mode are of this character which also draws high third harmonic currents (150Hz). The third harmonics and its odd multiples, that is, 9th, 15th, do not eliminate in the neutrals; it sums to a high neutral current in a three phase four wire power system, the unused current returns through the neutral as shown in Figure 3.2 to increase the system losses.

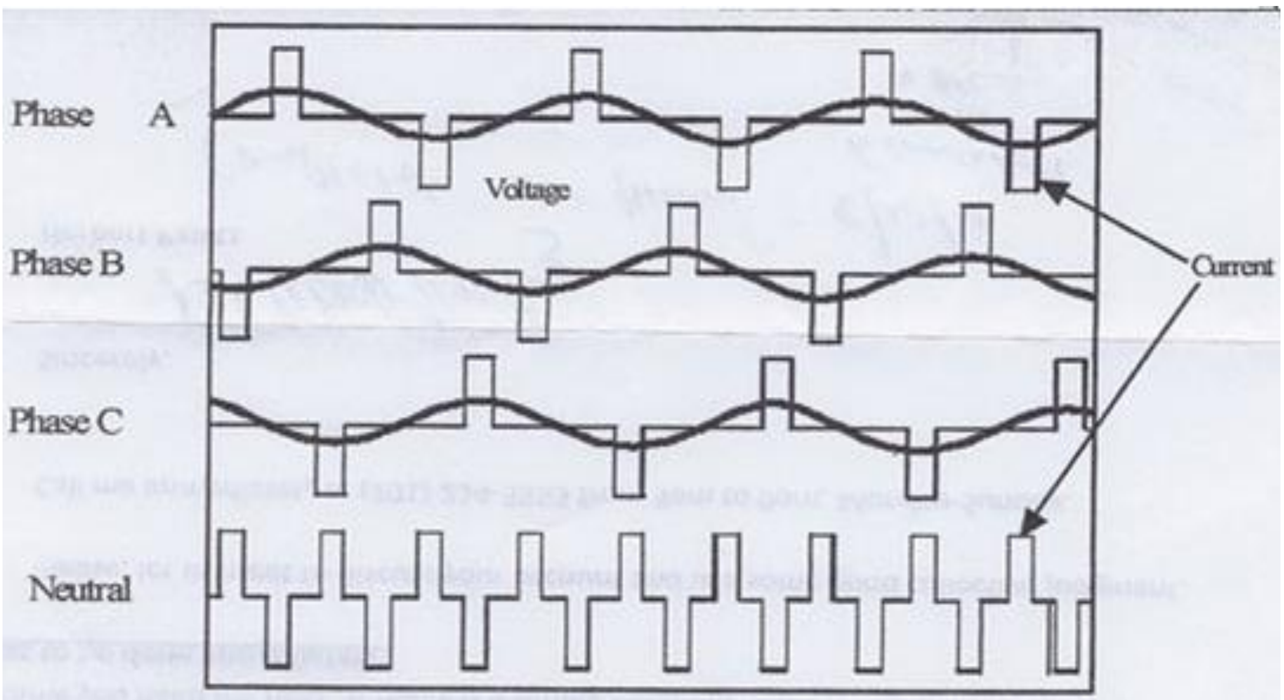


Figure 3.2 A balanced linear 3-phase system with neutral current [2].

However, in the rigorous work done in [90], it was observed that the maximum power that is AP can be transmitted when the resistance is zero

3.4 Impact of Load and Voltage Reduction on Losses

Connected load type is of great effect on power demand and power loss in the power system. The accuracy of the model used in determining the load to be connected to the system is of great importance to predict the losses in the power system. Paul and Jewe [91] analysed three common ways to model a load which is:

(a) The constant Impedance load model, that is, Z (constant); this is a static load model where both the active load and the reactive load are directly proportional to the square of the voltage magnitude:

$$P_{load} = (\frac{V}{V_1})^2 * P^a_{Load} \qquad 3.7$$

$$Q_{Load} = (\frac{V}{V_1})^2 * Q^a_{Load} \qquad 3.8$$

Taking

P^a_{Load} and Q^a_{Load} as the rated active and the reactive load respectively at voltage V_1 while

P_{Load} and Q_{Load} are also the rated active and reactive power respectively at voltage V.

In this model, a decrease in the voltage will lead to a decrease in the load; hence reducing the current.

(b) The constant current model, that is, I (constant); this is a static load model in which the active and the reactive powers are directly proportional to the voltage magnitude:

$$P_{Load} = (\frac{V}{V_1}) * P^a_{Load} \qquad 3.9$$

$$Q_{Load} = (\frac{V}{V_1}) * Q^a_{Load} \qquad 3.10$$

In this method, there is a reduction in the power consumed when the voltage is reduced compared to the constant impedance load model; hence the current remains constant leaving the line loss the same.

(c) A constant power load model, that is P + jQ (constant); this is a static load model in which the active and reactive power is constant; hence the power does not change with the voltage magnitude.

For a constant power load, the reduction in voltage leads to an increase in the current proportionally; with this, there is an increase in energy tariff due to the increase in the line loss with the same load connected to the system.

3.5 Power Factor and Non-linear Load

In the explanation of power factor, consideration should be made on the total power factor of a system, that is, the displacement power factor and the distorted power factor [92]. The harmonics content usually increases the divergence between the displacement power factor and the true power factor in a power system [47]. Reviewing the power factor for linear load with a single frequency, the instantaneous values of the current and voltage are,

$$I(t) = I_m \sin(\omega t - \varnothing) \qquad 3.11$$

$$V(t) = V_m \sin \omega t \qquad 3.12$$

$$\omega = 2\pi f$$

V_m *and* I_m are the maximum values of voltage and current of the sinusoidal waveform. The instantaneous power (P) is the product of the instantaneous current and instantaneous voltage;

$$P = V.I = V_m \sin \omega t \; X \; I_m \sin(\omega t - \varnothing) \qquad 3.13$$

From 2. sin A. sin B = cos (A - B) - cos (A + B), it becomes,

$$P = \frac{V_m I_m}{2} cos\varnothing - \frac{V_m I_m}{2} \cos(2\omega t - \varnothing) \qquad 3.14$$

The active power which is the average or mean of the instantaneous power can be calculated as,

$$P = \sum_{n=1}^{\infty} V_n I_n \text{Cos}\,(\emptyset_n) \qquad 3.15$$

And the reactive power is represented by the equation below:

$$Q = \sum_{n=1}^{\infty} V_n . I_n \sin(\theta_n - \delta_n) \qquad 3.16$$

The power factor (Pf) of a system is defined as the ratio of the active (P) power to the apparent power (S) that is, the active power is the product of the power factor and the apparent power, it is also the cosine of the angle between the voltage and current [47].

$$Pf = \frac{P}{S} = \cos\emptyset \qquad 3.17$$

Hence, the power factor is the actual fraction of the apparent power doing the real work in the power system.

In an undistorted linear circuit, the power factor is called a displacement power factor (dPf),

$$dPf = \frac{P}{\sqrt{Q^2 + P^2}} = \cos\emptyset \qquad 3.18$$

Moreover, apparent power (S) of a distorted power is said to depend on the following qualities, the real power (P), the reactive power (Q) and the distortion power (D), it measured volt-ampere as in (equation 3.19); in a pure sinusoidal system, distortion power is zero [93].

$$\text{Hence} \quad S = \sqrt{D^2 + Q^2 + P^2} \qquad 3.19$$

Hence, in a distorted power system, the RMS values of current and voltage with harmonic are:

$$I = \sqrt{I_1^2 + I_2^2 + I_3^2 \ \dots\dots \ I_n^2} \qquad 3.20$$

$$I = I_1\sqrt{1 + THD_I^2} \qquad 3.21$$

While the voltage is,

$$V = \sqrt{V_1^2 + V_2^2 + V_3^2 \ \dots\dots \ V_n^2} \qquad 3.22$$

$$V = V_1\sqrt{1 + THD_V^2} \qquad 3.23$$

Taking the active power to be AP and the non-active power to be ($Q_a^2 + Q_A^2$) and from equation 4. 19, the apparent power now becomes

$$S_{app} = \sqrt{AP^2 + (Q_a^2 + Q_A^2)} \qquad 3.24$$

The power factor will now be the true power factor which is not equal to the cosine of the angle between the voltage and the current [47], which is,

$$tPf = \frac{AP}{Sapp} = \frac{AP}{\sqrt{AP^2 + (Q_a^2 + Q_A^2)}} \qquad 3.25$$

In determining the efficiency concept of the load current in a power system, power factor is used, as unity power factor shows a balanced sinusoidal voltage and current without any neutral current [94]. Using a system with a distorted waveform, the distortion power factor is,

$$Pf_{distortion} = \frac{1}{\sqrt{1+THD_I^2}\sqrt{1+THD_V^2}} \qquad 3.26$$

However, the neutral current in an unbalanced power system is undesirable, and it creates an increase in the system power loss; the most effective way to reduce the fundamental current in the neutral is by ensuring load balance across the three phase supply system [95]. Equation 3.27 below can be used to illustrate the power loss in a three phase four wire system.

$$P_{Loss} = (I_R^2 + I_Y^2 + I_B^2) \, . \, R_L + I_N^2 . \, R_N \qquad 3.27$$

taking I_R, I_Y, and I_B as the current in each line, I_N as the current in the neutral line, R_L and R_N are the resistance of the line and the neutral respectively.

3.6 Balanced and Unbalanced Load

The relationship between the current and the voltage waveforms in an alternating current (ac) circuit shows the implication of balanced or unbalanced effect of the load on the system. In a balanced three-phase ac system, the voltage and the current are to be equal both in magnitude and angle with the displacement of 120^0 from each other as shown in Figure 3.3. The harmonic of the phase current and that of the voltage have equal magnitude and well-known phase sequence, at fundamental, the harmonic in a balanced system follows a symmetrical rotation, while the odd harmonics follow the sequence component theory. The anti-clockwise movement of the R, Y, B, (A, B, C) three phases of a power system can be represented in the following sequence at the fundamental frequency:

$$I_R^{(1)} = I_R^{(1)} < 0^0$$

$$I_Y^{(1)} = I_Y^{(1)} < -120^0$$

$$I_B^{(1)} = I_B^{(1)} < +120^0$$

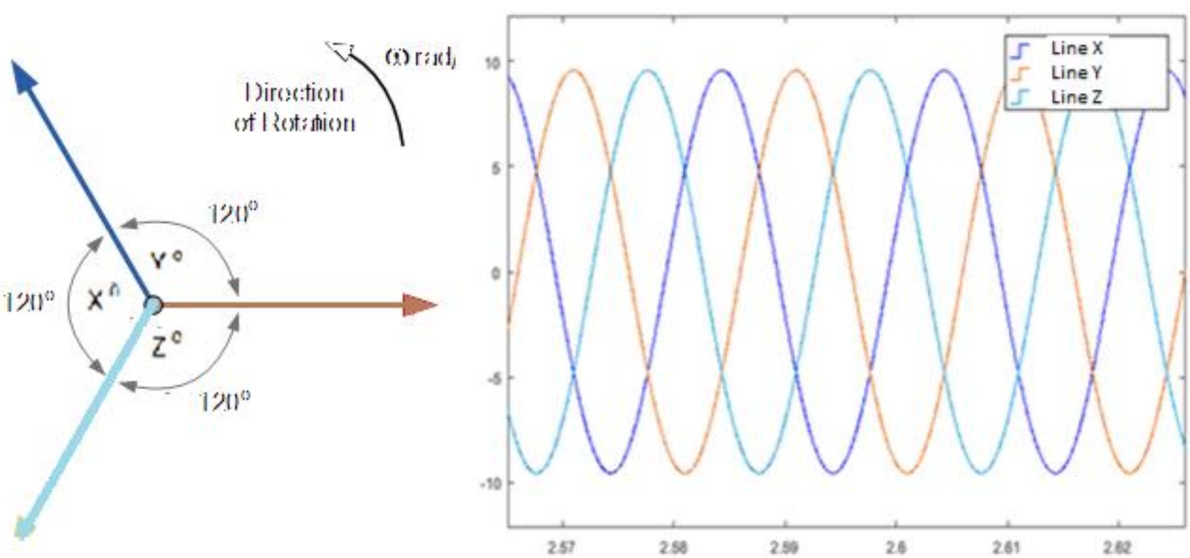


Figure 3.3 Waveforms of a balanced load system. (X = Y = Z)

The principal causes of an unbalanced system at the customer side are the operative factor; the odd harmonics do not follow the sequence component theory as the balanced system does, since the phase and the magnitude of fundamental and harmonic are not the same. Due to the latest technology in power system, harmonics problems have arisen in different homes and offices since, modern power electronics equipment such as printers, monitors, computers, auto-teller machines and many other telecoms systems, are mostly non-linear loads. Each harmonic in an unbalanced system needs to be treated differently by applying symmetrical component theory since they are displaced at a different angle. In an unbalanced situation, the three-phase current I_R, I_Y, I_B do not add up to zero in phasor addition, and there will be a significant value of current flowing through the fourth wire (neutral).

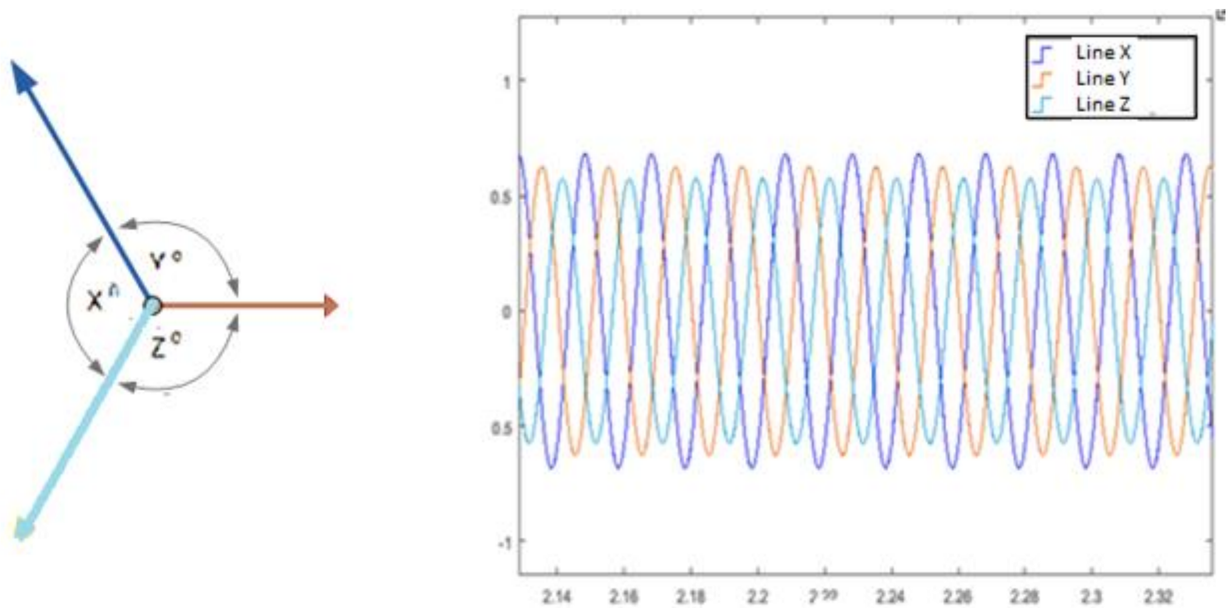


Figure 3.4 Waveforms of unbalanced load system (X ≠ Y ≠ Z)

Figure 3.4 above shows the level of harmonics created by the unbalanced load in the network system; this shows that it will be difficult for a system of an unbalanced load to supply current at fundamental, and this will lead to the generation of heat in the system through the return wire to the transformer which not only causes damage to equipment but also leads to power loss. The most common in this category are fluorescent, gas discharge bulb, the wind and solar power generator, computer, copy machines, television sets, battery charging, fuel cells and electrical arc-furnace all of which make nonlinearity between the current and the system voltage.

3.7 Causes of Unbalance.

The system operator tries to always provide a balance to the voltage at the PCC between the customer and the electricity provider; meanwhile, the voltage at the PCC is always determined by the load current from the customer’s end, which is subjected to balanced or unbalanced load since unequal coupling in the transmission line system is not always symmetric.

Unbalance in a power system can be due to different factors which include:

- Single phase loading in three phase systems.
- Unequal coupling between transmission lines.
- Voltage unbalance due to single phasing condition

3.8 Power Losses due to unbalanced Load

The introduction of harmonic load leads to change in the parameters of the system since electrical energy is shared among the nodes based on the line impedance. Although the system voltage is balanced in accordance with the Kirchhoff’s Laws, whenever the configuration changes, the flow shifts, and the generation also shifts with the load requirement [96].

The power loss on the line P_L in such a system is the sum of the losses experienced in the phase P_P and the losses in the neutral conductor P_N;

$$P_L = P_P + P_N \qquad 3.28$$

Where

$$P_p = (I^2_{L1} + I^2_{L2} + I^2_{L3})\, R_P \qquad 3.29$$

$$P_N = I^2_N R_N \qquad 3.30$$

I_{L1}, I_{L2}, and I_{L3} are the RMS values of the current in phases 1, 2 and 3.

R_P is the resistance of the phase conductor.

I_N is the RMS value of the current in the neutral conductor.

R_N is the resistance of the neutral conductor.

Hence, the efficiency of generation and supply **cannot** be based on the assumption that the voltage, and current waveform are in phase, balanced and purely sinusoidal. With respect to this, the present transmission charges in many countries are likely to change

The unbalanced load on power system leads to distortion of current and system voltage from the sine wave; affecting power quality and power, delivery in the transmission system of electricity. This can only be improved by a good transmission tariff that takes into accounts the effect caused by the presence of non-active power [97]. Efficiency in the delivery of power is not limited to the correction of the displacement angle between the voltage and the current alone, but also by balancing the loads in a three-phase power system always on the network; hence reducing the losses and increasing the efficiency of the generated and delivered power. Non-linear loads cause serious problems in power system due to the introduction of harmonics into the system; the harmonics lead to higher heating of the system equipment, component aging, and reduction in the efficiency of the power system with increases in the system losses (line and transformer).

Unbalanced loads on power systems are problems both economically and technically. In addition to increasing the cost of generating power, it affects the choice of system equipment, such as conductors and transformers.

3.9 The Conventional Power Triangle

In a power system, the instantaneous power p(t) delivered to a three-phase load in one period of a waveform is the sum of the product of the instantaneous current i (t) and the instantaneous voltage v (t) in each of the phases measured from a common point called the neutral point as shown in equation 3.31 below. The real power P in such a system is the average of the so called instantaneous power over a cycle, while the apparent power S that is, the vector sum of the real power P measured in (W) and the reactive power Q measured in (Var) that appear in the system over a cycle, is the sum of the products root mean square (RMS) of the system current (I_{RMS}) and the system voltage (E_{RMS}) in each phase, measured in (VA) as shown in equation 3.32. The three components of power are related using the conventional power triangle shown in Figure 3.5.

$$P(t) = e_1(t) \times i_1(t) + e_2(t) \times i_2(t) + e_3(t) \times i_3(t) \qquad 3.31$$

$$S = E_1I_1 + E_2I_2 + E_3I_3 \qquad 3.32$$

The power factor in the conventional triangle is the measure of the system efficiency in transferring the electrical energy on the power line and it is the ratio of the real power (P) to the apparent power (S)

$$Pf = P/S$$

However, in a practical power system with real and reactive power, there is a phase angle between the system current and the voltage which is denoted by the power factor angle φ; this angle depends on the reactive power of the system.

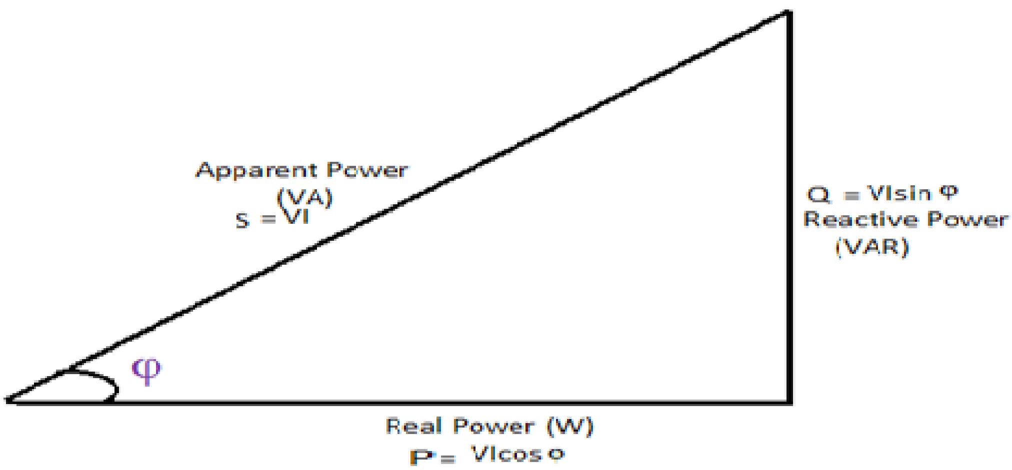


Figure 3.5: Conventional Power Triangle

3.10 The General Power Triangle

In the calculation of power loss caused by the load and the generator, the total losses as determined using the conventional power triangle only define the reactive power which is represented by Q (inductive and the capacitive Var) as seen in Figure 3.5. However, the rigorous work done by Gaunt and Malengret in [83], developed a theory on instantaneous power from linear algebra and vector analysis around a multi-phase system, the work defines instantaneous current as compensated supply line current that gives instantaneous power with minimum line losses when the voltage is constant. The work was further extended to the difference between the term reactive power and non-active power in a companion paper [65]. The paper gives the idea of the total inefficiency caused by harmonics, unbalance, zero sequence or DC component since this inadequacy cannot be related to the displacement angle between the load current and the voltage vector. The concepts of reactive power and distortion power introduced by Gaunt and Malengret [65] give the awareness of reactive power as capacitive and inductive components, while distortion power is caused by the unbalance and harmonic distortion. However, the two components which are orthogonal to each other are termed non-active power. Figure 3.6 shows the extended three-dimensional shape power triangle, where Q (the total non-active power) is separated into two orthogonal components which are, Q_a the components that can be compensated without energy storage and Q_A the components that require energy storage for compensation [97].

According to Gaunt and Malengret [65], the two causes of inefficiency, also known as the non-active power of the power system are as shown in the extended three-dimensional shape in Figure 3.6.

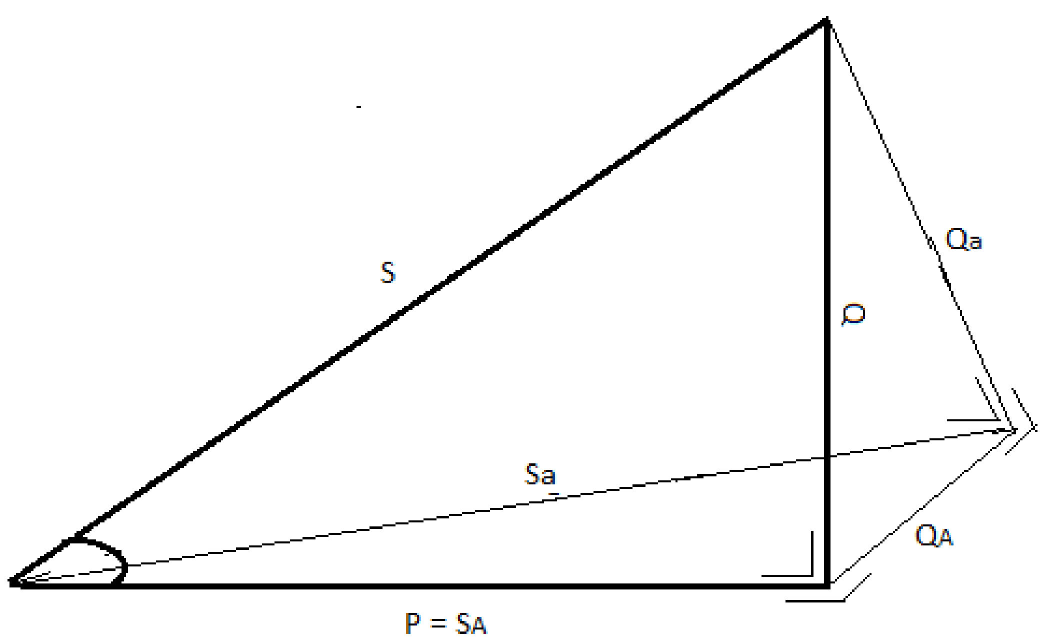


Figure 3.6: The extended three-dimensional shape power triangle, in which *Q = total non-active power, where Q_a is the component that can be compensated without energy storage and Q_A the component that requires energy storage for compensation. S = apparent power without any compensation, Sa the apparent power after compensation without energy storage, and S_A the apparent power after complete compensation, so that P= S_A* [65]

$Q^2 \quad = \quad Q_a{}^2 + Q_A{}^2$ 3.33

Reactive power Q in Figure. 3.5 takes into consideration the inductive and capacitive component (compensating) of the transmission line losses, without considering the losses produced by unbalanced load and distortion [65]. From Figure 3.6, the extended three-dimensional shape takes into consideration the need for energy storage in a non-ideal condition of power system load; hence the square of the apparent power (S) is the sum of the square of the active power (P) and the square of the total non-active power (Q).

