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ANALYSIS OF LINE OUTAGE DETECTION IN NIGERIA 330KV TRANSMISSION LINES USING PHASOR MEASUREMENT UNITS

THESIS

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF ENGINEERING
IN
POWER AND MACHINES ENGINEERING

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CERTIFICATION

This is to certify that this project "Analysis of Line Outage Detection in Nigeria 330kV Transmission Lines using Phasor Measurement Units" was carried out by Obodoagwu Nkem Francis (PG/ENG1410534) and submitted to the Department of Electrical/Electronic Engineering, Faculty of Engineering, University of Benin, Benin city, Nigeria and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This project is dedicated to God Almighty who has been my source of strength and impetus.

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ACKNOWLEGEMENT

Bless the Lord oh my soul and forget not His benefits. Thanks to God the giver of strength and in whom all wisdom dwells.

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ABSTRACT

In this work, an analysis of line outage detection in Nigeria 330kV transmission lines using Phasor Measurement Units was presented. This requires collection and analysis of the data obtained from Transmission Company of Nigeria with the aid of PSAT 2.10.1 / MATLAB SIMULINK using Newton-Raphson power flow algorithm and also to determine the effectiveness of PMU when introduced in our power system network. 12 buses and 3 Generators system were considered for the studied.

This was achieved by collecting relevant transmission parameters for 330kV line and was simulated on PSAT 2.10.1 and MATLAB 2015a using Newton-Raphson power flow algorithm. The work involved an offline and online analysis. For the offline analysis the admittance / impedance matrix for Y-bus and bus voltage for pre-outage was obtained via the power flow analysis and change in impedance for the lines were calculated. These values were further normalised in order to reduce the value to a row echelon form. Then for the online analysis; the change in phase angle from the Phasor Measurement Unit (PMU) online simulation for pre-outage and also post-outage was calculated and a normalised column matrix was gotten.

Finally, the effectiveness of the line outage detection was graphically represented using MATLAB software to plot the values of the normalised values of the offline and online analysis; i.e., by comparing the normalised form of the offline and online values. These results clearly show that PMUs gives an accurate monitoring and total observability when introduced in Nigeria power system.

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LIST OF SYMBOLS AND ABBREVIATION

A/D	Analogue to Digital
AAF	Anti- Aliasing Filter
ADC	Analogue / Digital Converter
ADMM	Alternating Direction Method of Multi-Phasors
AI	Artificial Intelligence
AIS	Artificial Immunity system
BIP	Binary Integer Programming
DCS	Distributed Control Systems
DFR	Disturbance Fault Recorder
DFT	Discrete Fourier Transform
GPS	Global Positioning System
GS	Generation Station
ILP	Integer Linear Programming
KF	Kalman Filter
LSE	Linear State Estimation
NIPP	Nigeria Independent Power Project
NLP	Non-Linear Programming
OPP	Optimal Placement Problem
PLO	Phase Locked Oscillator
PMU	Phasor Measurement Unit
PSAT	Power System Analysis Toolbox
PSCAD	Power System Computer Aided Design
QIEA	Quantum Inspired Evolutionary Algorithm

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RBF	Radial Basis Function
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SPC	System Protection Centre
SQP	Sequential Quadratic Programming
SVM	Support Vector Machine
TCN	Transmission Company of Nigeria
TS	Transmission Station
WAMPAC	Wide Area Measurement Protection and Control
WAMS	Wide Area Measurement System
WLS	Weighted Least Square

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

The Nigerian power system network (Figure 1.1), like other network elsewhere, is made up of a large interconnected network that is spread across the country nationwide. This grid presently consists of seventeen generating stations, which comprises thermal, gas and hydro plant with an installed capacity of 9065MW (Ogbuefi & Madueme, 2015), while the transmission lines is currently made up of 9,454.8km of 330kV lines, 8,985.28km of 132kV lines, 23km of 330/132kV sub-stations and -91km of 132/33kV substations (Omorogiuwa & Ogujor, 2012). Table 1.1 represents the complete power generating and existed power stations that is currently in used with their available installed capacities, while Table 1.2 represents the generating stations with their suppose installed capacities.

Table 1.1. Operating Power plants in Nigeria and their rated capacities

S/N	Station	State	Turbine	Installed Capacity (MW)	Available Capacity (MW)
1	Jebba	Niger	Hydro	504	352
2	Kainji	Niger	Hydro	760	259
3	Shiroro	Niger	Hydro	600	402
4	Egbin	Lagos	Steam	1320	900
5	A.E.S (Egbin)	Lagos	Gas	250	211.8
6	Afam I-V	Rivers	Gas	726	60
7	Afam VI (Shell)	Rivers	Gas	650	520
8	Delta (Ughelli)	Delta	Gas	912	281
9	Gerugu	Kogi	Gas	414	120
10	Ibom	Akwa-Ibom	Gas	155	25.3
11	Okpai (Agip)	Delta	Gas	900	221
12	Olorunshogo phase I	Ogun	Gas	100	54.3
13	Olorunshogo phase II	Ogun	Gas	200	105.5
14	Omoku	Rivers	Gas	150	53
15	Omotosho	Ondo	Gas	304	88.3
16	Sapele	Delta	Gas	1020	170
17	Trans-Amadi	Rivers	Gas	100	57.3
	Total Power			**9,065**	**3,880.5**

Source: Omorogiuwa & Ogujor (2012)

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