$S^2 = P^2 + (Q_A{}^2 + Q_a{}^2)$ 3.34

$$P_{loss} = \frac{R_i}{E_i^2}[P_i^2 + (Q_i + Q_a)^2 + \frac{R_i}{E_i^2} [P_j P_I cos\delta_{ij} + (Q_i + Q_a)\left(Q_j + Q_a\right) \text{ Cos}\delta_{ij} - P_i(Q_i + Q_a)sin\delta_{ij} + P_j\left(Q_j + Q_a\right)sin\delta_{ij} \quad 3.35$$

The equation 3.35 above shows the effect of angular displacement δ on the apparent and the effective power which is used to define the power factor. The reactive power can also be affected when harmonic components of the fundamental frequency are present in enough magnitude to distort the waveform of the load current. True power factor is the combination of simple phase displacement and harmonic distortion.

The network power losses associated with the current drawn at a PCC can be estimated using the Thévenin's equivalent of the circuit as,

$P_{loss} = R_{Th} I^2 = P_{loss}$ 3.36

But,

$\boldsymbol{Z_{Th}} = R_{Th} + \text{j } X_{Th} = \frac{R_{Th}}{\Delta p} * \Delta_s$ From Figure 2.3

$P_{loss} = \frac{R_{Th}}{E_{Th}^2} \left[P_{Th}^2 + Q_{Th}^2\right]$ 3.37

Where the non- active power is, $Q_{Th} = \sqrt{Q_{ATh}^2 + Q_{aTh}^2}$ From equation 3.33

$Q_{(A)Th}$ = corrected with energy storage

$Q_{(a)Th}$ = corrected without energy storage.

3.11 Summary

This Chapter starts with the discussion of the power loss due to unbalanced load and the harmonic impact on transmission losses, it also dwells on how it affects the efficiency of power delivery on the network. The transmission line which serves as the means of transportation of electricity and also the wholesaler between the producer and the consumer has an important role to play in the daily run and operation of the system. The type of load connected to the system is of great effect on power demand and power generated due to the losses that may arise on the network if the power factor is low. Improved power factor leads to a greater efficiency of the system, reduces carbon emissions and decreases I^2R loss, thus making the customer realize great savings from tariff reduction.

The difference in the measurement of conventional power and the general power theory which shows the modification in the present approach of power loss measurement under a non-ideal condition as defined by the IEEE in [30] necessitates the determination of the impedance of the system from the point of load connection. Furthermore, the impact of the system generator and the transformer impedance coupled with other factors that lead to technical power losses cannot be neglected in the allocation of the power losses; this calls for the total summation of all the system entities as done using the Thévenin equivalent. Finally, the chapter differentiates between the conventional power triangle and the three-dimensional power triangle of the general power theory which illustrate the difference between the GPT and conventional power measurement.

One of the research questions is answered with the introduction of GPT in power measurement; (**How does using the conventional methods (based on reactive power) differ from using the general power theory in the determination of power losses?**). However, there is a need to develop the area of Thevenin impedance determination so that the hypothesis can be validated.

CHAPTER FOUR

GRID IMPEDANCE ESTIMATION

*Power networks are affected by conditions that rely upon the steady state of current and the system voltage. This chapter starts with an overview of the Power System State Estimation, the system power flow, followed by the passive method of determining the grid impedance by switching between two parallel loads and the active method through the double current injection technique. Both methods which are simple to understand and obey Kirchhoff's law were simulated using MATLAB/*Simulink *to determine the line parameters of the system.*

4.1 The Power System State Estimation

State estimation is a method formulated to offer an approximation of an unknown network state variable and to examine the estimated state variable before it is employed for real-time power-flow calculations. Thus, the need for a real-time network model becomes a necessity in a restructured power environment, where the pattern of load flow in the network is unpredictable when compared with a vertically integrated system. This model is based on the results obtained from state estimation and are used in the network application, such as transfer capability, voltage, transient stability and optimal power flow [98]. Effective operation and performance of electric power networks need a precise, accurate and true understanding of the network model, for economic and technical decision through the network power flow analysis. The real-time modelling of a power network is a mathematical representation of the system condition. State estimation in power system undergoes the following processes to achieve a good result: gathering of the network data, processing of the systems structure, the system monitoring analysis, system evaluation, reconfiguration of the system data and the model recognition [99].

4.2 Load Flow

Load flow has been used to solve complex power flow analysis problems in electrical power system generation, transmission, and distribution. It has also been used to analyze the network transmission losses, generator losses, as well as the losses in individual components like losses in the transformers and losses created by the individual load. It gives the losses in real and non-active power at each bus on the power system, as well as separating the losses by their algebraic sum from the generation, transmission and the load center. In a power system, the two methods of load flow analysis mostly used for analyzing are, Newton-Rapson method and Gauss-Seidel method [100]. These two methods can be modified in many ways to meet the needs and give a better result than what has been in the literature above. The method by which the input parameters are supplied to the system are of great importance since; the power system is categorized in different ways. In power system, the information derived from the load flow analysis and the determination of the system parameters is key to industrial plant and network operators in realizing efficient operation.

Moreover, most of these applications can be solved through simultaneous nonlinear equations by using MATLAB/Simulink which is suitable for this research due to its real-time implementation, the graphical output which can be easily optimized for iteration. Another application is embedded in the iteration mentioned above either in Fourier series or trigonometric formula, although the Newton-Rapson method is mostly used due to its easy and fast convergence. However, the proposed method captured the traces of both the voltage and the current in the load flow.

4.3 Impedance Estimation Based on Load Switching (Passive Method)

An alternative way of improving the power system loss allocation is to determine the Thévenin equivalent parameters of each participant in the system from the point of load/generator connection. Estimating the grid impedance through the switching method used in this research is derived from Tellengen’s theory, the method which depends on the distributed load, but not solely on the actual impedance of the lines may result in different values. The method can be used in both passive and active ways through the switching of two parallel loads connected at the PCC as shown in Figure 4.1. In identifying the parameters of each line, all connection points are equally treated at the point of connection irrespective of the number of lines.

The I^2R losses associated with the electric power drawn at any PCC can be derived from the equivalent circuit of the network, as viewed from the PCC. In Figure 4.1 the passive method of two parallel load switching is used for determining the equivalent parameters of the system.

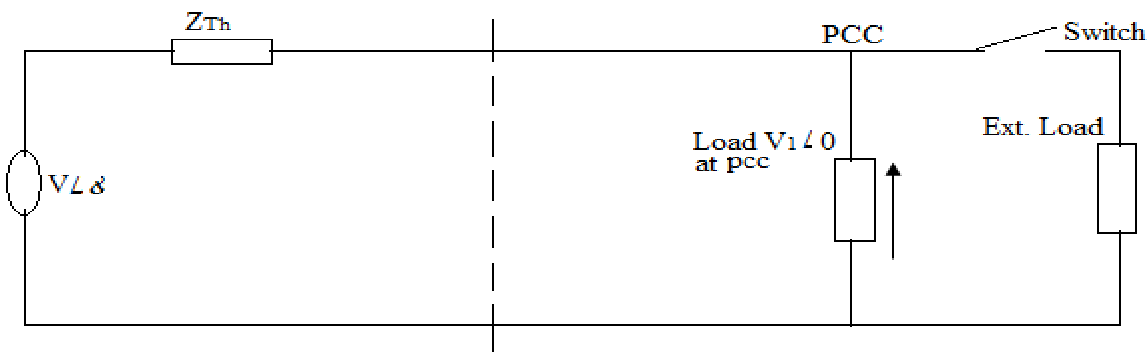


Figure 4.1. An equivalent circuit with load at PCC.

The Thévenin equivalent parameters of the system can be determined with respect to the load, while the Thévenin source voltage is taken to be V_{Th}; the entire resistance of the system is denoted as R_{Th}; the inductance of the network is X_{Th}.

The Thévenin network equivalent impedance Z_{Th} can be calculated from two sets of consecutive voltage and current phasors measured at the PCC [101]. Z_{Th} can be derived from the following formula:

$$\boldsymbol{Z_{Th}} = R_{Th} + \mathrm{j}\, X_{Th} = \frac{\Delta \boldsymbol{V}_{12}{}^{*}}{\Delta \boldsymbol{I}_{12}} \qquad 4.1$$

$\Delta \boldsymbol{V}_{12}$ and $\Delta \boldsymbol{I}_{12}$ are the voltage and current phasor differences, where $\Delta \boldsymbol{V}_{12} = \boldsymbol{V_1} - \boldsymbol{V_2}$ and $\Delta \boldsymbol{I}_{12} = \boldsymbol{I_1} - \boldsymbol{I_2}$. See Figure 4.2.

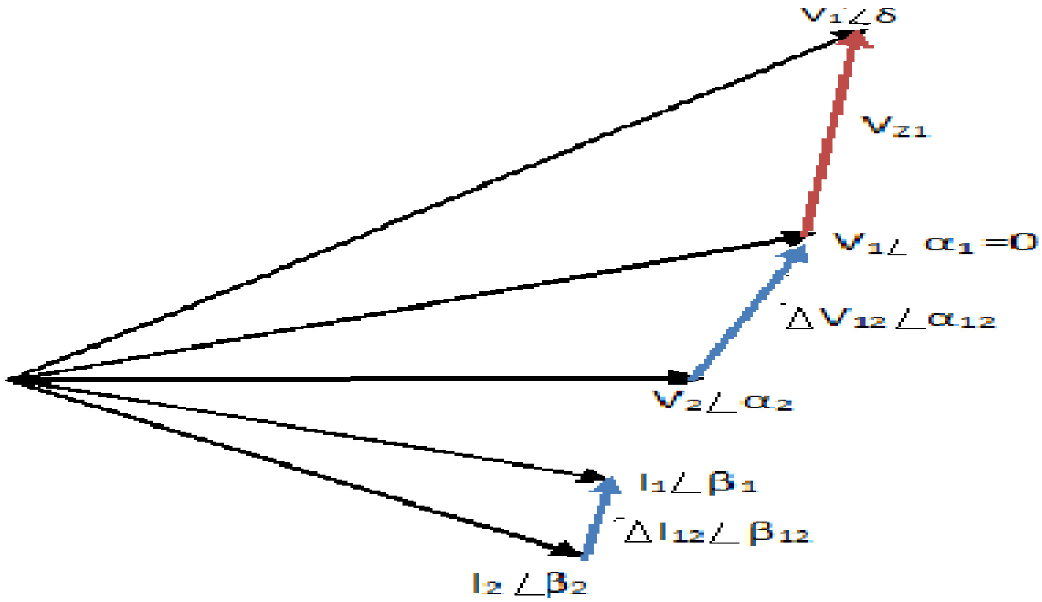


Figure 4.2. Voltage and Current phasors during switching.

Zth is obtained from two consecutive sets of voltage and current traces over two cycles. These traces can be obtained with a storage oscilloscope. The zero time origin (see Figure 4.3) is taken at the moment of the load change. The load change is obtained by adding an external load with a switch to make and break the external load.

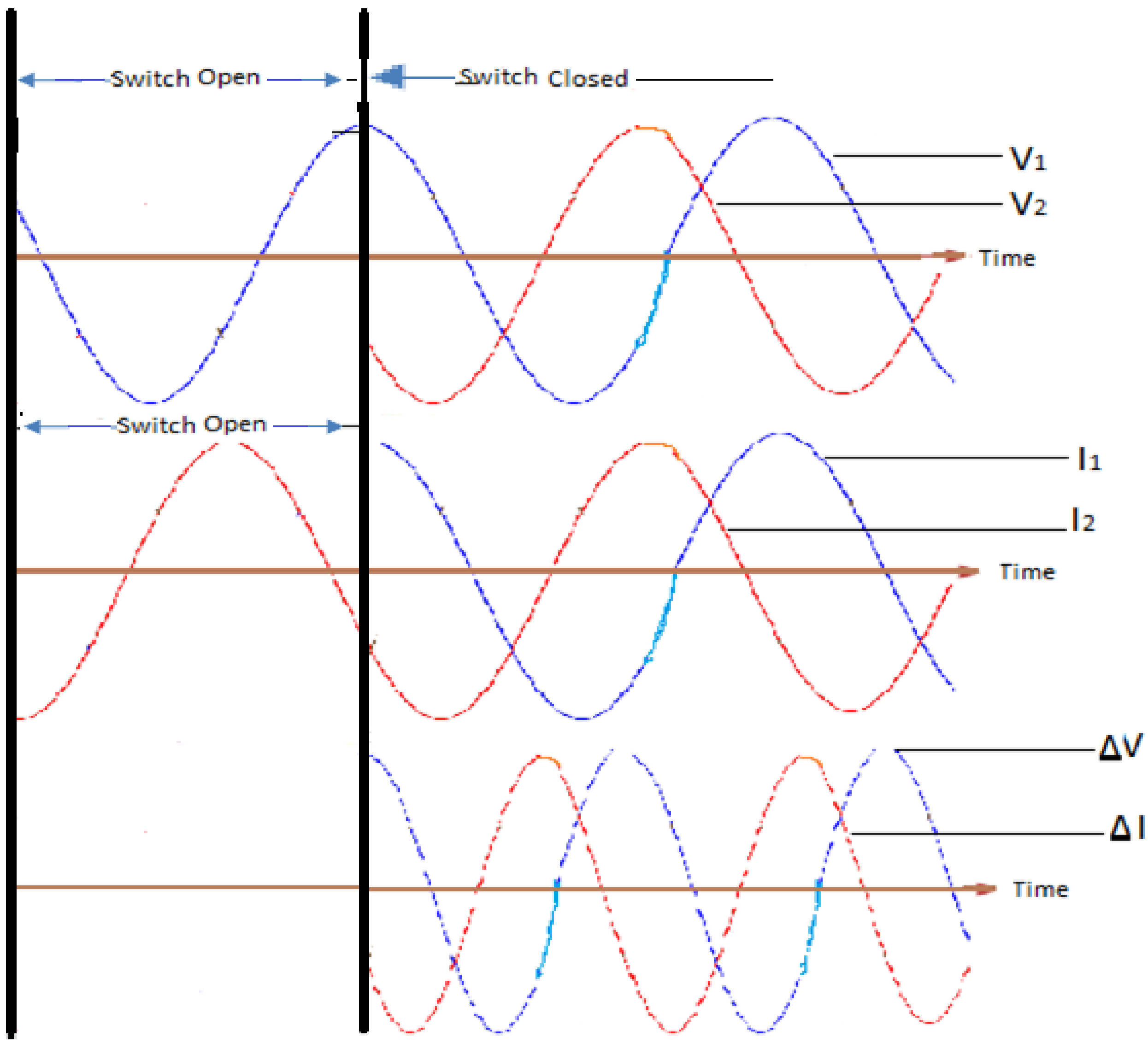


Figure 4.3 Time delay and phase difference of sinusoidal waveforms of voltage, current and the change in voltage and current.

It should be noted that the voltage and the current before and after the load change must be taken in one continuous sweep to ensure that the voltage angle relationship relative to what it was before the switching is kept, as the magnitude alone is not sufficient. The same applies to the current before and after angle relationship. This implies that the voltage and current before and after cannot be recorded at separate times. In practice, this signifies that a storage measuring device is needed to store the voltage and current traces with time for at least a cycle before and after the change in load. The network Thévenin voltage magnitude, frequency and phase angle are assumed to remain constant during the cycle before and after the load change. This is as illustrated in the waveform of Figure 4.3 where $\Delta v_{12}(t)$ can be seen as the difference of what $v_1(t)$ would have been if the load had not changed and what $v_2(t)$ is after the load change.

$\Delta \boldsymbol{V}_{12}$ in Figure 4.3 is the phasor voltage difference corresponding to the voltage trace $\Delta v_{12}(t)$ above. $\Delta \boldsymbol{I}_{12}$ is obtained in a similar way and can also be seen in Figure 4.2.

$$\Delta \boldsymbol{V}_{12} = \boldsymbol{V}_1 - \boldsymbol{V}_2 \quad \Delta \boldsymbol{I}_{12} = \boldsymbol{I}_1 - \boldsymbol{I}_2 \qquad 4.2$$

Thévenin's impedance Z_{th}=Rs+jXs can now be calculated using equation 3.1.

R_{Th} can be calculated as follows:

$$R_{Th} = (\Delta P_{12} / \Delta S_{12}) \text{ x } |Z_{Th}| \qquad 4.3$$

Where ΔP_{12} = the average of $\Delta v_{12}(t)$ x $\Delta i_{12}(t)$ over a cycle T_2 (after the switch closure) and where:

$$Z_{Th}| = \frac{|\Delta V_{12}|}{|\Delta I_{12}|} \qquad 4.4$$

The following section shows how the above method can be implemented in Simulink.

4.4 Methodology Implementation Using Simulink.

The change in voltage and current obtained by a change in load needs to be determined. The change in load is obtained by adding a second impedance in parallel with the original one by closing a switch. The voltage and current traces are obtained before and after the closure of the switch.

Since the initial parameters, such as input voltage of the system are not known, a model which will be able to take the initial condition, analyse a dynamic system using a block diagram to simulate both linear, non-linear and discrete circuits in a real-time to provide a graphic user inter-phase is required. A MATLAB simulator contains power library editor of tools which can be used to build the input/output devices and can work on both discrete and continuous models needed for the simulation.

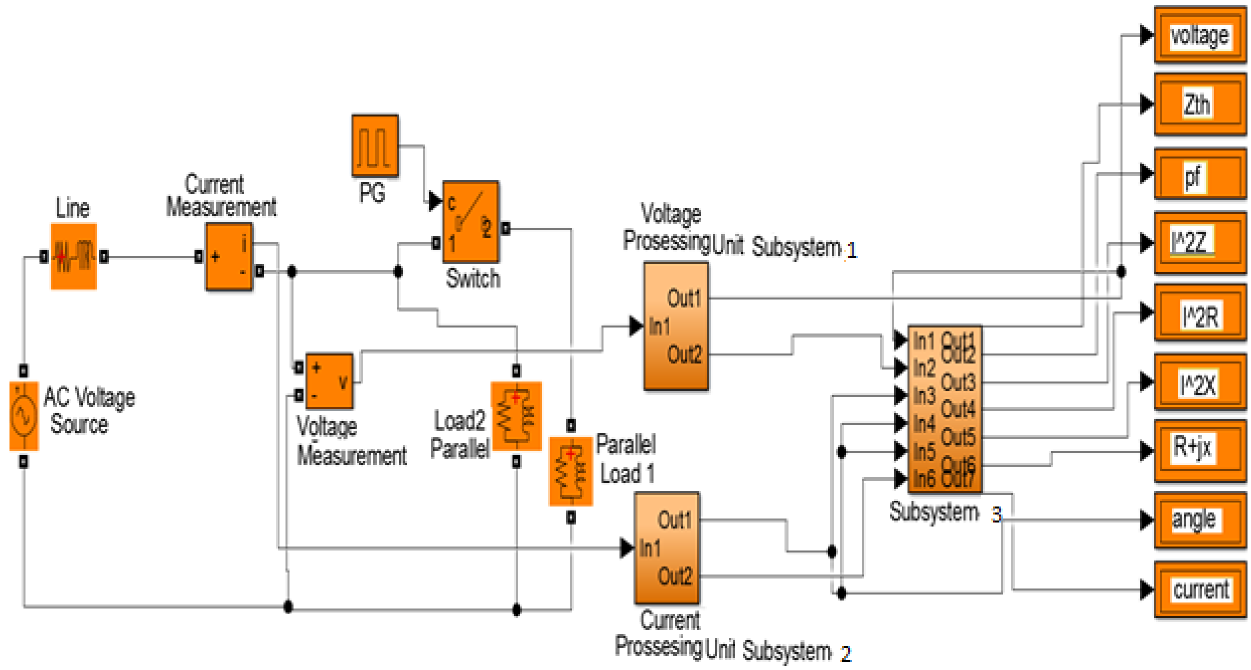


Figure 4.4. The Simulink derivation model for a single phase switching method.

In achieving the delay process, a Simulink transport delay block is used to delay the source voltage by 0.20 sec., to calculate the difference between the load voltage before and after switch closure.

The switch is placed between the two loads as shown in the circuit diagram of Figure 4.1 and called the switch in Figure 4.4. This gives the change in voltage and current for the closing and opening and time between them. The process is done through the transport delay, stores the input signals and simulation in a buffer, it does not interpolate the discrete signal but only gives the discrete value at the set time.

The change in voltage (ΔV) is the phasor voltage difference which is obtained by taking the difference between V_1 and V_2 (V_1 is voltage before closing the switch and V_2 is the voltage after closing the switch), while the same record of ΔI shows the same process illustrated in Figure 4.5.

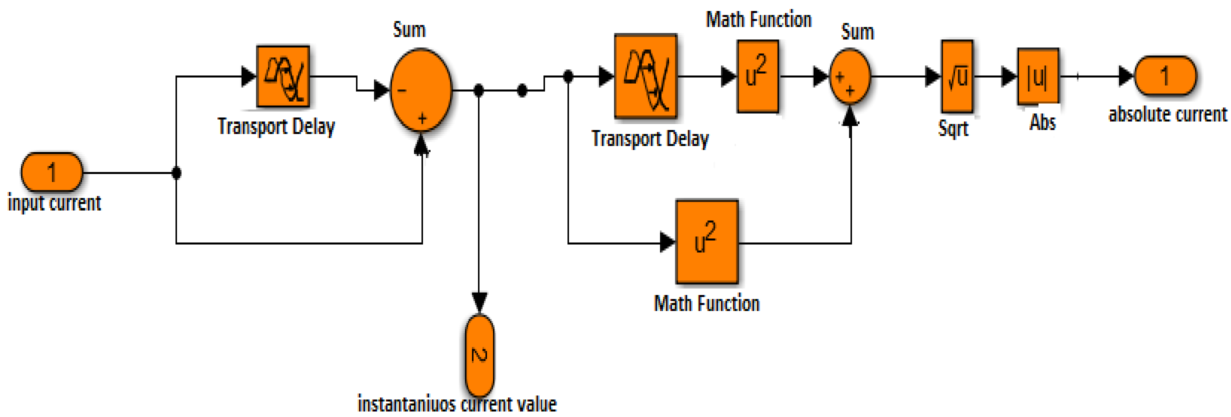


Figure 4.5 The Simulink derivation model Components of the current stage of Figure 4.4

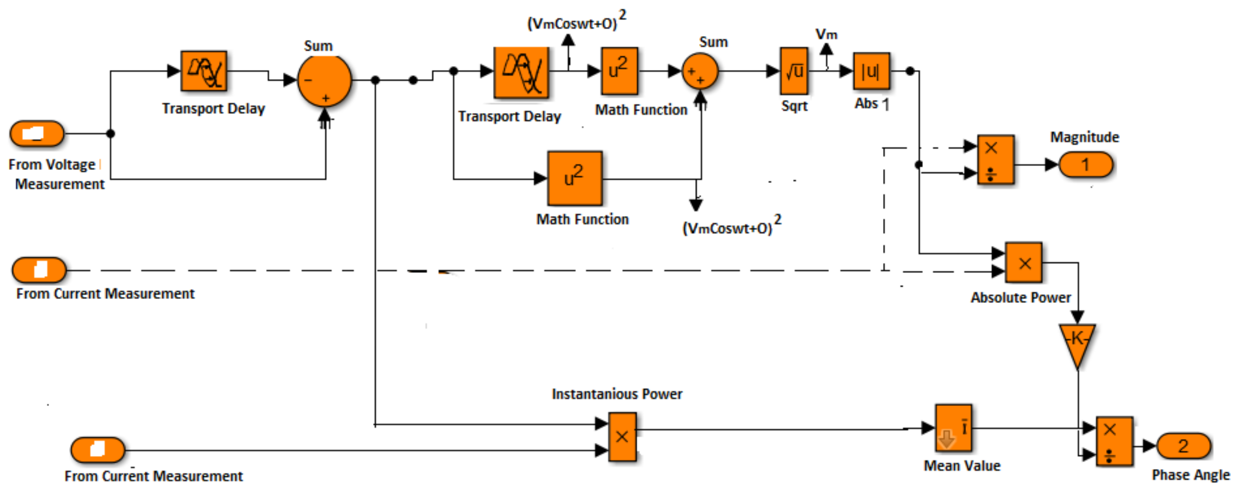


Figure 4.6 The Simulink derivation model Components of the voltage and the current stage of Figure 4.4

From Figure 4.4 above, subsystem 1 (the voltage processing unit) and sub system 2 (the current processing unit) extract the change in instantaneous voltage Δv (t) and current Δi (t) respectively, with respect to time using the components in Figures 4.5 and 4.6 respectively; while subsystem 3 determines the phase difference change in voltage |Δ***V***| magnitude and current |Δ***I***| magnitude respectively. The product of the instantaneous current and instantaneous voltage gives the change in instantaneous power in respect to time, namely Δ*p* (t) while the product of the absolute voltage and current is used to achieve the change in apparent power ΔS.

The amplitude value of Δv_{12} (t) is derived through Simulink from the voltage trace by using the root mean square pulse of the voltage or current waveform as seen in Figure 4.7

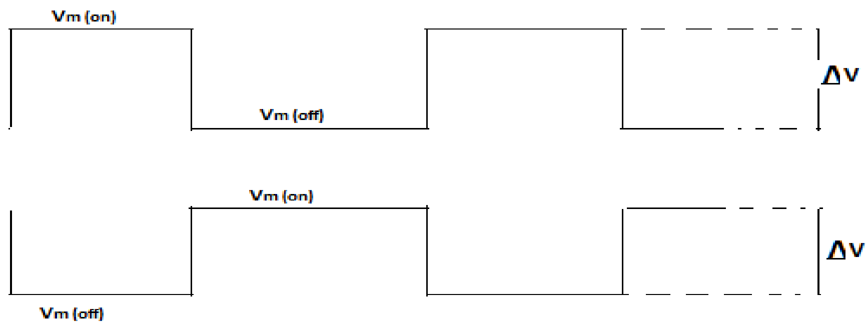


Figure 4.7 Change in voltage due to the switch to determine the impedance magnitude.

$$\Delta v_{12}(t)^2 + \Delta v_{12}(t - T/4)^2 = 2\,\Delta V_{12}^{\,2} \qquad 4.5$$

$\Delta \boldsymbol{I}$ the RMS value of the current phasor difference is derived in a similar way as above.

The Thévenin's impedance magnitude can now be obtained, where:

$$|Z_{Th}| = \frac{|\Delta V_{12}|}{|\Delta I_{12}|} \qquad 4.6$$

In a power system, the Thévenin's impedance needs to be continually determined, since it is well agreed that *the line impedance always continuously changes with loads, network element and system conditions* [78]

Meanwhile, in the determination of the phase angle (θ), which is the phase change between ΔV and ΔI caused by the impedance, the angular shift between the waveform produced by the change in current and the waveform produced by the change in voltage is used to determine the phase angle. The difference between the two sinusoidal waveforms is the measurement of the Thévenin impedance angule as shown in Figure 4.8. The phase difference is expressed as the time shift (t) in seconds.

Hence,

$\delta^0 = \quad 360^0 * f * \Delta t$ 4.7

Where,

$\delta^0 =$ the phase angle in degrees

f = the frequency

$\Delta t =$ the change in time between the voltage and the current

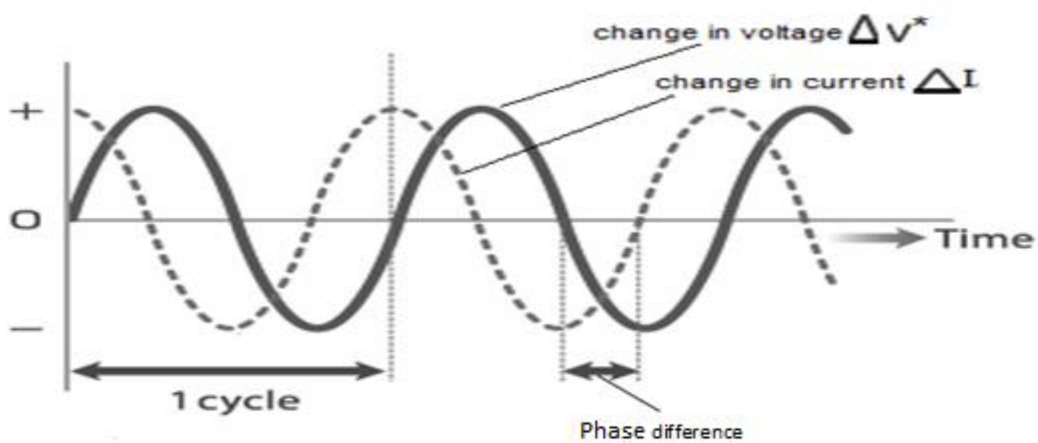


Figure 4.8 Change in voltage and change in the current waveforms to determine the phase angle.
The Thévenin's resistance (R_{Th}) resistance is then derived using equation 4.3

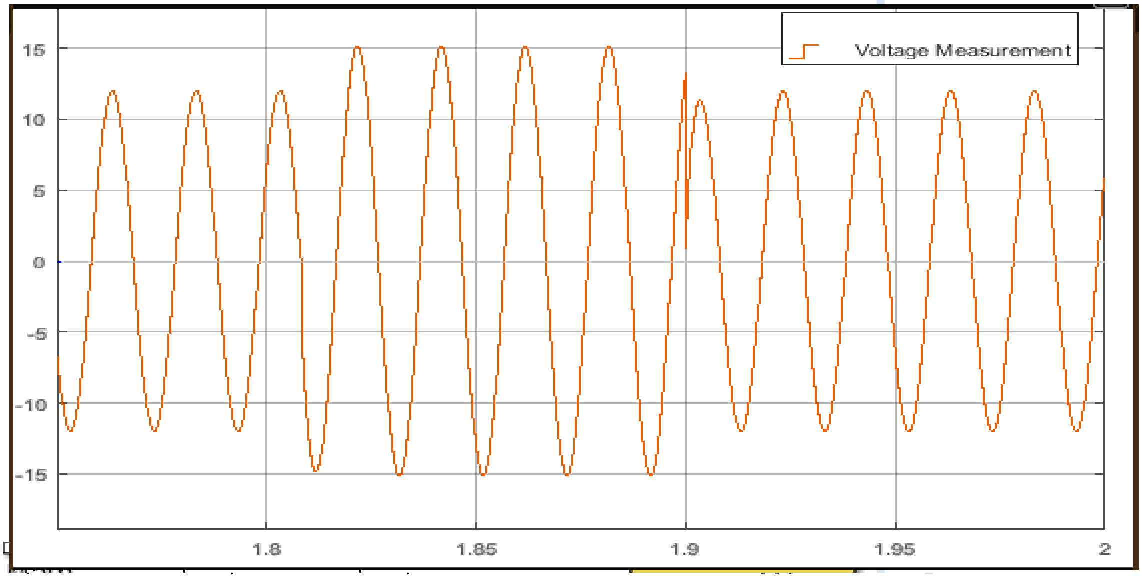


Figure 4.9 The result of the voltage switching at the PCC due to load change.

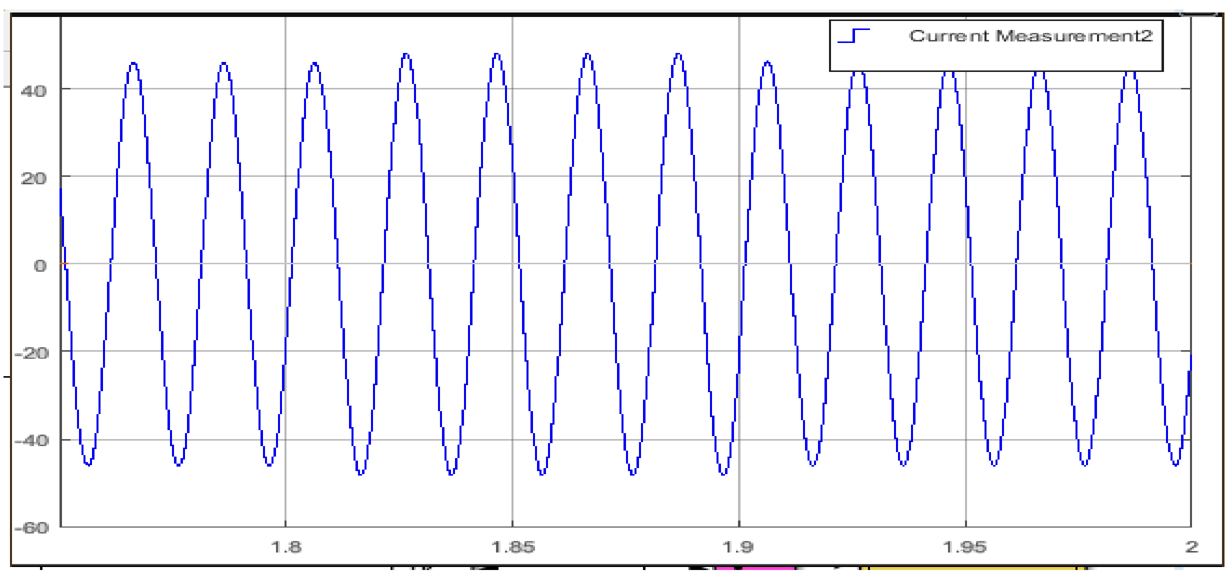


Figure 4.10 The result of the current switching at the PCC due to load change.

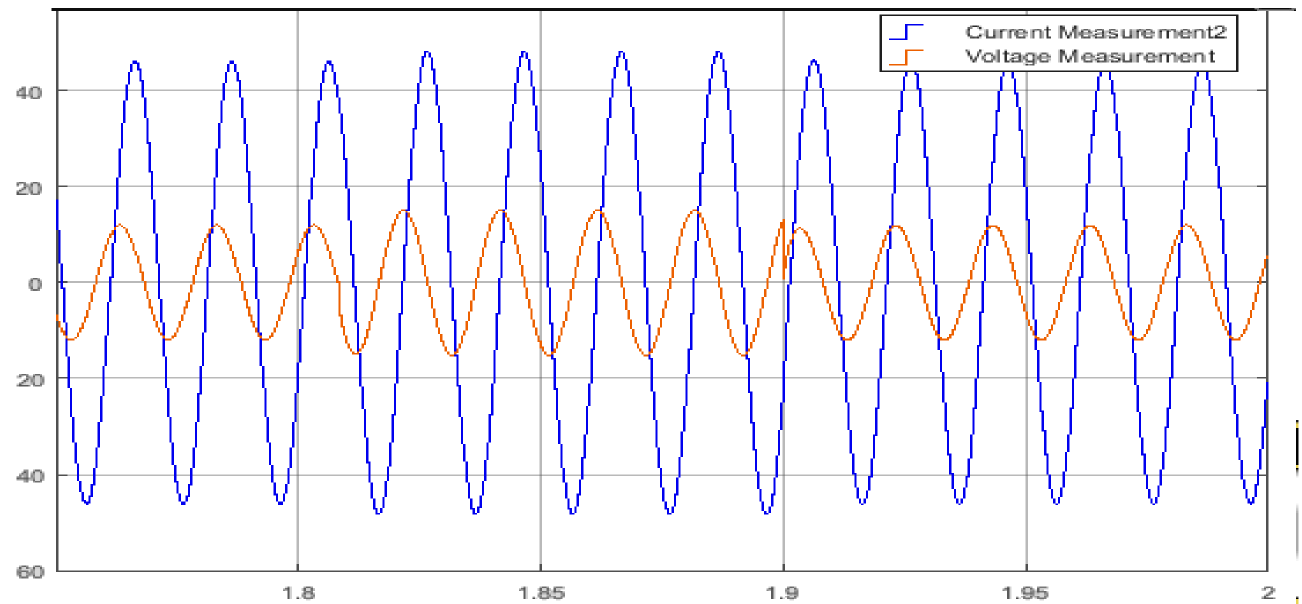


Figure 4.11 The waveform effect of the voltage and the current shift to show the phase difference and time delay in a single-phase system.

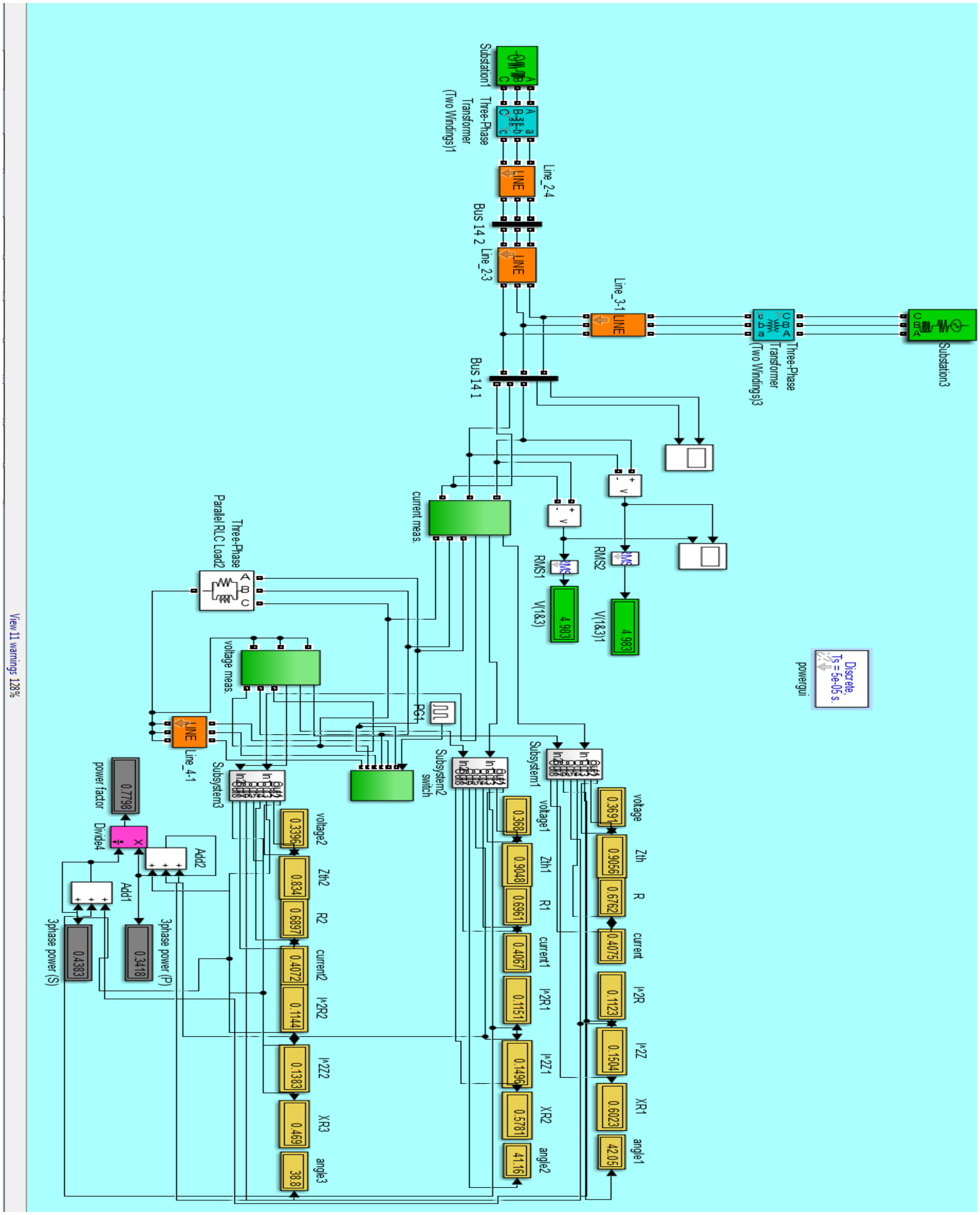


Figure 4.12 A simulation model of a three-phase switching method to find the equivalent impedance parameters.

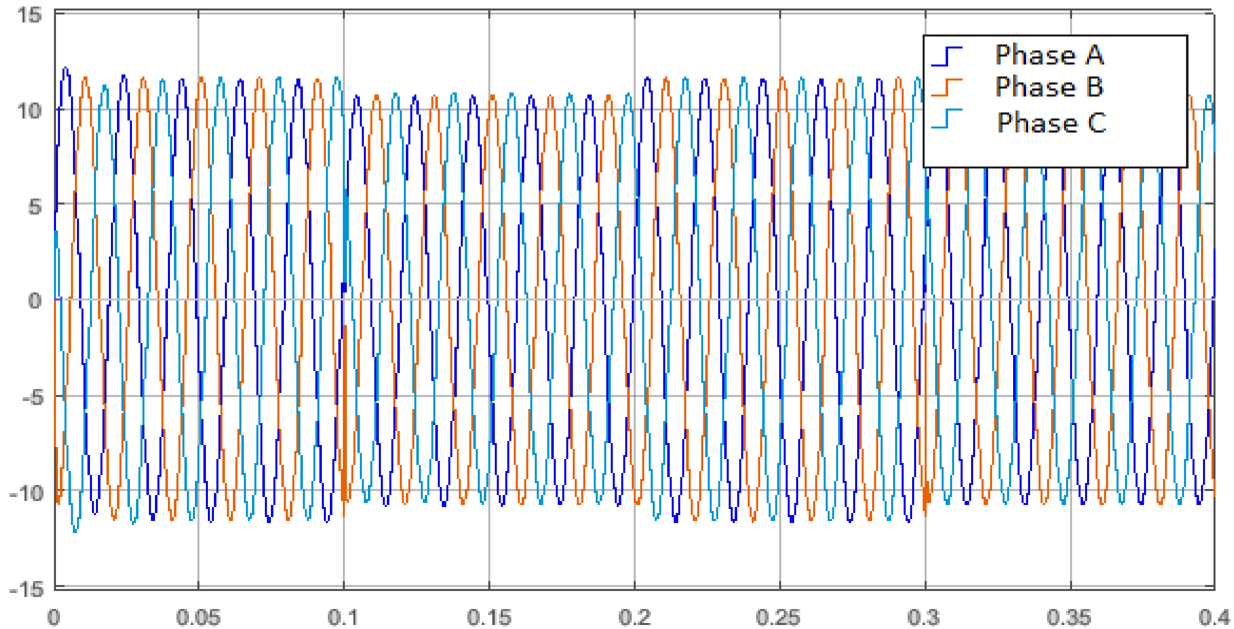


Figure 4.13 The result of the voltage switching at the PCC due to load change on three phase systems.

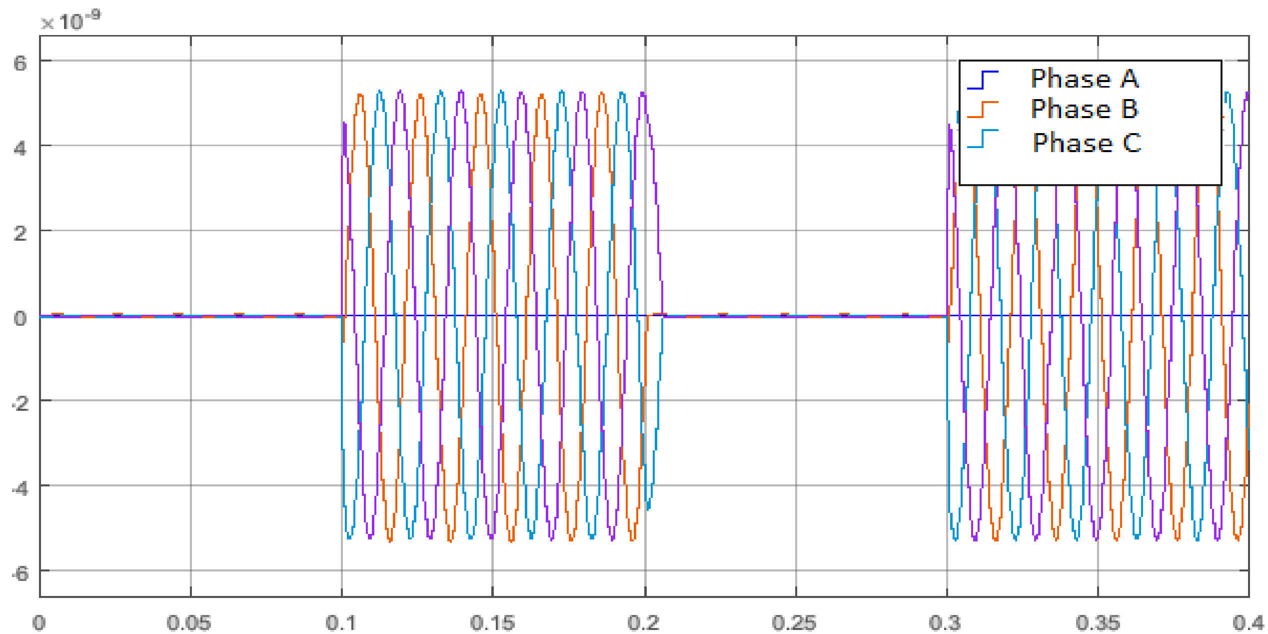


Figure 4.14 The result of the current switching at the PCC due to load change on three phase systems.

The process used in simulating the single-phase model was also used in validating the passive method in a three-phase model of Figure 4.12, and the result is as shown in the change in voltage in Figure 4.13 and change in current in Figure 4.14 for the determination of the line impedance in a three-phase system.

4.5 Impedance Estimation Based on Current Injection (Active Method).

The active method of determining the Thévenin's impedance based on double current injection is described below using MATLAB/Simulink block model; the purpose is to allow the injected currents to create a harmonic signal in the system; the two currents injected are of a different frequency higher than the fundamental frequency. This current, as shown in Figure 4.15, can be of 3rd harmonic and 5th harmonic respectively, or at a harmonic level higher but of an odd-orders. The current and the voltage in the two harmonic frequencies are extracted to determine the magnitude of the line impedance created by each of the harmonic frequencies by using Ohm's law. Hence the fundamental frequency of 50 Hz is estimated simultaneously to determine the line impedance. The method, which follows the principle of US patent US 6933714 B2 that involves two different inter-harmonic frequency signals [102] injected into the lines and the frequency signal. The harmonic frequency is taken from the system current and the system voltage by modulating and demodulating the two into their various components to determine the system equivalent impedance at the fundamental frequency.

Also, many other harmonic currents can be injected to perform the measurement with each giving the magnitude of the equivalent impedance corresponding to its harmonic frequency without affecting each other since they are all orthogonal to one another as specified in equation 4.8.

$$\omega_1 \neq \omega_2 \rightarrow A1 \sin(\omega_1 t + \O_1),\ A2 \sin(\omega_2 t + \O_2) \qquad 4.8$$

To validate the method several harmonic currents were injected while meeting the condition of equation 4.8.

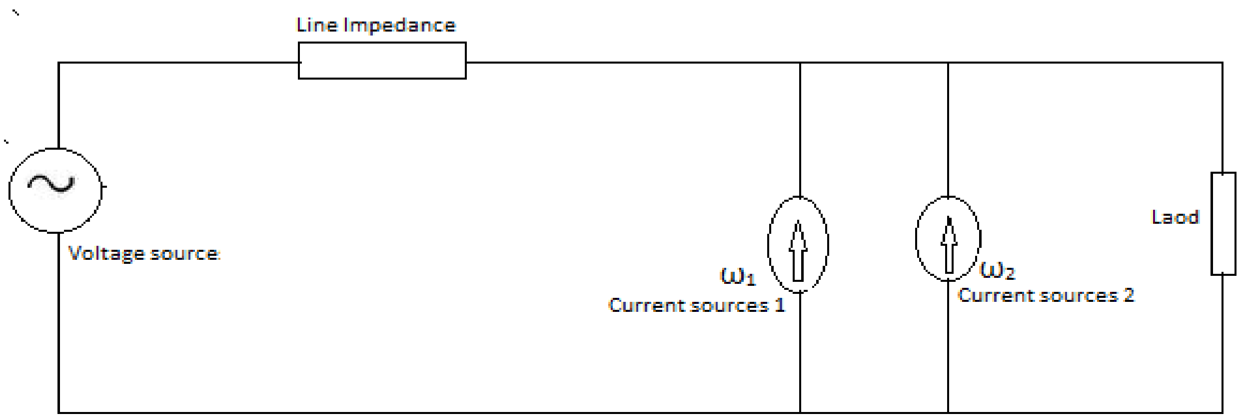


Figure 4.15 An equivalent circuit showing the two sources of injected current and the load.

4.6 Multiple Current Injections

Figure 4.15 shows injecting multiple currents of different frequencies to determine the Thévenin's equivalent of a network. This process allows the magnitude of the line impedance and the angle to be determined to be used in deriving the $I^2 R$ losses associated with the system equivalent circuit as seen from the PCC. This simple method uses Ohm's law, where the potential difference (voltage) is directly proportional to the current and the constant of proportionality is the line impedance. The magnitude of the line impedance (Zp and Zq) of each frequency can be evaluated in two different stages, since the injected currents are orthogonal to each other. The equivalent circuit impedance can be determined by simultaneously solving two sets of equations, 4.13 and 4.14, using the magnitude of each injected current frequency to determine the system grid parameters. With this method, the problem of calculating phase angle has been solved since the procedure involves only the magnitude of the voltage and the system current. Moreover, the two frequencies to be chosen should be, two consecutive odd harmonics to minimise the results error due to distance margin.

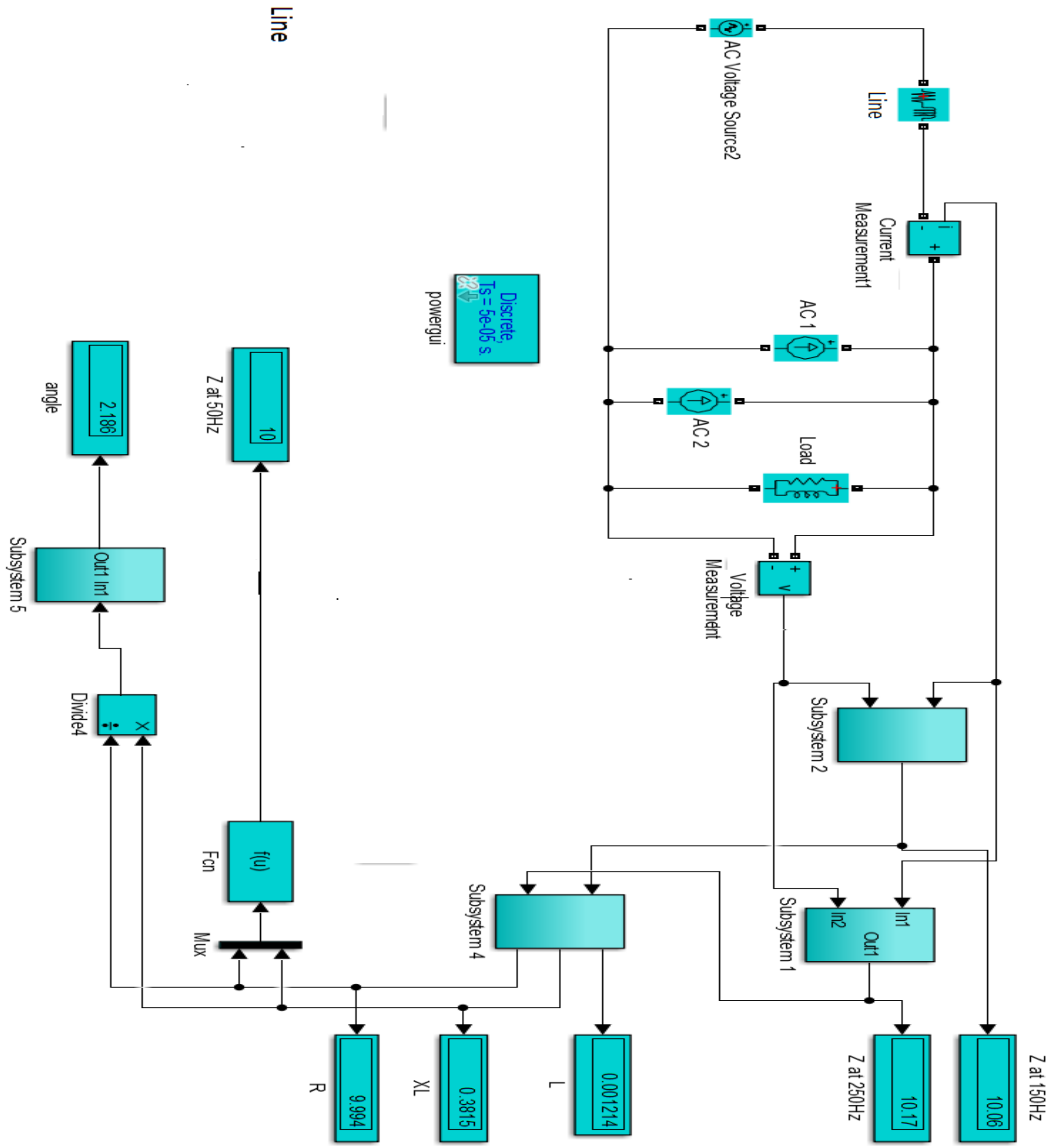


Figure 4.16 The Simulink derivation model for a current injected method.

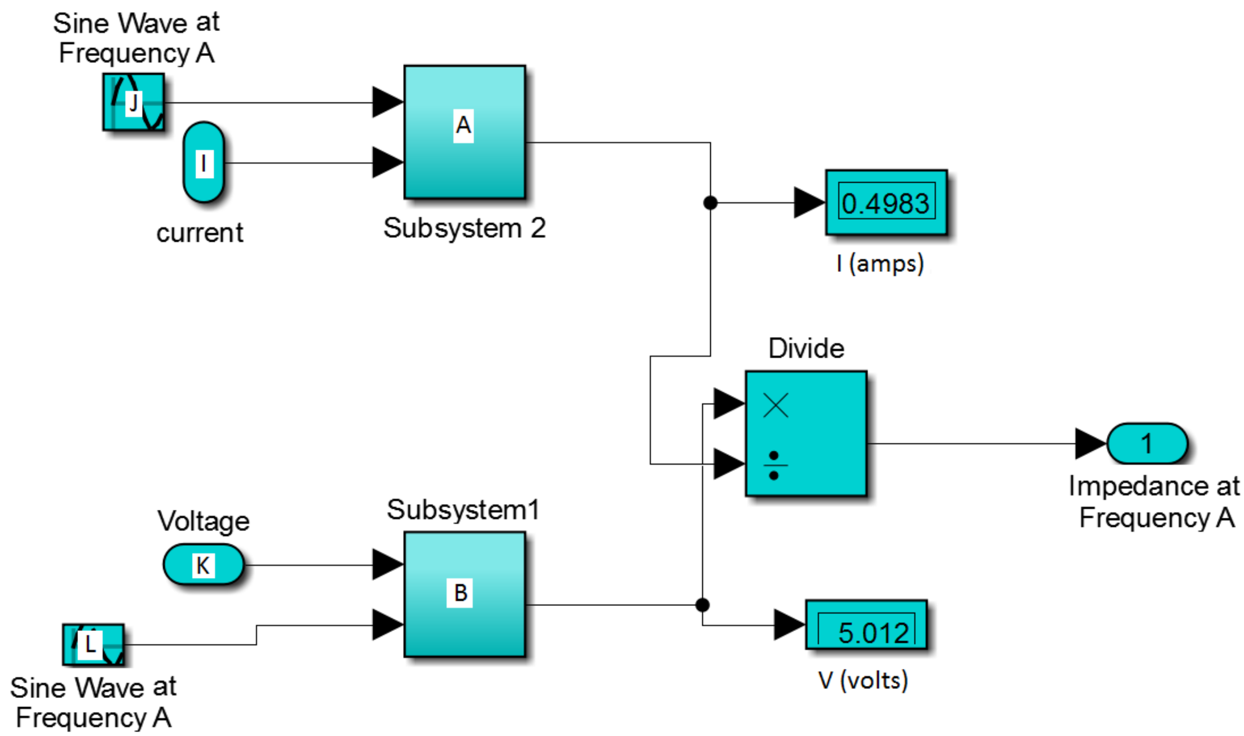


Figure 4.17 The components to determine the corresponding impedance (Z_p) at a different frequency from that in Figure 4.16.

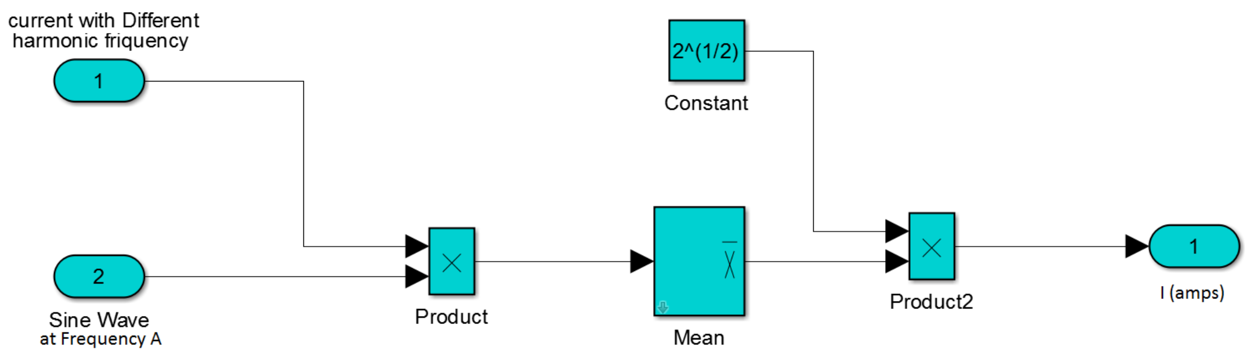


Figure 4.18 The modulated signal components for the corresponding current I of sub system1 in Figure 4.17.

In the Figure 4.17, the modulated current block is represented by A and the modulating voltage is represented by B. Both blocks perform the same modulating process of the incoming harmonic signals I and J for the current and signals K and L for the voltage, while block A determines the magnitude of the current with respect to the harmonic frequency P, block B determines the magnitude of the voltage with the same harmonic frequency P through equation 4.11.

$$I = \text{Sin}\,(\omega_p t) \qquad 4.9$$

$$J = \text{Sin}\,(\omega_p t) = \text{Amp*Sin (Freq*t + Phase) + Bias} \qquad 4.10$$

$$A = \overline{(I\ .\ J)} * c = \overline{(\sin(\omega pt)\ .\sin(\omega pt)\ )} * c \qquad 4.11$$

It is possible to determine the line impedance of the grid Z_p with respect to the level of current harmonics using Figure 4.17 by using the current output at A and the voltage output at B, using equation 4.12. Equation 4.14 is the repetition of the process, but with a higher level of the harmonic frequency.

$$/\ Z_p/ = /\ \frac{V\ (p)}{I\ (p)}/ \qquad 4.12$$

Hence, as earlier stated the magnitude of the line impedance of each frequency Z_p and Z_q are,

$$Z_p^2 = R_{eq}^2 + \omega_p^2 .\ L_{eq}^2 \qquad 4.13$$

$$Z_q^2 = R_{eq}^2 + \omega_q^2 .\ L_{eq}^2 \qquad 4.14$$

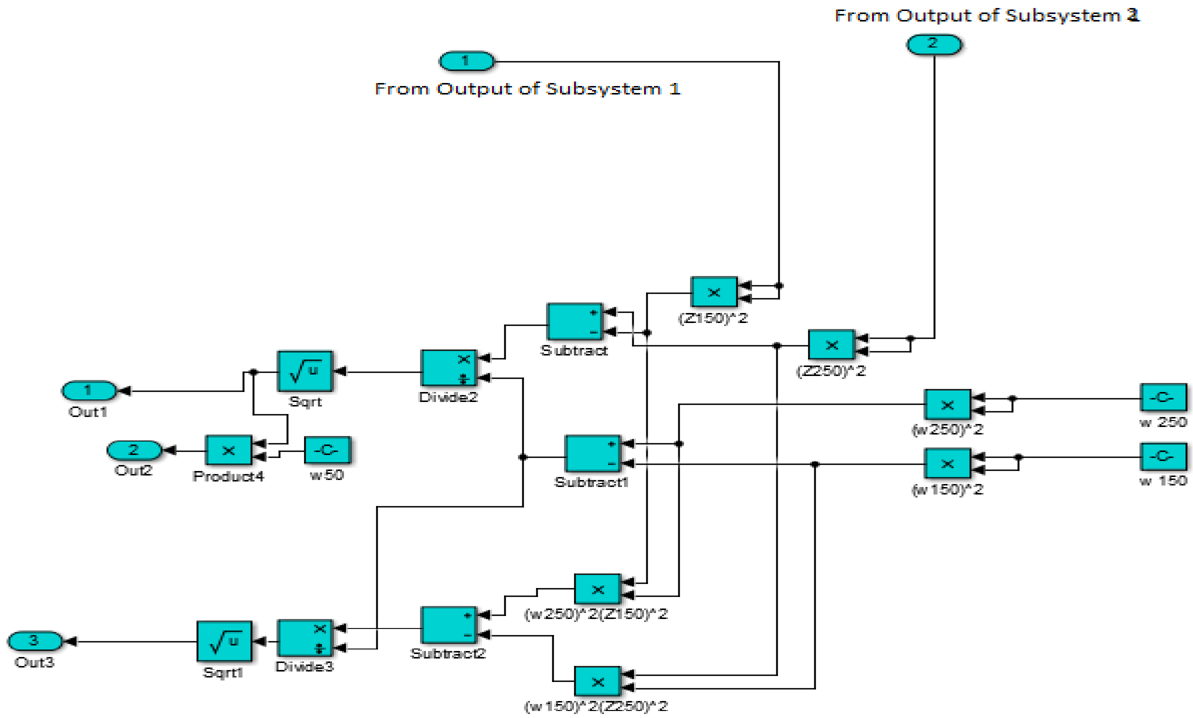


Figure 4.19 The components to extract Z@50Hz in Figure 4.16

The resistive value R_{eq} of the system can be measured using Figure 4.19 based on equation 4.15

$$R_{eq} = \sqrt{\frac{\omega_p^2 \, . \, Z_q^2 - \omega_q^2 \, . \, Z_p^2}{\omega_p^2 - \omega_q^2}} \qquad 4.15$$

While the inductive part L_{eq} of the system can also be measured using Figure 4.18 based on equation 4.16 below

$$L_{eq} = \sqrt{\frac{Z_p^2 - Z_q^2}{\omega_p^2 - \omega_q^p}} \qquad 4.16$$

while p and q are the harmonic frequency level of the injected current and $p < q$

Hence, $\boldsymbol{Z_{Th}} = R_{Th} + \mathrm{j}\, X_{Th}$ 4.17

From equation 4.17, the magnitude of the Thévenin's impedance of the active method can be obtained using equation 4.18

$$Z_{Th} = \sqrt{R_{eq}^2 + L_{eq}^2} \qquad 4.18$$

And the phase difference which is the phase angle between the Thévenin current and the Thévenin's voltage can be obtained using equation 4.19

$$\tan\theta = \frac{X_{Leq}}{R_{eq}} \qquad 4.19$$

Where,

R_{eq} = the equivalent grid resistance at the PCC

X_{Leq} = the equivalent grid inductance at the PCC

Z_{eq} = the equivalent grid impedance at the PCC

$\omega = 2\pi f$

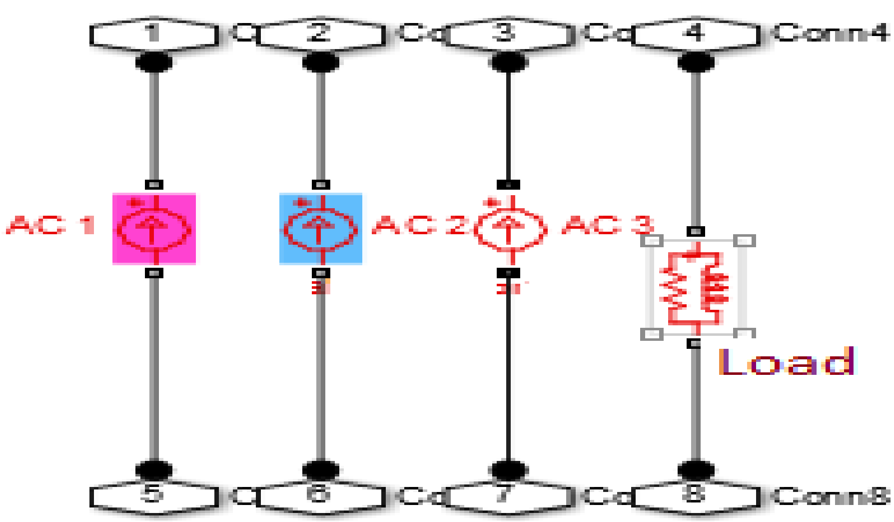


Figure 4.20 The components of non-linear load.

The current injection part of the model can be replaced by a non-linear load, as shown in Figure 4.20, which creates harmonics in the system. The nonlinear load is the unbalanced load with a different fundamental frequency; this unbalanced load can be used to create the harmonics in the system. Examples are rectifiers, personal computers, the fluorescent lamp, and the television.

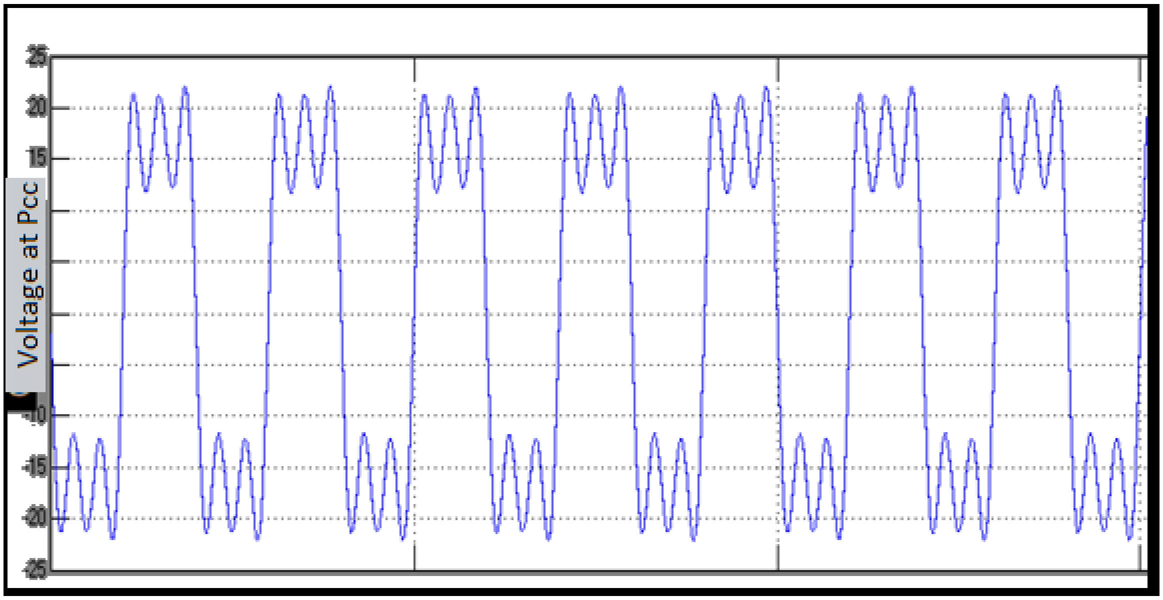


Figure 4.21 The grid voltage during the harmonic injection of sin(wt) + sin(3wt) +sin(5wt)

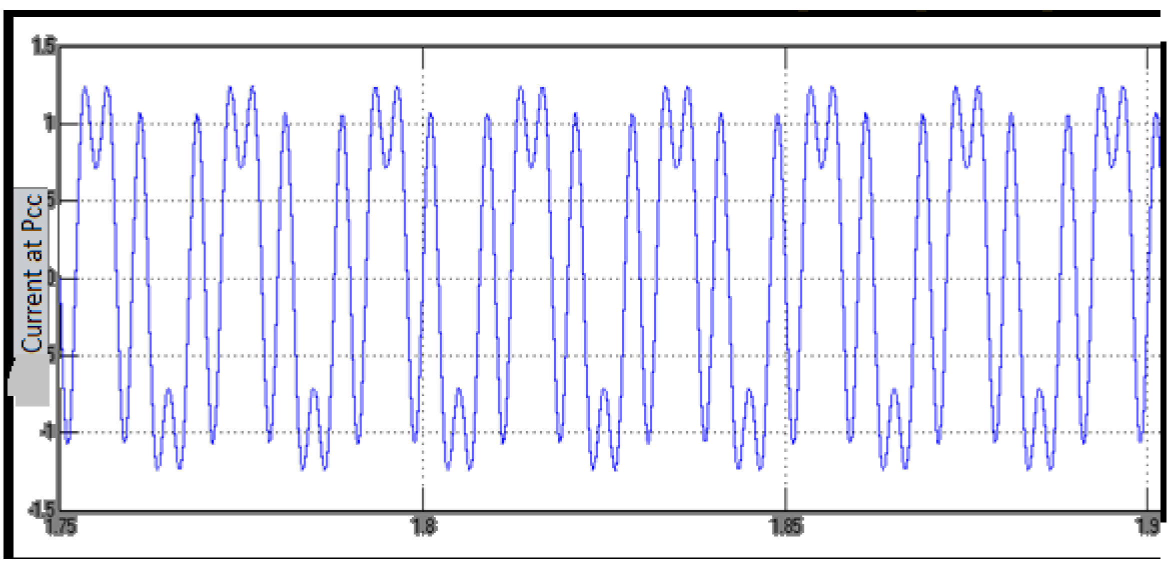


Figure 4.22 The grid current during the harmonic injection of sin (wt) + sin (3wt) +sin(5wt)

Figures 4.21 and 4.22 show the voltage and the current respectively, at the PCC when the harmonics were injected into the system; the disturbance was experienced by the current and the voltage in the system.

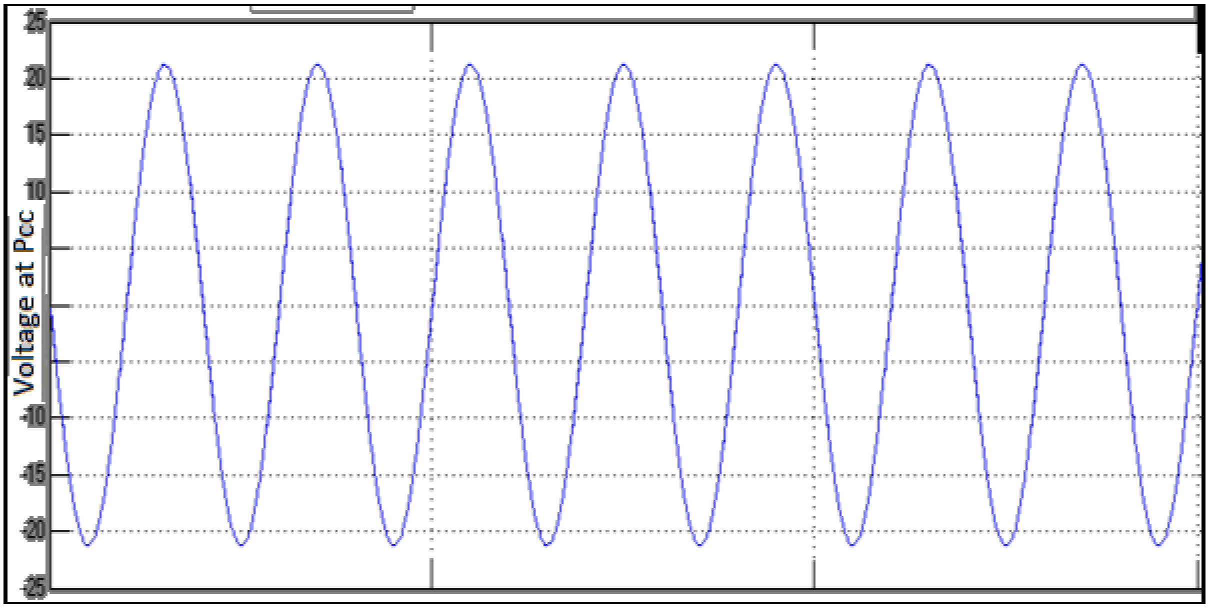


Figure 4.23 The grid voltage at the fundamental after the harmonic was extracted.

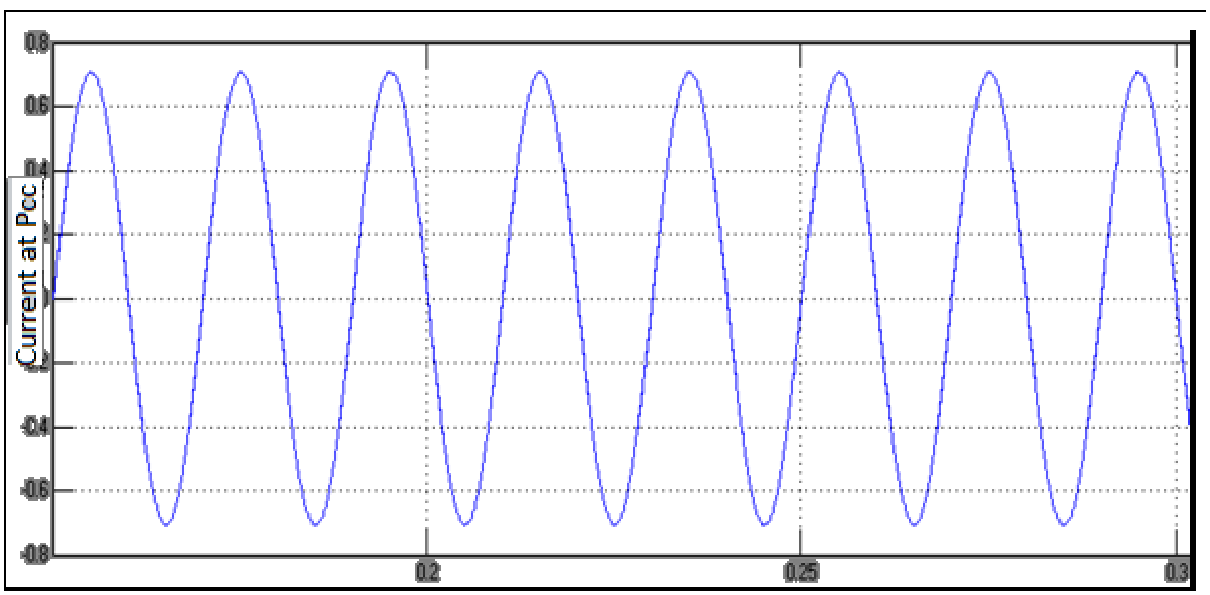


Figure 4.24 The grid current at the fundamental frequency after the harmonic was extracted.

Figures 4.23 and 4.24 show the voltage and the current waveforms respectively, after the current harmonics has been extracted from the system to determine the line impedance at fundamental.

4.7 Summary

The chapter has critically presented the passive and the active novel and easy to understand methods of determining the Thévenin parameters of a power network which can be used for accurate determination of power loss allocation on the transmission and distribution networks. The passive method takes the change in the system voltage and current due to switching between two loads that are connected in parallel from the PCC to determine the line parameters, while the active method uses the principle of double current injection techniques taken from the patent US 6933714 B2 to determine the line parameters. The method was simulated using MATLAB/Simulink to simulate a model built in MATLAB, to show the theory development. Though different methods can be used for the determination of grid impedance, this method has proved to be very effective; it required no large mathematical calculations, and both methods are faster in implementation than some mentioned in literature. Hence, the positive result obtained in this chapter is used in the practical validation of the theory in the laboratory in the next chapter to determine the Thévenin equivalent of a power system that can be used for power loss allocation.

CHAPTER FIVE

EXPERIMENTAL VALIDATION OF THE SIMULATION

This chapter dwells on the laboratory experiment which was conducted to validate the two-impedance measuring techniques which were simulated in a MATLAB/Simulink environment in the last chapter; several experiments were conducted to validate the result of the simulation in the previous chapter.

5.1 Purpose of Experiments

Estimation of grid impedance has become one of the most important factors in the transmission of electric power due to the continuous connection and disconnection of a load from the grid. In some countries today, the estimation of the line impedance has become necessary due to the Photovoltaic (PV) system connected to the grid and the islanding detection purpose. Determination of the line impedance is very important in finding line fault, grid unbalances and finding the grid source voltage for the characterization of the power system. In the allocation of losses, proper estimation of the line parameters is a key factor in finding the line impedance either in the active or in a passive way. However, the laboratory test is to confirm and emulate the simulation done in the previous chapter practically.

5.2 The Implemented Test Setup (Passive Method).

The experimental validation of the passive method in this research was based on the switching between two parallel loads to estimate the grid impedance as discussed in the previous chapter. A simple laboratory experimental test was carried out which is like the simulation model; the schematic arrangement shown in Figure 4.1 is carefully arranged as shown in the pictorial lab arrangement in Figure 5.1. The model of the voltage source is the supply from the variable transformer (Variac), while the measurement was recorded with the help of an IEC76-1 Yokogawa WTI600 Digital Power Meter. With this meter, the online, instantaneous value of current i and voltage e can both be recorded numerically and their waveforms, stored for post analysis separately. The pictorial display of the Yokogawa meter is as shown in Figure 5.2, while Figures 5.3 and 5.4 shows the change in current and voltage respectively, due to the change in load when the switch toggled between on and off.

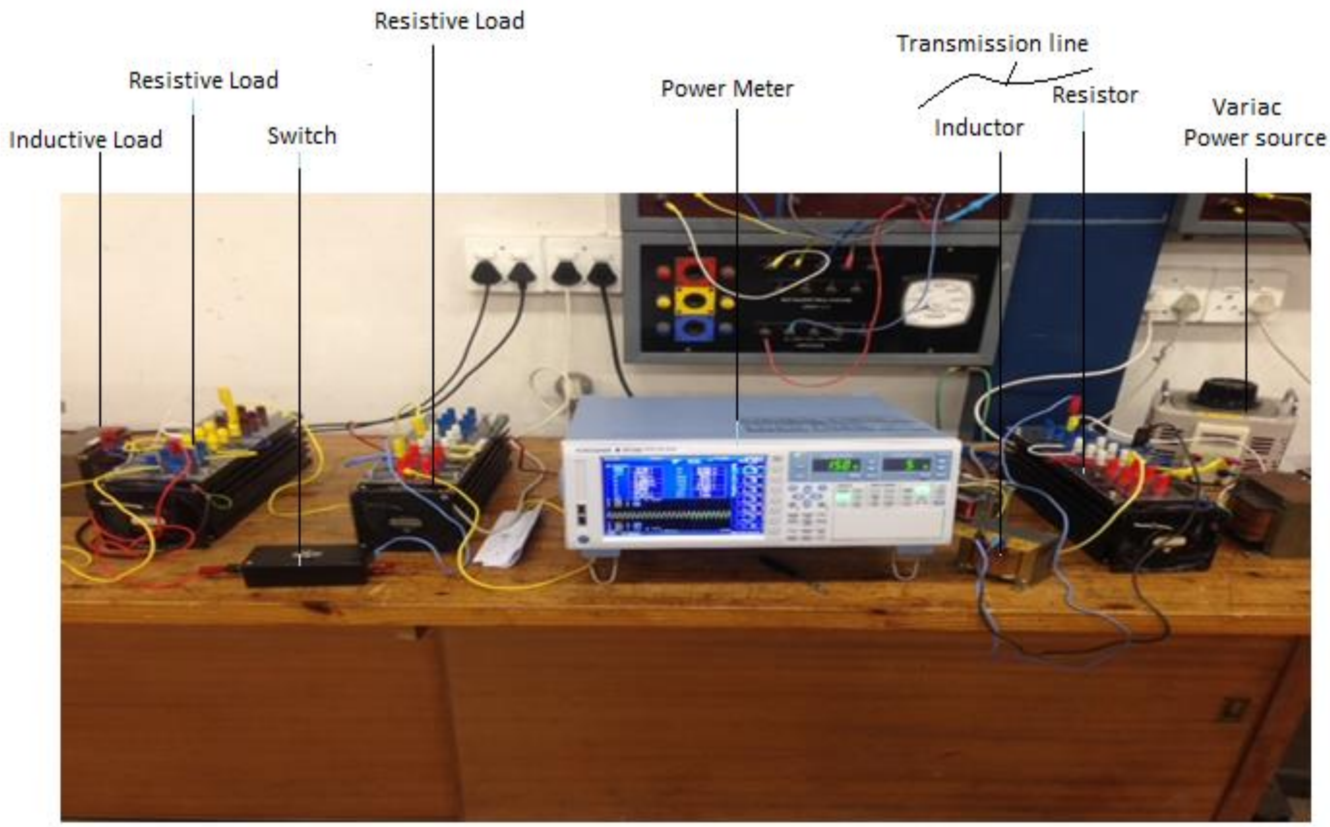


Figure 5.1 The pictorial bench setup for a passive method.

Figure 5.2 Reading from Yokogawa power meter.

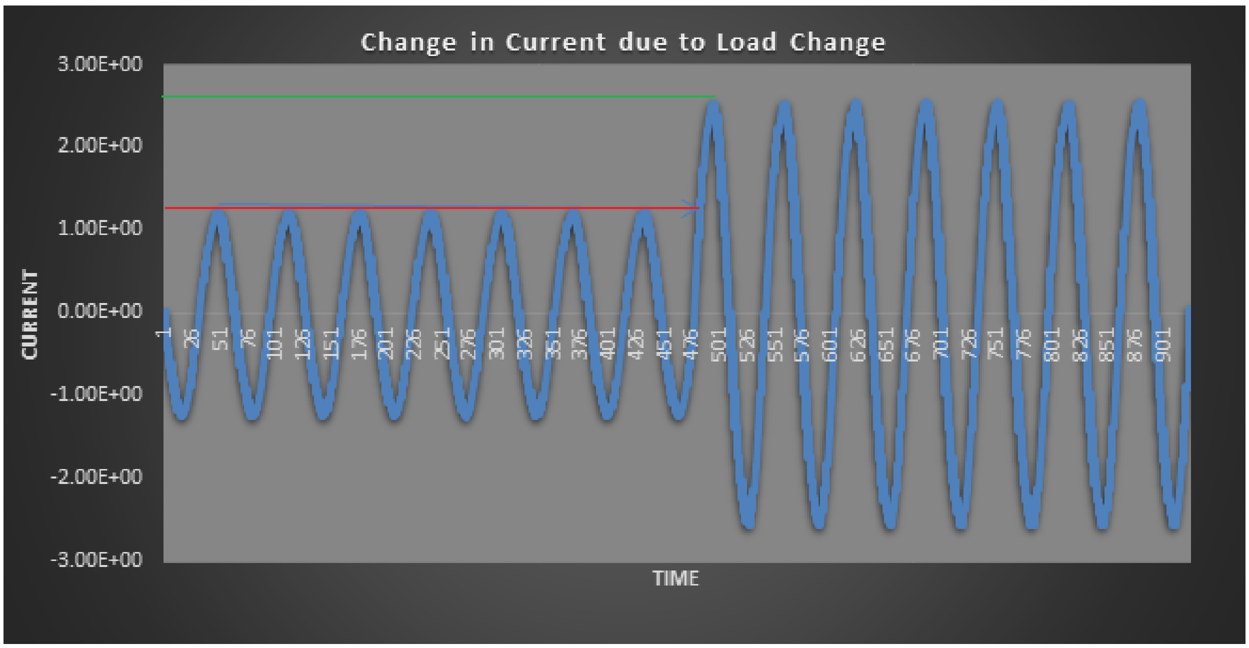


Figure 5.3 Change in current due to load change at 1Ω and 17mH.

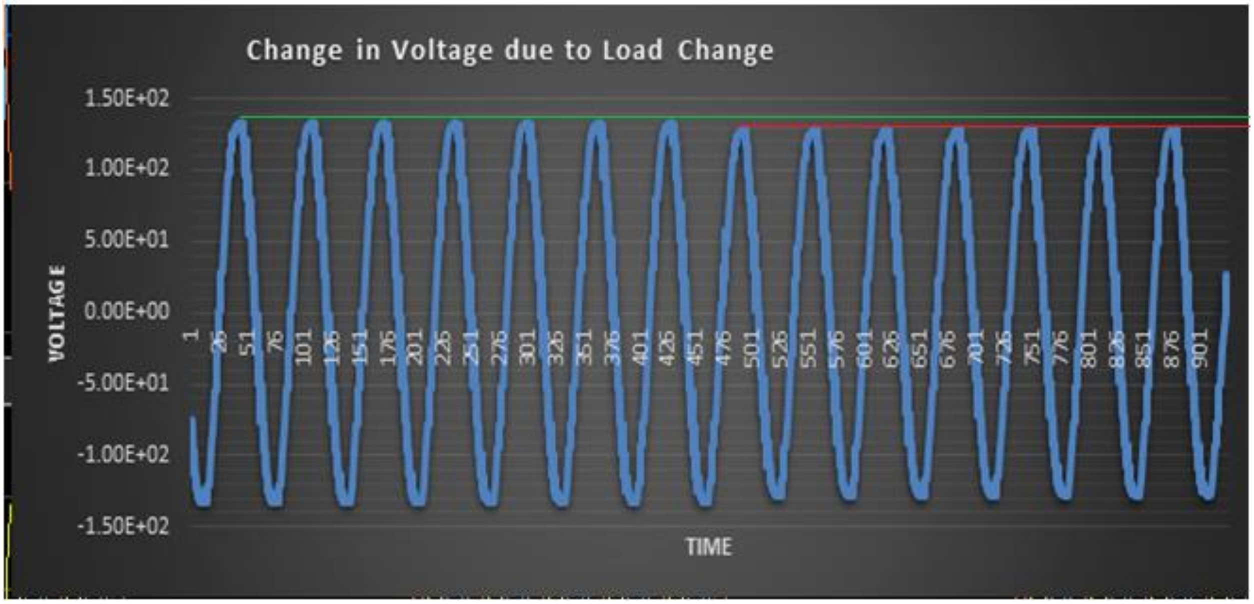


Figure 5.4 Change in voltage due to load change at 1Ω and 17mH.

To attain a good result, the following conditions were necessary,

(a) The voltage before and after the load change must be taken in a continuous sweep for accurate voltage angle displacement.

(b) The current before and after the load change must be measured in a continuous sampling.

(c) There must be a storage, measuring device, to store at least two consecutive cycles with time.

(d) The network Thévenin voltage, frequency and the angle must be constant before and after the load change.

However, it was possible for all these thoughts to be achieved using the power meter.

5.3 The Implemented Test Setup (Active Method)

The laboratory setup is like the simulation model; the schematic arrangement is illustrated in Figure 5.5, while it was set up in the laboratory as shown in the picture of Figure 5.6. The grid is set up with a voltage source of fundamental frequency 50 Hz of a pure sinusoidal voltage signal, while the line is the combination of a resistor and an inductor connected in series to form the transmission line; the system load is a transformer connected for saturation.

The method is based on the creation of disturbance at the Point of Common Coupling (PCC) where harmonic current is injected into the system through deliberate saturation of a transformer acting as a highly inductive load making the system unbalance. The current creates harmonic pollution and converts the part of the fundamental positive sequence active powers to fundamental negative sequence and zero sequences active power that add to the line and electrical motor losses. This method is called the double harmonic injection. The calculation of the line impedance is through the measurement of current and voltage respectively; this is done through two harmonic frequency components which gives the impedance for the two measured frequencies. These two values can then be scaled to the fundamental frequency of the grid by linear interpolation. The method allows the connection of more than one generating unit, that is cogenerated source electricity, which is well synchronized since the determination is through the Thévenin's equivalent of the network.

The method uses the absolute mean values of the injected current corresponding to its voltage at that harmonic frequency (meaning taking two injected harmonics as analyzed by the power meter analyzer); hence taking two of the harmonic frequency values, the line parameters that is, resistance, inductance, and the impedance can be calculated using equations 4.15, 4.16 and 4.18 respectively.

5.4 Implemented Test Setup and Results.

The proposed method for double current injection for the grid impedance equivalent has been tested on a single-phase connected network in the laboratory; the network circuit is shown in Figure 5.5, and the laboratory equipment setup is shown in Figure 5.6, where a power transformer is saturated to bring forth a direct current. The transformer primary side is overloaded from excessive voltage, making the core flux to reach saturation at a peak level of the sinusoidal wave cycle and producing a distorted waveform not related to the primary voltage supplying the primary coil. Hence, the distorted sine wave passes from the primary side of the transformer to the secondary side to bring forth harmonic frequency at the output of the transformer which may be asymmetrical in nature, since the transformer is geometrically constructed, with the help of the Yokogawa power meter, the analysis was easily performed. The power meter separates the frequencies to different harmonic components, where two odd frequencies can be picked for analysis. Figure 5.7 shows the display of the power meter.

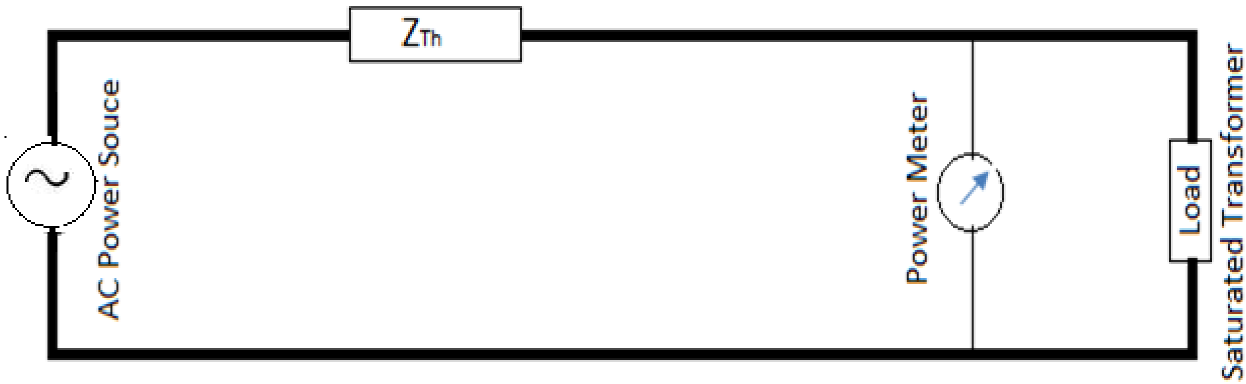


Figure 5.5; An equivalent circuit showing the experimental setup.

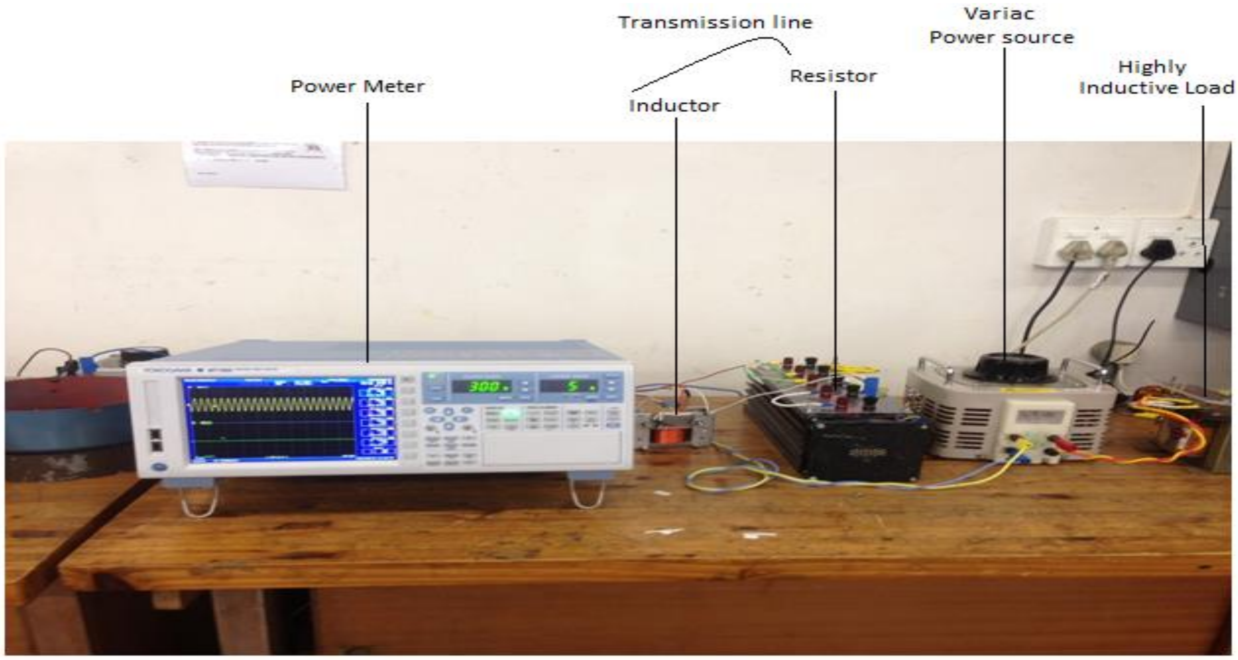


Figure 5.6 The pictorial bench Setup for active method.

Figure 5.7 Yokogawa power meter displaying harmonic voltage and current values.

A saturated transformer is used as a highly inductive load in this experiment; it also serves as non-linear load to generate harmonic current into the network. The saturated transformer generates a DC current aimed at creating double harmonics to the network, while the errors that may occur due to the existing unbalanced load in the system were taken into consideration and eliminated during the reading. This method also takes into consideration the pre-existing harmonic voltages before connecting the saturated inductive load. Figure 5.8 and equation 5.1 illustrate the voltage at the terminals as equal to V_{Ha1} at fundamental due to the pre-existing harmonic in the system. When the load is switched-on, a harmonic current I_{Ha1} will be generated from the load into the network, creating a new harmonic voltage V_{Ha2} to the system.

$$V_{Ha2} = V_{Ha1} + I_{Ha}Z_{Ha} \qquad 5.1$$

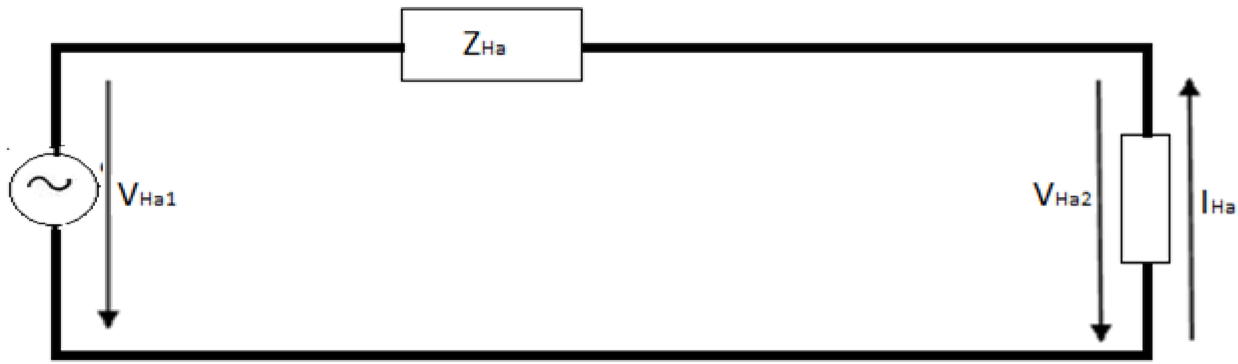


Figure 5.8 Determination of line impedance taking into consideration existing disturbance in the system.

While V_{Ha2} the harmonic voltage when the load is connected

V_{Ha1} The system harmonic voltage before the load is connected

I_{Ha} The harmonic current due to the unbalanced load.

Z_{Ha} The line impedance corresponding to each harmonic order.

Hence the Z_{Ha} now becomes,

$$Z_{Ha} = (V_{Ha2} - V_{Ha1}) / I_{Ha} \quad 5.2$$

5.5 Summary

The chapter has practically demonstrated an accurate and virtually non-grid disturbing passive and active method of impedance measurement which is based on load switching and injection of current respectively. The procedure discussed in carrying out the simulation in the last chapter was used in setting up the laboratory experiment in the laboratory to demonstrate the real-time implementation of the process in which several tests were carried out to validate the results. At the close of the experiment, it was confirmed that the two methods can be applied in the determination of the Thévenin equivalent parameters of a power grid. The practical results gave a good validation as both the simulated results and the experimental solutions are similar. Although the two grid impedance methods developed have been tested both in simulation and laboratory bench work to have given an accurate result, they have not been tested on a real power network.

CHAPTER SIX

SELECTED SIMULATION AND EXPERIMENTAL RESULTS

According to the literature, [103] [104]*, different methods can be used to estimate transmission line impedance, this chapter therefore shows the results of the two proposed methods of grid impedance. The results consist of two main parts, the simulation results (the passive and the active methods) and the experimental result of the two methods as carried out in the bench laboratory work. The chapter also shows the validity of the results using mathematical calculations.*

6.1 Simulation Model and Result (Passive).

The MATLAB/simulation of the passive method which obeys the Kirchhoff's current and voltage principle was implemented with a single-phase network model of different line resistance of $R_{(\Omega)}$ ohms and inductance $L_{(mH)}$ to make up for the line impedance. The set up as shown in Figure 4.4 consists of two parts, namely the network parts which comprises the system supply and the line impedance, while the other part is the measuring side that comprises of the current, voltage, switching breaker, and the delay circuit with the displays. The simulated result of the line impedance is Z_{Th}(Ω@50Hz, while the displaced angle is $\theta_{(deg)}$ as shown in Table 6.1; validating the outcome, the mathematical calculation was done for each same value of resistance and inductance as seen in Table 6.2 and label No 1, 2, 3 and 4 in the first column of the table and comparing both the simulated results with the calculated results, there is no significant variation between both. The circuit consist of source voltage (60 V) with an active load of 7.4 kW having a reactive power of 100 mVar in parallel with a load of 0.1kW. The change in voltage and current was determined using a switch which toggles between 1 and 0, for the pulse generator parameter as shown in Table 6.3. The output waveform for 1 and 2 in Table 6.1 is shown in Figures 6.1 and 6.2 respectively.

Table 6.1 Simulations Results of the line impedance for a single phase passive method

No	R $_{(\Omega)}$	$X_{L@50Hz\ (\Omega)}$	L $_{mH}$	$Z_{Th}\Omega_{Line@50Hz}$	Angle $\theta_{(deg.)}$
1	1.79553	1.009	3.2125	2.06	29.41
2	0.55	0.50	1.592	0.7434	41.87
3	0.06	0.28	0.895	0.1065	55.68
4	1.0	0.16	0.500	0.1020	11.34

Table 6.2 Mathematical calculated result of the line impedance for a single phase passive method

No	R $_{(\Omega)}$	$X_{L@50Hz\ (\Omega)}$	L $_{mH}$	$Z_{Th}\Omega_{Line@50Hz}$	Angle $\theta_{(deg.)}$
1	1.79553	1.009	3.2125	2.05973	29.339
2	0.55	0.50	1.592	0.7434	42.87
3	0.06	0.28	0.895	0.1065	55.88
4	1.0	0.16	0.500	0.1020	11.44

To achieve the simulated result, the MATLAB/Simulink pulse generator parameters are set as shown in Table 6.3, while using time-based variable discrete solver and simulation time to control the switching breaker.

Table 6.3 Pulse Generator Parameters

Pulse Type	Time Base
Pulse Period	0.2Sec
Pulse Width	50% of a period
Pulse Delay	0.1Sec
Pulse Amplitude	1
Time	Simulation Time

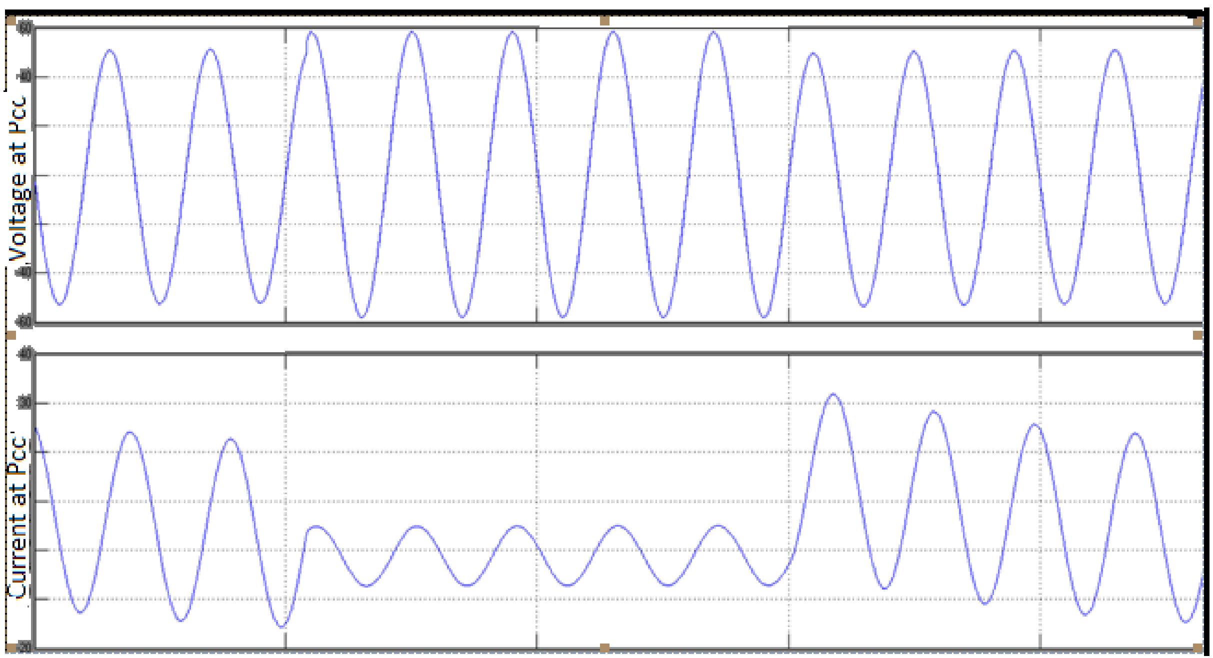


Figure 6.1 The waveform effect of the voltage and current shift at 0.17 Ω and 1.273 mH.

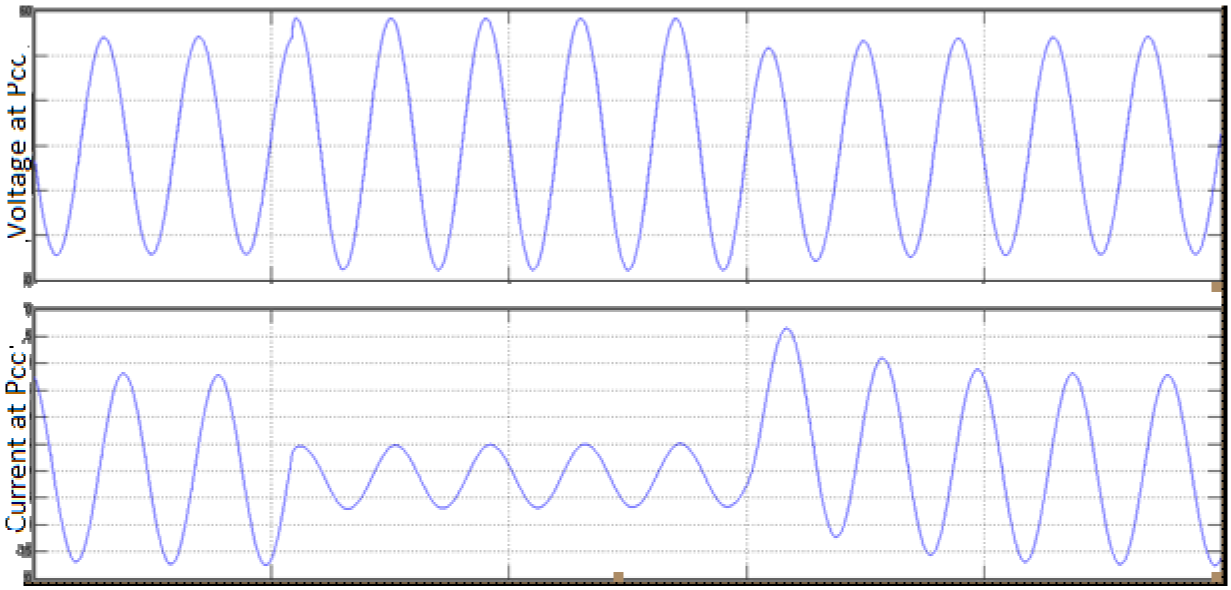


Figure 6.2 The waveform effect of the voltage and current shift at 0.55Ω and 1.592mH.

6.2 Three Phase System

The process was carried out on a three-phase system to test the validity on multiple wires as shown in Figure 4.12. The tabulated result in Table 6.4 was achieved on each of the three phases using both series/parallel line resistance and inductance. The three-phase circuit arrangement and the line parameters are shown in the Appendix A with Figures A1, A2 and A3.

Table 6.4 Simulations Results of the line parameters for a three-phase passive method.

No	$R_{Th(\Omega)1}$	$R_{Th(\Omega)2}$	$R_{Th(\Omega)3}$	$Z_{Th(\Omega)1}$	$Z_{Th(\Omega)2}$	$Z_{Th(\Omega)3}$	$\theta_{(deg.)1}$	$\theta_{(deg.)2}$	$\theta_{(deg.)3}$
1	1.088	1.107	1.10	1.323	1.309	1.259	39.01	38.02	38.00
2	0.855	0.873	0.867	1.107	1.101	1.059	41.03	40.22	40.16
3	0.6762	0.6961	0.6897	0.9056	0.9048	0.897	42.05	41.16	40.19

6.3 Simulations Results Active

Tables 6.5 and 6.6 show the line impedance estimation using the double current injection as is used in MATLAB/Simulink; the results show a highly accurate result with the mathematical calculation taking the line resistance (R) 1Ω with the line inductance (L) (0.5mH) and resistance (R) 10Ω with the line inductance (L) 980μH respectively. To test the effectiveness of the proposed method, different values of R and L were used in the simulation as shown in Table 6.7 to show its validity.

Table 6.5 Using 1Ω and 0.5mH as the line impedance for harmonic injection.

Harmonic order	Frequency $_{(Hz)}$	V $_{(vol.)}$	I $_{(amp.)}$	Z_{Th}
3^{Th}	150	0.9345	0.9060	1.031
5^{Th}	250	0.9795	0.9010	1.087
7^{Th}	350	2.093	1.7870	1.172
9^{Th}	450	1.135	0.8831	1.285
11^{Th}	550	1.244	0.8706	1.429
13^{Th}	650	1.372	0.8558	1.603

Table 6.6 Estimated line impedance from the simulation (as the grid impedance)

Harmonic order	Z_{Th}	Angle	R (Ω)	X_L (Ω)
3^{Th} & 5^{Th}	1.002	4.925	0.9985	0.0861
5^{Th} & 7^{Th}	1.042	6.010	1.037	0.1092
7^{Th} & 9^{Th}	1.111	6.827	1.103	0.1320
9^{Th} & 11^{Th}	1.207	7.426	1.197	0.1560
11^{Th} & 13^{Th}	1.333	7.843	1.320	0.1819

Table 6.7: Using 10 Ω and 980 μH as the line impedance for harmonic injection

Harmonic order	Frequency (Hz)	V (vol.)	I (amp.)	Z Th
3Th	150	5.014	0.4982	10.06
5Th	250	5.039	0.4950	10.18
7Th	350	10.150	0.9807	10.39
9Th	450	5.125	0.4841	10.59
11Th	550	5.185	0.4765	10.88
13Th	650	5.266	0.4675	11.24

With the Tables 6.5 and 6.7, the Thévenin equivalent impedance of the network can be obtained through the mathematical expression presented in equation 4.15 for the network resistance (R), equation 4.16 for the line inductance (X_L), while 4.18 gives the Thévenin equivalent impedance (Z_{Th}) of the network as shown in Tables 6.6 and 6.8 respectively in the simulation.

Table 6.8 Estimated line impedance from the simulation (the grid impedance)

Harmonic order	Z Th	Angle	R (Ω)	X_L (Ω)
3Th & 5Th	10.01	2.186	09.999	0.3817
5Th & 7Th	10.09	2.683	10.080	0.4723
7Th & 9Th	10.23	3.099	10.220	0.5533
9Th & 11Th	10.44	3.462	10.420	0.6301
11Th & 13Th	10.70	3.783	10.670	0.7058

6.4 Experimental results

Having tested the two-impedance measuring methods by simulation using MATLAB/Simulink block set in the simulation environment and achieving a good result, the process was carried out in the laboratory for experimental and validation purposes. The following results were obtained in the laboratory;

Table 6.9: Evaluation of impedance using a 5Ω resistor as the line parameter with different harmonic frequencies.

Harmonic order	Frequency (Hz)	V_o (volts)	V_1 (volts)	ΔV	I (Amp)	Z_{Th} (Ω)
3^{Th}	150	5.01	15.57	10.56	2.479	4.26
5^{Th}	250	3.37	8.68	5.31	0.992	5.35
7^{Th}	350	2.91	1.51	1.40	0.261	5.36
9^{Th}	450	1.96	1.62	0.34	0.065	5.23
11^{Th}	550	0.69	0.90	0.21	0.040	5.25
13^{Th}	650	0.69	0.66	0.03	0.006	5.10

The table gives the initial voltage V_0 before the harmonic was injected at each frequency and the final voltage V_1 after the harmonic has been injected into the system; the change in voltage ΔV is determined for each frequency and Ohms law is obeyed in the determination of the line impedance Z_{Th} at that particular harmonic frequency. Hence, following the same mathematical expression of equations 4.15, 4.16 and 4.18, the Thévenin parameters of the line are determined as shown in Table 6.10.

Table 6.10: Estimated line parameters from the bench work for the grid impedance

Harmonic order	Z_{Th} @ 50 $_{Hz}$	R (Ω)	XL (Ω)
3^{Th} & 5^{Th}	3.500782	3.500781	0.002575
5^{Th} & 7^{Th}	5.339563	5.339563	0.000213
7^{Th} & 9^{Th}	5.553168	5.553168	0.000660
9^{Th} & 11^{Th}	5.189264	5.189264	0.000230
11^{Th} & 13^{Th}	5.610356	5.610356	0.000572

The experiment was repeated several times for the validation of the method using different resistance and inductance. The results are shown in Table 6.11; with the result, the bench experiment emulates the simulation earlier done to affirm the method.

Table 6.11: Evaluation of impedance using a 3.5Ω resistor as the line parameters with different harmonic frequencies

Harmonic order	Frequency (Hz)	V_o (vot)	V_1 (volts)	ΔV	I (Amp)	Z_{Th} (Ω)
3^{Th}	150	4.97	13.35	8.38	2.793	3.00
5^{Th}	250	3.37	7.27	3.90	1.102	3.53
7^{Th}	350	2.59	1.58	1.01	0.268	3.77
9^{Th}	450	2.04	1.73	0.31	0.080	3.88
11^{Th}	550	0.64	0.43	0.21	0.054	3.89
13^{Th}	650	0.70	0.59	0.11	0.029	3.79

Table 6.12: Estimated line parameters from the bench work as the grid impedance

Harmonic order	Z_{Th} @ 50 $_{Hz}$	R (Ω)	X_L (Ω)
3^{Th} & 5^{Th}	2.655795	2.655794	0.001480
5^{Th} & 7^{Th}	3.261273	3.261272	0.000859
7^{Th} & 9^{Th}	3.595046	3.595045	0.000516
9^{Th} & 11^{Th}	3.859671	3.859670	0.000140
11^{Th} & 13^{Th}	4.131356	4.131355	0.000402

Table 6.9 and Table 6.11 shows the measurement of a sub-harmonic voltage component caused by a sub-harmonic current value as extracted from the Yokogawa power analyser, this gives the value of the line impedance for that specific sub-harmonic frequency (Z_{Thh}). The difference between the two frequencies chosen in the conversion of the measurement results to the grid fundamental frequency of 50 H_Z is necessary and is enough to keep the result in a minimum error during the interpolation. The mathematical analysis can be performed as indicated in equation 4.15 for the line resistance (R), and equation 4.16 for the line inductance X_L while the line equivalent Thévenin impedance (Z_{Th}) is achieved through equation 4.18. The real part of the system component gives the resistive component R of the grid impedance, which will eventually lead to the (I^2R) losses of the system, while, the imaginary part gives the inductive component X_L as shown in Table 6.10 and Table 6.12

The experimental result gives good validation of the passive method. Although there is a little inconsistency in the impedance values which is due to the variation in the supply voltage caused by the numbers of nonlinear loads connected in the laboratory, the experiment will give a better result if the input voltage and current are pure sinusoidal waves.

6.5 Summary

The estimation of the Thévenin impedance is a key to power loss allocation, the presented results of the two methods proved to be effective in the determination of grid impedance. The result from the passive method was validated both mathematically and in the laboratory bench work. Likewise, the result from the active method which was based on double current injection was simulated and validated using the laboratory bench work. Though the determination of the grid impedance was focused on being used for loss allocation in this thesis, from the result, the outcome can also be used in many applications in power system. To choose a better grid impedance estimation method, the switching method is noticed to be more accurate taking from the presented results.

This chapter and the last two preceding chapters brought a clarity to one of the research questions, (**What is the impact of the Thévenin impedance estimation on loss allocation using non-active power**?).

CHAPTER SEVEN

PRACTICAL ANALYSIS OF TEST SYSTEM

This chapter presents the analysis of GPT. The GPT is used in the determination of a system's avoidable loss, while both the GPT and the Thévenin parameters (calculated from the point of load connection) are used in allocating a system's unavoidable loss. This method is tested on a standard network and compared with existing loss allocation methods, and the avoidable loss is determined to show what can be saved economically or charged in a tariff

7.1 Application of The General Power Theory

Due to the increase in the usage of modern-day electronic devices, which create high distortion in voltage and current on the transmission line, the decomposition of the current into *useful and useless* through the decomposition of power using the general power theory as described in [83] was carried out. Malengret and Gaunt [83] have emphasized the needs for reducing transmission losses caused by the phase shift between the current and the voltage and the unbalancing effect of the load on the generation in three-phase power systems.

The approach developed from the generalized theory of instantaneous power, for multi-phase wire in a power system which was valid for average power was used to determine the losses contributed by each load and generator in a power network. This theory is applicable for both sinusoidal and non-sinusoidal three-phase current and voltage, balanced and unbalanced load and a system with or without zero-sequence current and voltage [84] [90].

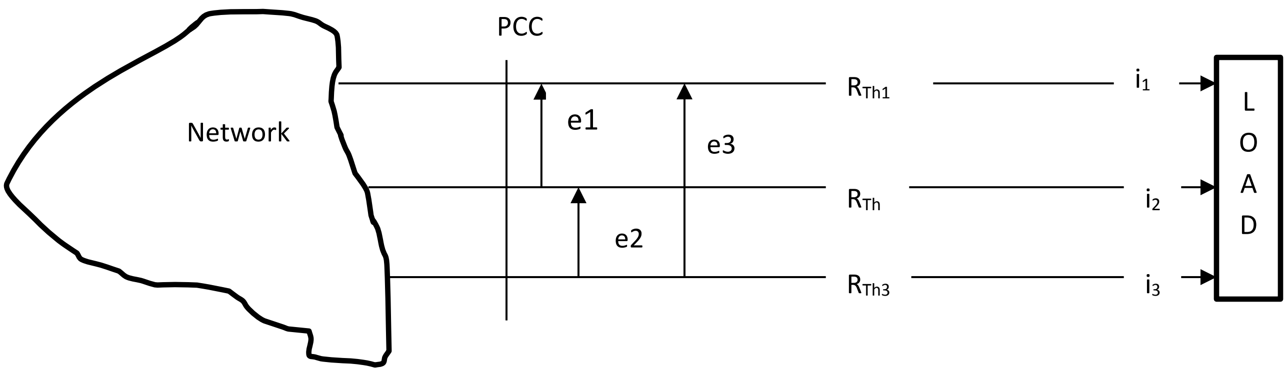


Figure 7.1 Three wire system with Thévenin resistances R_{Th1} R_{Th2} R_{Th3} supplying the load with voltage e = (e_1, e_2) measured from one of the wires, and the current i = (i_1, i_2, i_3).

7.2 Balanced Load System

To determine the minimum power that can be achieved when making all the load on the three-phases to be balanced, a load flow of a system was carried out for a particular load pattern to determine the line parameters for the balanced loads. Considering that the losses associated with transmission power depends on the line resistance and the optimum current that can transmit the same power with minimum losses, the resistance R and current I determined were used to evaluate the loss. The load flow solution gives the active power, the reactive power, the load current and Thévenin resistance of a particular three-phase balanced load in the system as shown in Table 7.1 to arrive at the system loss.

Table 7.1 Simulated results of a balanced load.

	Phase 1	Phase 2	Phase 3	**3- Phase**
Active Power (pu)	0.149	0.149	0.149	**0.447**
Inductive Power (pu)	0.050	0.050	0.050	**0.150**
Current (i)	0.1407	0.1399	0.1404	
R_{Th}	**0.2910**	**0.2983**	**0.2890**	

From the summarized arithmetic derivation of optimal supply current for both balanced and unbalanced systems as described in [83] which can be used in the general approach of M- wire system to 3 and 4 wires for various values of neutral wire resistance,

$$e_{ref} = \frac{\sum_{n=1}^{m}\left({e_n}/{r_n}\right)}{\sum_{n=1}^{m}\left({1}/{r_n}\right)} \tag{7.1}$$

Equation 7.1 is the reference point for the voltage that considers the line resistance of the system. From Table 7.1, the phase resistance (R_{Th}) is the Thévenin resistance of the line, while the current (i) is the instantaneous line current and the power in the circuit is an active power.

In Akaji's approach [105], the case of a 3-phase 4-wire system was not considered. Also, the components of power and current were calculated from average values and not instantaneous values, therefore this was reformulated by Malengret and Gaunt [82], The determination of the reference voltage for M = 3 is chosen as the virtual point of the three wires not taking cognizance of the neutral wire even if it exists in the system. The voltage reference point is carefully defined to determine the active current norm which results in the minimum delivery.

$= (e_{ref,}\ e_{ref,}\ e_{ref,}\ e_{ref,}\ .\ e_{ref})$

Line voltage on the bus,

$V_{11} = e_1 = 0.$

$V_{12} = e_2 = 0.8842$

$V_{13} = e_3 = 0.8842$

$e_{ref} = 0.5877$

To determine the line voltage from the line reference point of equation 7.1, equation 7.2, was used while equation 7.3 was used for the determination of the weighted voltage vector. Recognizing that the line resistance may not be equal in all cases, the conductance was determined through equation 7.4; and the active current vector was determined using equation 7.5.

$V_2 = (e- e_{ref}) = [(e_1 - e_{ref}), (e_2 - e_{ref}), (e_3 - e_{ref})]$ (7.2)

= {-0.5877, 0.2965, 0.2965}

$V_2' = V_2 R_{Th}^{-1/2}$ (7.3)

= {-1.0895, 0.5428, 0.5515}

$||V_2'||^2$= {1.1870, 0.2946, 0.3042}

= 1.7858

$g = P /||V_2'||^2$ (7.4)

While P = 0.0173 W

g = 0.00969 (7.5)

$i_a = g V_2 Rd_{th}^{-1}$ = {-0.0196, 0.00963,0.0099}

$i_a' = i_a Rd_{th}^{1/2}$ = {-0.0363, 0.0176, 0.0185} (7.6)

The minimum Power $P_{la} = || i_a'||^2$ = 0.001968 W, which is the instantaneous power to be achieved in the system:

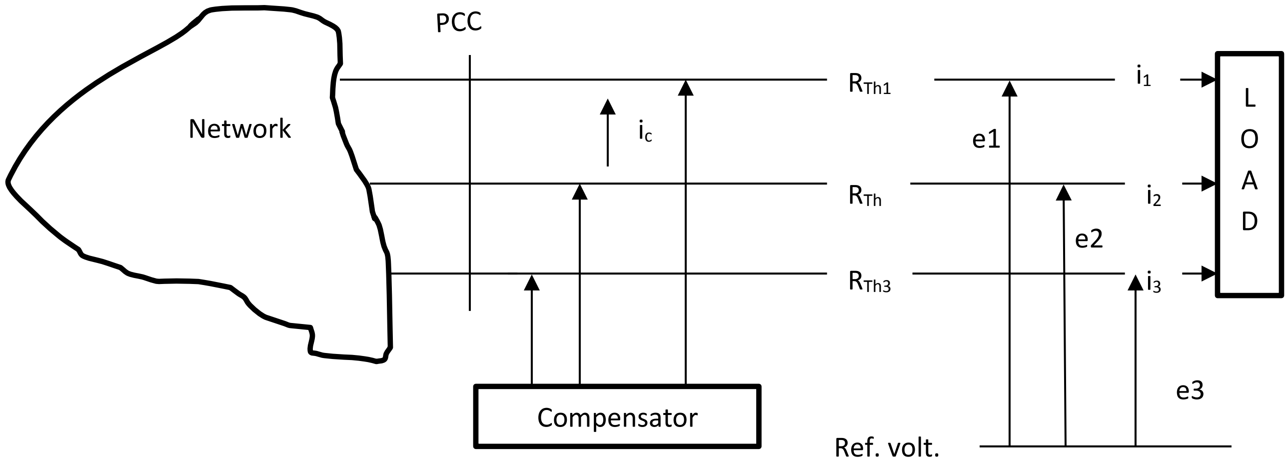


Figure 7.2: Three wire system with Thévenin resistances R_{Th1}, R_{Th2}, R_{Th3} supplying load with voltages

e = (e_1, e_2, e_3) and current i = (i_1, i_2, i_3), with a current compensator supplying current i_c.

As demonstrated in Figure 7.2 above, which reveals the Thévenin equivalent of the network, the whole system can be represented by its equivalent Thévenin circuits and the network parameters (Thévenin source voltage V_{Th}, Thévenin resistance R_{Th}, Thévenin reactance X_{Th} and Thévenin impedance Z_{Th} for each wire) which can be worked out as stated in chapter three. The "null point of the voltage" that is, the reference voltage, can also be determined [83].

From Table 7.1 $i_1 = 0.1407$

$i_2 = 0.1399$

$i_3 = 0.1404$

Where, i_1, i_2, i_3, are the currents in phases 1, 2, and 3 of the network respectively.

The non-active instantaneous current i_c not weighted

$i_c = i - i_a$ = {0.1407, 0.1399, 0.1404} – {-0.0196, 0.0096, 0.0099}

= {0.1603, 0.1303, 0.1305}

$||i_c||^2$ = {0.02570, 0.01698, 0.01703}

= 0.05971

$||i||^2$ = {0.0198, 0.0196, 0.0197}

= 0.05911

To determine the line losses, the current in the system was measured with their corresponding line resistances.

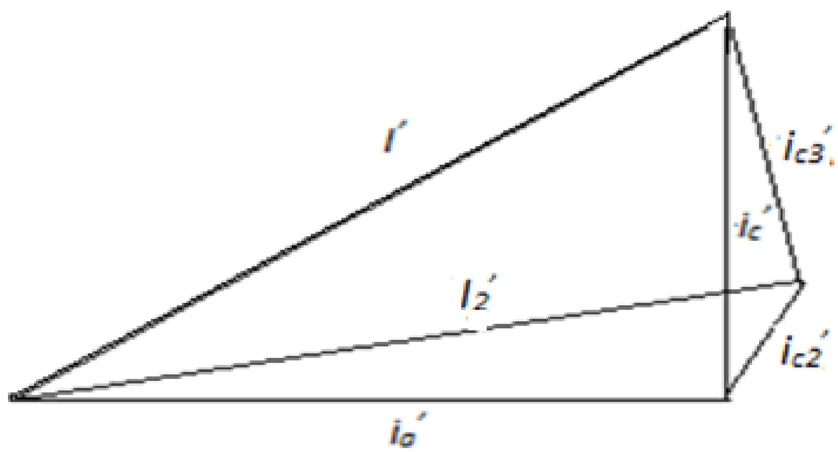


Figure 7.3. The orthogonal relationship of the RMS currents.

($|| I'||^2 = || i_a'||^2 + ||i_c'||^2$) and ($||i_c'||^2 = || i_{c2}||'^2 + ||i_{c3}'||^2$) while after the compensation, ($I_2' = i_a'$).

Taking I' as the total line current without compensation, i_a' is the current after total compensation and is also represents the real power; i_c' is the total non-active current which is a measure of the current that can be compensated without energy storage i_{c3}', is the power that oscillates between the line and i_{c2}', the current that required energy storage which oscillates between the supply to the system and the load. This current does not have a storage at any stage. i_2 the current after compensation without energy storage [65].

The weighted active current

i_a' = {-0.0363, 0.01763, 0.0185}

$||i_a'||^2 = 0.00196$

$i' = [0.1407, 0.1399, 0.1404] * \sqrt{R_{Th}}$

$= \{0.0759, 0.0764, 0.0755\}$

The weighted non- active instantaneous current = i_c'

$||i'||^2 = || i_a'^2|| + ||i_c^2|| = ||i_a'^2|| + ||i_{c2}'^2|| + || i_{c3}'^2||$

$i_c' = i' - i_a' = \{0.0759, 0.0764, 0.0755\} – \{-0.0363, 0.0176, 0.0185\}$

$= \{0.1122, 0.0588, 0.0570\}$

$||i_c'||^2 = 0.01929$

$||i'||^2 = ||i_a'||^2 + ||i_c'||^2$

$= 0.00196 + 0.01929 = 0.0200$

Making i_c' and i_a' to be an orthogonal vector.

$S^2 = (||i'||^2 - ||i_a'||^2) ||V_2'||^2 + P^2$

$Q^2 = S^2 - P^2 = (||i'||2 - ||ia'||2) ||V2'||2$

$Q = \sqrt{((||i'||2 - ||ia'||2) ||V2'||2)}$VAr

However, $S^2 = P^2 + Q^2 = P^2 + Q_A^2 + Qa^2$

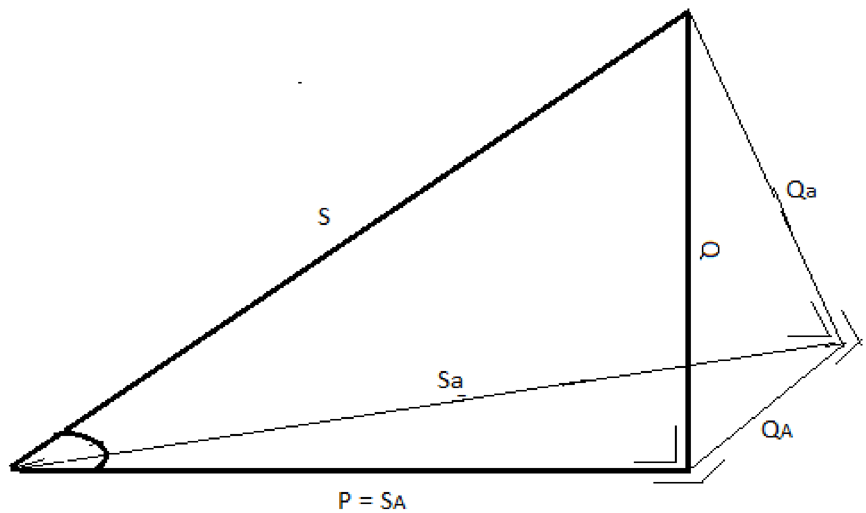


Figure. 7.4 The orthogonal nature of the elements of a complete power triangle.

Q which is considered as the reactive power of the system comprises two non-active currents (components) the components that can only be compensated with energy storage (Q_A) and the other which requires no energy storage (Q_a); Q is therefore related to the size of the compensator needed to take the power factor to unity (1). This can be defined as the non-active power.

$$Q^2 = Q_A^2 + Q_a^2 \text{ which is the non-active power}$$

The size of the component that requires energy storage for compensation is

$$Q_A = (S_A^2 - P^2)^{1/2}$$

$$Q_A = ||i_{c2}'|| * ||V_2'||$$

The size of the component that can be compensated without energy is,

$$Q_a = ||i_{c3}'|| * ||V_2'||$$

$$S_a = (S^2 - Q_{c2}^2)^{1/2} = ||i_{c2}'|| * ||V_2'||$$

For a totally compensated load, the power factor is the ratio of the P, the minimum power that can be used for transfer, to the apparent power S_A after compensation, $P = S_A$

$$\emptyset_{a} = P / S_A = P / \|V_2'\| (I - i_{c3} - i_{c2}) = P/P$$

$$= 1$$

This shows that the unity power factor can only be achieved when the system has been compensated with energy storage.

7.3 Unbalanced Load System

Though most of the time, a power system operates with a balanced sinusoidal supply, at other times the conventional definition gives misleading result due to the presence of distortion, and unbalanced load in the system. For an unbalanced load system, the load flow was also carried out on the same system as before, but making the load, unbalanced, the resistance value was noticed to change due to the imbalance in the load, Table 7.2 below shows the same load when made unbalanced in the three phases as in Table 7.1.

Table 7.2: Simulated results of an unbalanced load.

	Phase 1	Phase 2	Phase 3	**3- Phase**
Active Power (W)	0.149	0.109	0.189	**0.447**
Inductive Power (Var)	0.040	0.050	0.060	**0.150**
Current (i)	0.1387	0.143	0.1434	
R_{Th}	0.2865	0.5028	0.1992	

Taking the same process as for balanced system the line voltage on the bus is,

$V_{11} = e_1 = 0$

$V_{12} = e_2 = 0.8844$

$V_{13} = e_3 = 0.8844$

$e_{ref} = 273.69$

$V_2 = (e - e_{ref}) = [(e_1 - e_{ref}), (e_2 - e_{ref}), (e_3 - e_{ref})]$

$= [-0.5904, 0.2940, 0.2940]$

$V_2' = V_2 R_{th}^{-1/2}$

$= \{-1.1030, 0.4146, 0.6587\}$

$||V_2'||^2 = \{1.2166, 0.0864, 0.0864\}$

$= 1.3895$

$g = P/||V_2'||^2$

Where P = 0.1199 W

g = 0.0658

$i_a = g\ V_2\ Rd_{th}^{-1} = \{-0.1356, 0.0385, 0.0971\}$

$i_a' = i_a\ Rd_{th}^{1/2} \quad = \{-0.253, 0.0543, .2176\}$

The minimum Power $P_{la} = ||i_a'||^2 = 0.1144$ W

From the Table 7.2, $i_1 = 0.1387$

$i_2 = 0.143$

$i_3 = 0.143$

While i_1, i_2, i_3 are the currents in phases 1, 2, and 3 of the system respectively.

The non-active instantaneous current i_c not weighted

$i_c = i - i_a = [0.1387, 0.143, 0.143] – \{-0.1356, 0.0385, 0.0971\}$

$= \{0.2743, 0.1045, 0.0459\}$

$||i_c||^2 = \{0.0752, 0.0109, 0.0021\}$

$i_c = 0.0680$

$i' = \{0.1387, 0.143, 0.143\} * \sqrt{R_{Th}} \quad = \{0.0742, 0.1014, 0.0638\}$

$||i'||^2 = 0.0199$

The non-active instantaneous current weighted = i_c'

$i_c' = i' - i_a' = \{0.0742, 0.1014, 0.0638\} - \{-0.2533, .05425, 0.2176\}$

$= \{0.3275, 0.0472, - 0.1536\}$

$||i_c'||^2 = 0.1331$

$||i'||^2 = ||i_a'||^2 + ||i_c'||^2$

$= 0.1144 + 0.1331 = 0.2475$

$S^2 = (||i'||^2 - ||i_a'||^2) ||V_2'||^2 + P^2$

S = VA.

$Q^2 = S^2 – P^2$

Q = Var

$Q^2 = Q_A^2 + Q_a^2$ which is the non-active power the power and current components are calculated from instantaneous values and not average values.

The power factor before the compensation Ø that is defined as the ratio of the real power flowing to the load to that of the apparent power in the system is:

$Ø = P / (\|i'\|^2 - \|i_a'\|^{2\ 2}) \|V_2'\|^2 + P^2$

$$Ø = P / S$$

Hence relating this to Figure 7.4,

The size of the component that requires energy storage for compensation is:

$Q_A = (S_A^2 – P^2)^{1/2}$

$S_A = (Q_A^2 + P^2)^{1/2}$

$Q_A = //i_{c2}'// * //V_2//$

The size of the component that can be compensated without energy is,

$Q_a = //i_{c3}'// * //V_2//$

7.4 The Numerical Results Using Test System for Loss Allocation

Power losses are due to the current which passes through an imperfect electrical conductor. The conducting material has an impedance which causes a potential drop on the network and the dropped potential is proportional to the current flowing in the system [106]. However, the resistive part (R) of the impedance and the current flow (I) have a great impact on the physics of power loss of the system.;

Hence, I^2R. is taken as the losses caused by the load.

7.5 IEEE 5-Bus Test System

The application of the proposed method was tested and compared with other methods in the literature for the confirmation of the method's accuracy. A simple 5 bus system as described in [107] was used; the system comprises seven lines, three generators and four loads. The five bus system was simulated and the results of the system power losses and the Thévenin equivalent parameters from the point where each load is connected to the bus are tabulated in Table 7.3; a comparison result found in [108] is represented in Table B1 after rigorously testing the authenticity of the report. The method gives the total real power loss from all the buses as 4.801 MW using the Thévenin equivalent method from the point of connecting the load and the generator. Tables; B1 and B2 in Appendix B show the five-line data and bus data.

Table 7.3 The Equivalent Parameters of the System used to determine the losses

Bus No	$Z_{Th\ (\Omega)}$	$R_{th1\ (\Omega)}$	$R_{th2\ (\Omega)}$	$R_{th3\ (\Omega)}$	$I_{1\ (\Omega)}$	$I_{2\ (\Omega)}$	$I_{3\ (\Omega)}$
1	0.2334	0.0968	0.0968	0.0970	2435	2408	2542
2	0.1316	0.04762	0.04887	0.04779	2789	2762	2791
3	0.1396	0.05135	0.05144	0.05083	2643	2643	2659
4	0.1309	0.04799	0.04854	0.04831	1762	1752	1756
5	0.1803	0.07485	0.03523	0.03373	2520	2010	2498

7.6 IEEE 14-Bus Test System

The standard IEEE 14-bus test system which is commonly used for demonstration measurement, voltage stability and different simulation analyses in the literature was used to illustrate the Thévenin method of using the equivalent circuit to determine the loss allocation from the point of load connection. The same test system was used to compare the proposed loss allocation method with some well-known algorithms in the literature. The test system consists of five synchronous machines; three are synchronous compensators, eleven active loads with a total of 259 MW and twenty lines. The system whose data can be found in [109] is shown in Figure 7.5 with its line and bus data as shown in Appendix B5 and B6 respectively.

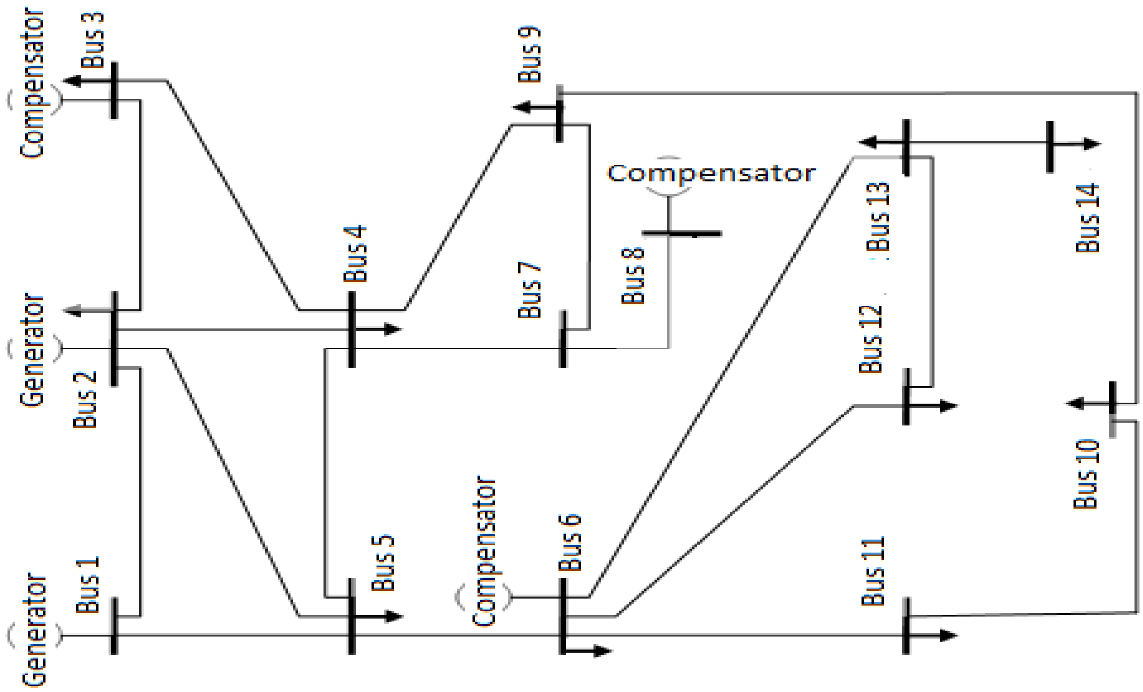


Figure 7.5: The IEEE 14 Bus Test System.

The determined parameters for the 14 bus IEEE system are tabulated and shown in Table 7.4 after the simulation with the corresponding power system model in Figure 7.5. The line data of the transmission lines in the system model is the line resistance and the inductance with the system frequency of 50 Hz. The generator of the system is a three-phase source in SimPower system, which generates the three-phase voltage.

The method which uses the switching on-and-off of current to determine the Thévenin equivalent parameter of the circuit as analyzed in chapters three and four was utilized. This method as earlier explained in the previous chapter is suitable for both balanced, unbalanced as well as the presence of distortion in the system as shown in Figures B1 & B2 in Appendix B.

The Table 7.4 shows the Thévenin equivalent parameters of the standard IEEE 14 bus used to determine the power loss to be allocated to each load. Buses 7 and 8 shows zero parameters since the two buses are without load nor generator. This method is advantageous because it requires no large mathematical calculations as compared to other methods in the literature, it is free of distortion which may affect the parameter approximations and faster during implementation when compared with other methods.

Table 7.4 Line Parameters of 14- bus IEEE Test System at the different bus

Bus No	Z_{Th} (Ω)	R_{Th1} (Ω)	R_{Th2} (Ω)	R_{Th3} (Ω)	$I_{Line\ 1}$ (Amp)	$I_{Line\ 2}$ (Amp)	$I_{Line\ 3}$ (Amp)
1	0.123	0.057	0.054	0.062	1044	1873	1263
2	0.336	0.215	0.215	0.215	2312	2312	2312
3	0.6008	0. 165	0.166	0.165	1247	1246	1247
4	0.566	0.255	0.254	0.254	1649	1652	1650
5	0.502	0.296	0.295	0.297	1864	1865	1864
6	1.107	0.277	0.276	0.277	962.5	962.3	962.3
7	0.000	0.000	0.000	0.000	0000	0000	0000
8	0.000	0.000	0.000	0.000	0000	0000	0000
9	1.250	0.111	0.113	0.113	958.7	960.2	960.6
10	1.251	0.258	0.258	0.259	1031	1032	1033
11	1.291	0.291	0.291	0.292	997.5	999.1	999.9
12	1.425	0.267	0.267	0.267	898.7	899.8	900.9
13	1.434	0.176	0.176	0.176	871.7	870.8	869.8
14	1.335	0.139	0.137	0.138	934.3	935.3	936.4

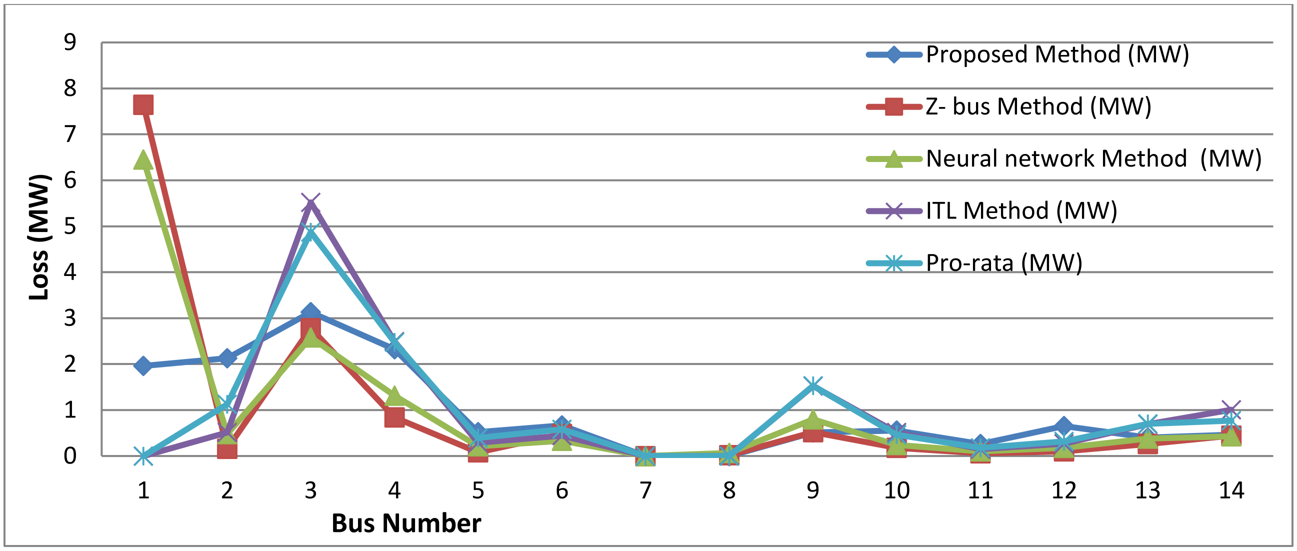


Figure 7.6: Comparison of the proposed method with others in the literature.

Testing the new method on a standard IEEE 14-bus test system provided the results of the proposed loss allocation method and the equivalent parameters of the network, which were determined through the switching of two loads; these results are shown in Table 7.4. Figure 7.5 shows the topology of the system network used, while Figure B1 in the Appendix shows the switching pattern of the voltage and current at bus 4, for a balanced load and Figure B2 in the Appendix gives the switching pattern when the load is made unbalanced. The presence of the generator attached to buses 1 and 2 gives a little divergence from the loss allocation in literature. The proposed method is highly responsive to the network geometry and connected load, which is the function of the power flow in the system.

The converged simulation of the 14-bus results shows the equivalent parameters of the system which are the line resistance, the line inductance, the bus line-line voltage, the angle, the line current and the Thévenin impedance of the system. The magnitude of the loss as caused by the load on each of the buses is shown in the proposed column of Table B4 in the Appendix B and as displayed in Figure 7.6; The Thévenin parameters for the IEEE 14 bus test system are used in determining the losses caused by each load at the point of common coupling using the model that has been built in MATLAB and SimPower system.

The result of the proposed method was compared with the ones obtained using Z-bus allocation method, the neural network method of loss allocation, the Pro-rata method, proportional sharing method and the incremental transmission loss method stated in [110] and [111] as listed in Table B4. The results of the proposed method vary slightly from the result of the other methods; though having the same total loss, the proposed method is a real-time determination which does not make assumptions in determining the equivalent parameters of the system. The method is also locational as it based its determination on the load positioning in the network. The operation of the proposed method is founded on the average power theory in the average domain. The losses can be measured from the Thévenin equivalent parameters at any point on the network from the instantaneous values of the voltage and current in the system without any prior knowledge of the line parameters. The proposed method takes full care of allocating losses on both balanced and unbalanced power systems.

The approach of the general theory of average power for multi-phase systems was applied with a combination of distortion, unbalance and direct instantaneous current components [84], and is consistent with the requirement for minimum losses in power systems. The general power theory demonstrates the ways compensation can be manipulated to allow for minimal losses in power systems, especially in systems with unbalanced loads. Through the GPT and Thévenin equivalent parameters, minimum power loss in the system can be identified, and more power can be transmitted for the same loss in proportion to the ratio of the norm of the current if the load is compensated towards unity power factor. Figure 7.7 shows the difference in the losses transacted in a conventional way and the losses which can be achieved if the power factor is well modified using the new method as shown numerically in Table B7 in the Appendix B. Thus, the losses which could be avoided are shown in Figure 7.8.

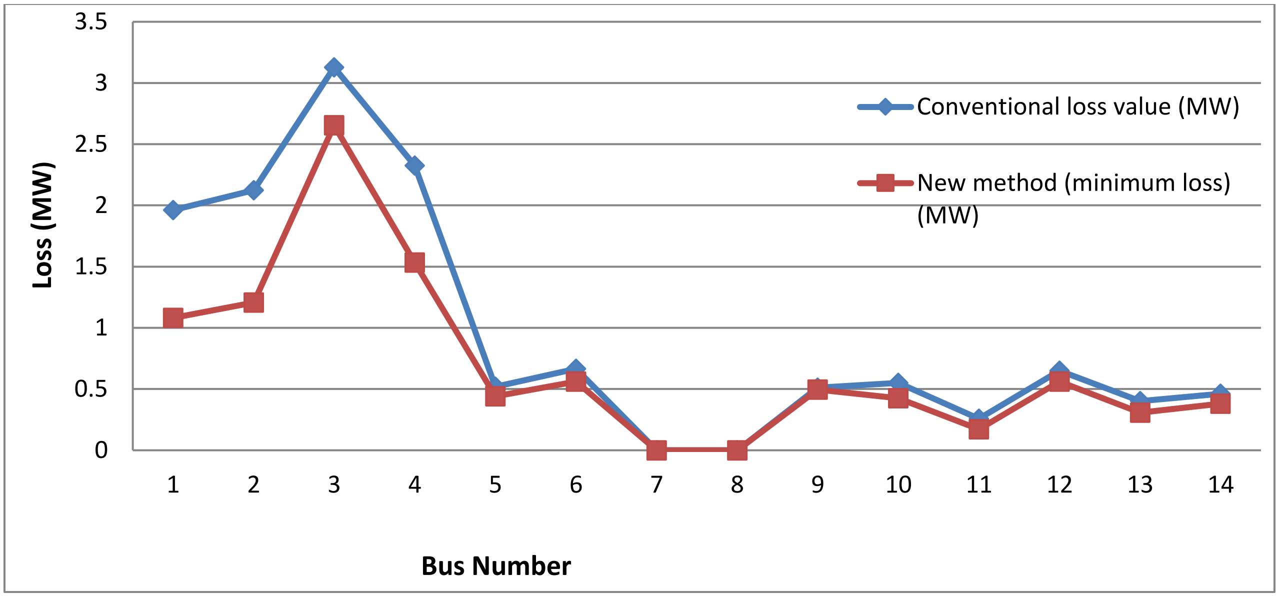


Figure 7.7: Comparison of the conventional method with the new method.

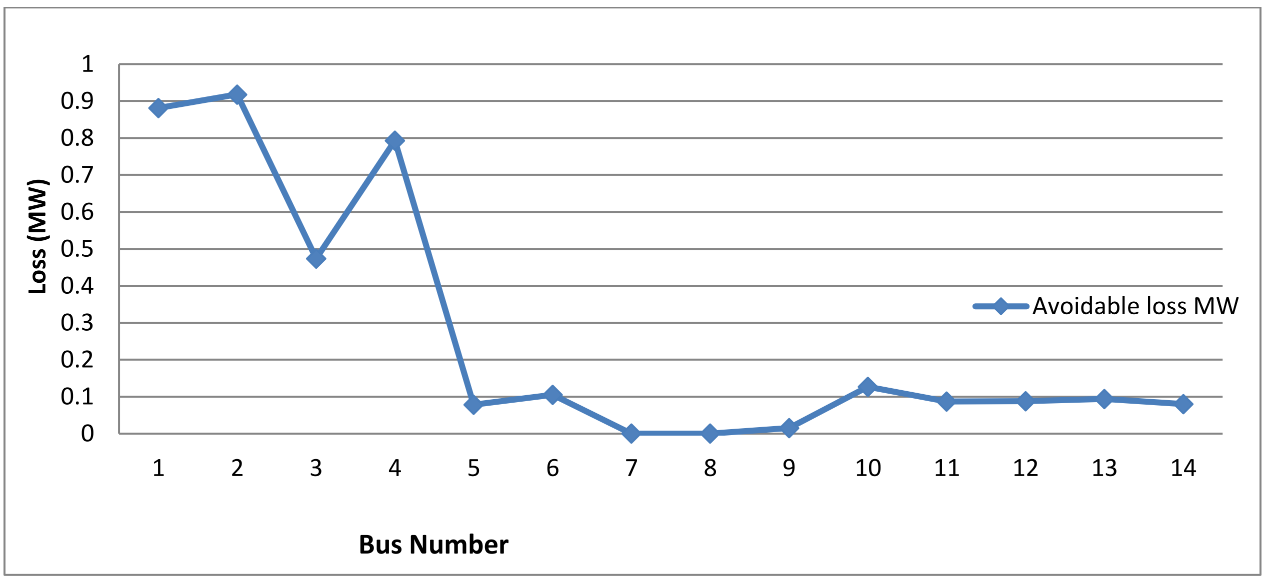


Figure 7.8: Avoidable loss

In power systems, the change in the connected load and the generator factors usually lead to power losses as it results in the change in the equivalent parameters of the line. In this study, the passive method of determining the Thévenin impedance from the point of connecting the load was tested on a standard IEEE test system, and the effect of non-active power on the transmission line loss was established. This shows the losses which can be avoided when Q (the two non-active components) are compensated locally by correcting the power factor of the load.

This novel method is expected to provide the prospect of a better economic tariff to both power producers and consumers since it also reflects the actual usage of the network by each client. It thus provides the necessary incentives to the power producer and consumers using their relative location and the magnitude on the network.

7.7 Summary

In the context of both regulated and deregulated market environments, a method of transmission loss allocation has been proposed that will allocate power loss among the participants in the system in a fair, simple and economically suitable manner. This method reflects the real impact of the load and location of each participant with every transaction on the grid taking into consideration the equivalent parameters of the system using Thévenin theorem.

The Thévenin theorem applied in determining the equivalent parameters of the system was utilised in allocating the losses to the individual participant, while the application of the GPT was made in the determination of the losses which can be avoided in the system. The method was tested on both standard IEEE 5 and IEEE 14 test systems to test the validity of the method and show numerical examples. At the end of the chapter, the question "(**How do we determine avoidable losses on transmission lines using the non-active power?)**'' was answered through the difference in the conventional power loss allocation and the calculations using the GPT both numerically in MW and graphically as shown in Figure 7.6. The difference shown in Figure 7.8 which is the loss that can be avoided will have a great impact on the tariff cost incurred by the participant and reduce the cost of generating more power; hence answering the question: "**How does this method change the cost of tariffs?**''**.** This shows that making the current and the supply voltage constant due to the null point calculation increases the capability of transmitting more power for the same line loss, thereby increasing the lifespan of network equipment, as well as reducing the power generation cost and tariff.

CHAPTER EIGHT

CONCLUSION

This chapter begins by answering the queries raised in the justification of the hypothesis, followed by stating the contributions of the research to knowledge and summarizing the thesis along the research questions, this was deduced according to the results achieved from the work.

8.1 Answers to Research Questions

The research hypothesis of this work was sharpened using five questions. This section summarizes the answers to these questions. These answers are based on the results of the MATLAB simulation done in conjunction with the laboratory test.

- **What are the demerits of conventional methods currently in use to determine transmission losses?**

The challenges posed by the allocation of power loss are not only about the accurate calculations of transmission loss to the individual participant, but also about how to get a fair, consistent, simple, precise and predictable allocation of power loss that will also give all the qualities needed as detailed in Table 2.1. Most of the current methods in use do not meet these requirements. With the use of Thévenin equivalent, which does not require initial information of the system, (the method is based only on local measurements), fair allocation of transmission losses can be achieved in a deregulated environment with multiple participants.

- **What is the impact of the Thévenin impedance estimation on loss allocation using non-active power?**

Proper loss allocation is a key issue in power system analysis, and this has led to the development of different methods for allocating transmission losses with respect to network dependency, volatility and economic advantage. Most of the techniques currently described in the literature either inject a disturbance into the system or require information about the system for proper impedance estimation. However, obtaining the Thévenin equivalent impedance of the system for both balanced and unbalanced networks will give the true estimate of the distributed load and not only the impedance of the wire as currently prescribed in the literature, and this would also be used, in determining the losses contributed by each participant.

- **How does using the conventional methods (based on reactive power) differ from using the general power theory in the determination of power losses?**

The magnitude of the total loss in the system is not due to the capacitive and inductive reactance (reactive power) of the system alone as is currently described in literature. The unbalance across the three phases results in an out-of-phase balance voltage drop making the resultant current to return through the fourth wire. Thus, using the GPT took into consideration not only the effects of reactive power already recognized in the literature but also of distortion power that increases the total loss on the line in the determination of power losses.

- **How do we determine avoidable losses on transmission lines using the non-active power?**

The theory of instantaneous power for M-wire in conjunction with average power for multiple phase systems with unbalance and distortion complies with the demands for minimum loss in a power system, and the general power theory demonstrates ways by which compensation can be achieved locally on the grids in order to allow for minimal losses in a power system, especially in a system with unbalanced loads and power electronic components, to avoid losses that are avoidable. Therefore, whatever loss that is estimated at unity power factor represents the total power loss, while any power loss calculated with a lower power factor leaves uncaptured the avoidable losses in the system.

- **How does this method change the cost of tariffs?**

Achieving the power factor correction locally (increasing the pf) through compensation of Q and reducing the apparent power supply by the utility will show the loss which can be avoided. Thus, reducing the unnecessary energy loss through distortion power would increase the efficient use of installed capacity, reduce heat on the line, prolong the lifespan of the system equipment and eliminate the needs for larger equipment. This potentially should translate to lower capital investment, lower expense, increased system performance and ultimately lower tariffs.

8.2 Validity of the Hypothesis

The introduction of the research and the objectives as stipulated out in Chapter One led to the hypothesis which states that:

A more accurate and indisputable estimation of power loss allocation can thus be achieved by determining the Thévenin impedance of the system and utilizing the general power theory to unmask the avoidable losses on the network.

The Thévenin impedance simulation results in Chapter Three, the laboratory experimental work in Chapter Four and the practical analysis test in Chapter Six, as well as discussions of the results, have shown the improvement and accuracy in power loss allocation and the possibility of reducing losses on the power system that will lead to tariff reduction.

8.3 Main Contributions

- **New Grid Impedance Estimation Method**

Two methods have been developed, simulated and tested in the laboratory in relation to the estimation of grid impedance. This method is presented in Chapter Three with both simulated and the laboratory test results confirming each other.

Passive method; The first method called passive method is through the voltage change and the change in current with time when switching between two parallel loads.

Active method; Even though many active methods of grid impedance estimation exist, this new method gives more accurate values for the line parameters and the method which is designed through the injection of double current with different harmonic frequencies into the system. Another unique feature of the two methods is the determination of the line parameters without any information with respect to the supply quantities for power flow.

- **New Loss Allocation Method**

A new method that can be used for transmission loss allocation in both regulated and restructured environments is developed. The method, which is detailed, allocates losses based on the individual participant transaction and easy to understand, has been designed**.**

- **Avoidable losses in Power System**

The thesis has introduced a new transmission loss allocation based on the general power theory to show the losses which can be avoided in power system bearing in mind that unity power factor can only be achieved after the compensation with energy storage in an unbalanced system. The approach which follows the basic electricity and mathematical principles could have an important role to play in the industries and the power generating company in reducing losses and improving the economic profitability.

8.4 Concluding Summary

The loss in power systems was defined in [112] as '*the amount of electricity injected into the transmission and distribution grids that are not paid for by the user*', but this may not be acceptable in a deregulated environment where all generated power either used or lost must be totally accounted for. A significant number of researchers have worked on improving different methods of allocating transmission power loss both in the pool market and in the bilateral market. Popular among them are the proportional power loss allocation method, the Z-bus power loss allocation likewise the improved Z-bus. Others are the incremental power loss allocation, the Pro-rata and the likes. The inadequacy and inability to take the avoidable losses into consideration in most of those existing loss allocation methods have been pointed out, thereby calling for power loss reduction and an accurate method of calculating and allocating power loss, especially in a deregulated environment like Nigeria and other developing countries. This research has been designed to show the avoidable loss in the transmission system, and to allocate the loss where it arises and by a method that reflects fairly and equitably for all market participants the real impacts of the total transaction of the whole power generated and delivered.

Power loss in a transmission network is a function of the fraction of the generated power to the transmitted power that is non-separable and nonlinear; this makes it difficult to allocate the losses to various participants in the system. Thus, this thesis has critically reviewed the various methods used in literature for load allocation in power system and impedance measurement; the errors in most of these methods were pointed out, and solutions were proposed to reduce the inadequacies. The research has developed a novel method of allocating transmission loss based on the approach that deals with the load flow and the positioning of the load on the power network. The thesis also shows that the system power factor of 1 can be achieved through the compensation of the system locally by reducing the delivery loss towards the minimum value for the active power.

Recognizing that the network element responsive to the power network load changes; the proposed approach has been tested both in the simulation and in the laboratory for its accuracy by using Thévenin theorem to determine the line equivalent parameters of a power network from the load/generator point to reduce the network complexity. The method which is different from the methods in literature requires no additional information with respect to the supply quantities for power flow. The equivalent parameters were used to examine the theoretical background of the general power theory in the determination of transmission loss formulae which can be suitable and indisputable in a deregulated power system. With this, the use of the true power factor and the impact of non-compensating losses in transmission power system to be used in tariff system is known.

Comparing the two proposed Thévenin impedance methods, it was noticed that the switching estimation method gives better results than the current injection method. However, both methods give good results in the determination of grid impedance and compare with the disturbance the system may experience with the current injection method, the switching method does not affect the power quality due to its passive act.

Realizing that, associated problems experienced in the power industry are termed technical issues; these include the power transmission access usage, determination of reactive power cost, transmission loss allocation, and the like. Which, if not well managed by the respective institution can lead to an economic loss to either a regulated or deregulated power system. This research work has dealt with the problem of loss allocation in the transmission system and how to allocate transmission loss in a transparent and economically marginal way. It developed a transparent method that allocates loss according to the loss incurred by the load using the Thévenin parameters of the system, including the effects of unbalanced loads across the three-phases, that usually results in out-of-balance voltage drop and increased power loss from the resultant current return to the source.

Also, this work has analyzed the impact of nonlinear loads in the distortion of the sinusoidal shape (harmonics) of the load current which reduces the efficiency of the power transfer showing that the inductive and capacitive reactance of the load is just a part of the cause of the inefficiency in power transfer. The research also shows the difference in the measurement of power loss between the conventional approach and the general power theory approach as reported by Malengret and Gaunt in [83] under the non-ideal condition of the power system. Thus, it has broken down the non-active current into its various orthogonal components through the instantaneous power theory that can be used in the correction of power factor locally and the correction of losses that are avoidable.

Finally, the research has addressed the problem of allocating losses in transmission systems in a transparent and economically marginal justifiable way. It has proposed the separation of the transmission losses into two components of unavoidable and avoidable losses. Identifying by local measurement the Thévenin equivalent parameters of the power system and applying the general power theory which was developed at the University of Cape Town, the approach quantifies the minimum possible losses for the delivery of the useful power component. The thesis shows that the remaining loss caused by the flow of non-active power, which is associated with phase displacement, unbalance between the phase wires, and distortion is specific to the load flow and the location of measurement. The research also shows that the cost of the avoidable losses can be allocated to the supplier or customer at the point of connection to the network, while the unavoidable losses can be shared. This new approach developed, can be applied to electricity tariffs and in power systems operating electricity markets.

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APPENDIX A

Measurements on different wires and positions to test variation of losses with location, described in 6.2.

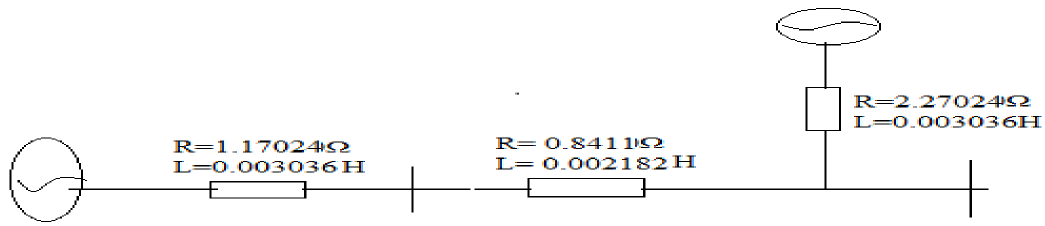

Figure A1. The equivalent parameters of three phase circuit arrangement from a point different from point in Figure A2 and Figure A3 to show the effect of Thévenin equivalent in the determination of losses from various load point.

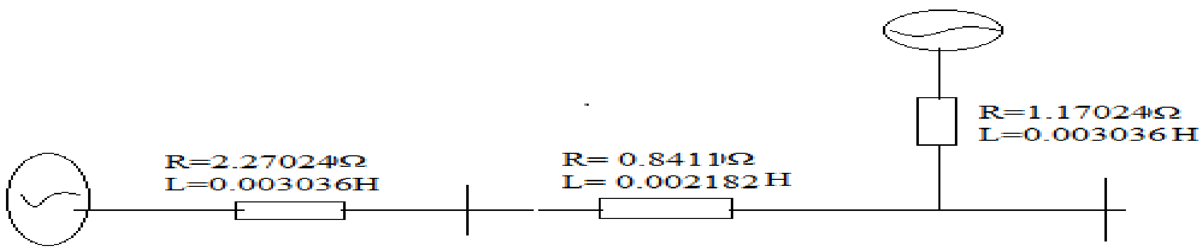

Figure A2. The equivalent parameters of three phase circuit arrangement from a point different from point in Figure A1 and Figure A3

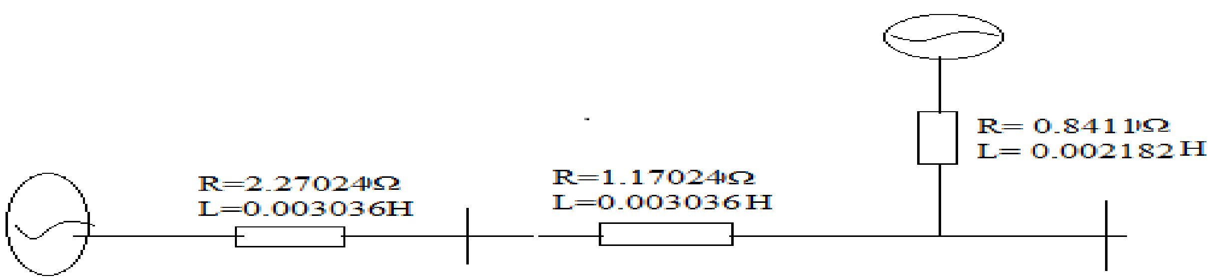

Figure A3. The equivalent parameters of three phase circuit arrangement from a point different from point in Figure A1 and Figure A2

APPENDIX B

Table B1. Comparison of the proposed method with others in the literature using the IEEE 5 bus.

Bus No	P Loss (MW)	PS	PSP	BWLA	Line Voltage (v) 1&2	Line Voltage (v) 2&3
1	1.714	1.8355	2.0884	2.131	892.2	693.2
2	1.016	0.8566	0.4318	0.33	1020	1019
3	0.678	0.6549	0.6708	0.73	969.1	969.7
4	0.487	0.5821	0.5946	0.65	644.4	644.7
5	0.906	0.8731	1.0167	0.962	915.8	916.7
	4.801	4.802	4.802	4.802		

Table B2. Line Data for a 5 Bus System.

From Bus	To Bus	R (p u)	X (p u)	B(p u)
1	2	0.02	0.06	0.03
1	3	0.08	0.24	0.025
2	3	0.06	0.18	0.02
2	4	0.06	0.18	0.02
2	5	0.04	0.12	0.015
3	4	0.01	0.03	0.01
4	5	0.08	0.24	0.025

Table B3. Bus Data for a 5 Bus System.

Bus No	Load (MW)	Load (MVAR)	Generator (MW)	Generator (MVAR)	Voltage (KV)
1	0	0	83.48	1.61	138
2	20	10	40	50	136.287
3	20	15	30	40	134.756
4	50	30	0	0	132.82
5	60	40	0	0	128.068

Table B4. Comparison of the proposed method with others in the literature using the IEEE 14 bus.

Bus no.	Proposed Method (MW)	Z- bus Method (MW)	Neural network Method (MW)	ITL Method (MW)	Pro-rata (MW)
1	1.962	7.640	6.450	0.000	0.000
2	2.125	0.160	0.480	0.510	1.123
3	3.128	2.780	2.580	5.520	4.874
4	2.326	0.840	1.310	2.490	2.473
5	0.519	0.080	0.210	0.290	0.393
6	0.667	0.480	0.330	0.440	0.580
7	0	0.000	0.000	0.000	0.000
8	0	0.020	0.070	0.002	0.000
9	0.512	0.520	0.800	1.520	1.526
10	0.552	0.180	0.240	0.510	0.466
11	0.259	0.060	0.100	0.150	0.181
12	0.65	0.100	0.180	0.270	0.316
13	0.401	0.260	0.380	0.690	0.699
14	0.462	0.440	0.430	1.010	0.771
Total	13.563	13.560	13.560	13.402	13.402

Table B5. IEEE – 14 Bus System Line Data

Serial No.	Sending Bus	Receiving Bus	R (Ω)	X (Ω)	B/2 (Ω)
1	1	2	0.01938	0.05917	0.0528
2	1	5	0.05403	0.22304	0.0492
3	2	3	0.04699	0.19797	0.0438
4	2	4	0.05811	0.17632	0.0340
5	2	5	0.05695	0.17388	0.0346
6	3	5	0.06701	0.17103	0.0128
7	4	5	0.0	0.04211	0
8	4	7	0	0.20912	0
9	4	9	0	0.55618	0
10	5	6	0	0.25202	0
11	6	11	0.09498	0.19890	0
12	6	12	0.12291	0.25581	0
13	6	13	0.06615	0.13027	0
14	7	8	0	0.17615	0
15	7	9	0	0.11001	0
16	9	10	0.03181	0.08450	0
17	9	14	0.12711	0.27038	0
18	10	11	0.08205	0.19207	0
19	12	13	0.22092	0.19988	0
20	13	14	0.17093	0.34802	0

Table B6. IEEE – 14 Bus Test System Load and Generator Data

Bus no.	Generation Real (MW)	Load Real (MW)	Load Reactive (MVAr)
1	232.4	0.00	0.00
2	40.0	21.70	12.70
3	0.00	94.20	19.10
4	0.00	47.80	3.90
5	0.00	7.60	1.60
6	0.00	11.20	7.50
7	0.00	0.00	0.00
8	0.00	0.00	0.00
9	0.00	29.50	16.60
10	0.00	9.00	5.80
11	0.00	3.50	1.80
12	0.00	6.10	1.60
13	0.00	13.50	5.80
14	0.00	14.9	5.00
Total		259	81.4

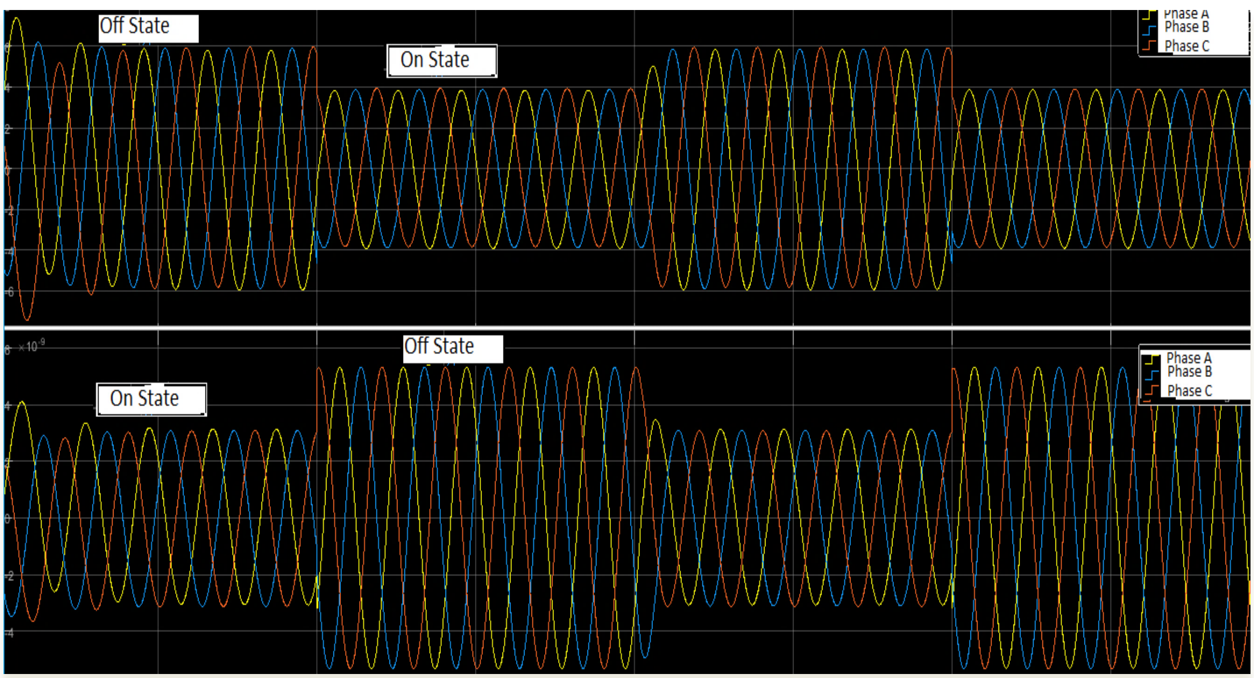

Figure B1: Switching pattern of the voltage and current for a balanced load.

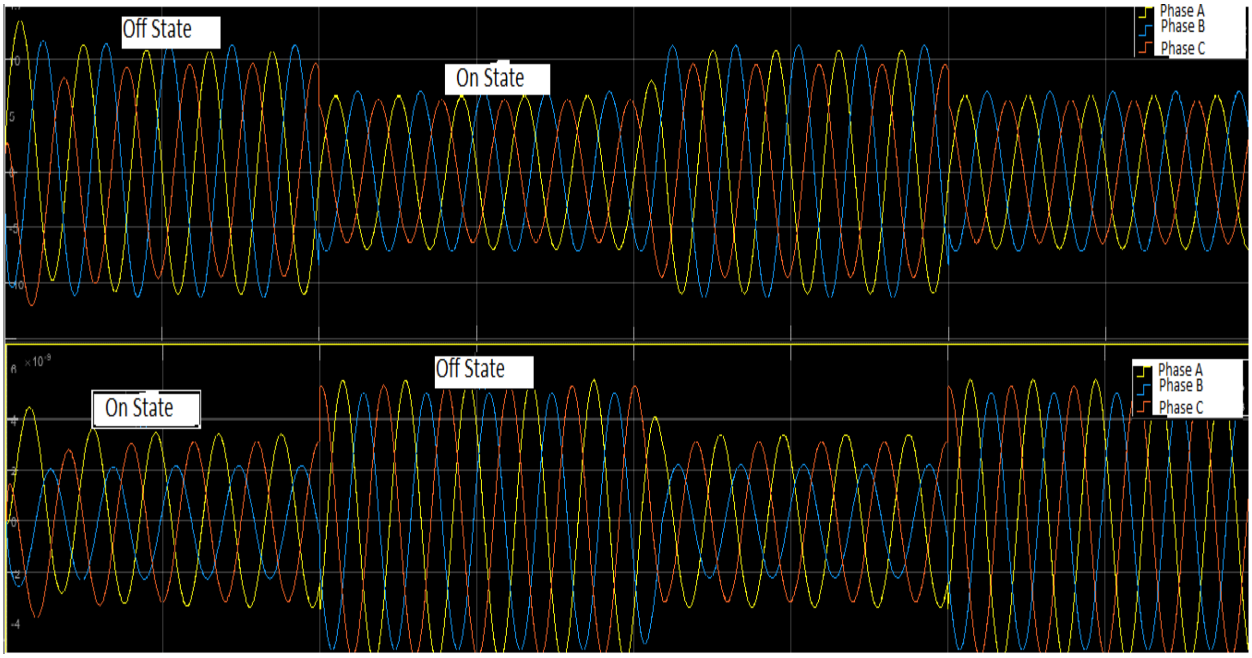

Figure B2: Switching pattern of the voltage and current for an unbalanced load.

Table B7. Comparison of the conventional method and new method using GPT.

Bus no.	Conventional loss value (MW)	New method (minimum loss) (MW)	Avoidable loss (MW)	Line Voltage (v) 1&2	Line Voltage (v) 2&3
1	1.962	1.081	0.881	6468	3194
2	2.125	1.207	0.918	5400	5407
3	3.128	2.654	0.474	3525	3524
4	2.326	1.533	0.793	3981	3988
5	0.519	0.441	0.078	4168	4175
6	0.667	0.562	0.105	2194	2194
7	0	0	0	0	0
8	0	0	0	0	0
9	0.512	0.497	0.015	2609	2619
10	0.552	0.425	0.127	2461	2466
11	0.259	0.172	0.087	2265	2269
12	0.65	0.562	0.088	2053	2057
13	0.401	0.307	0.094	2110	2115
14	0.462	0.382	0.08	2252	2257
Total	13.563	9.823	3.74		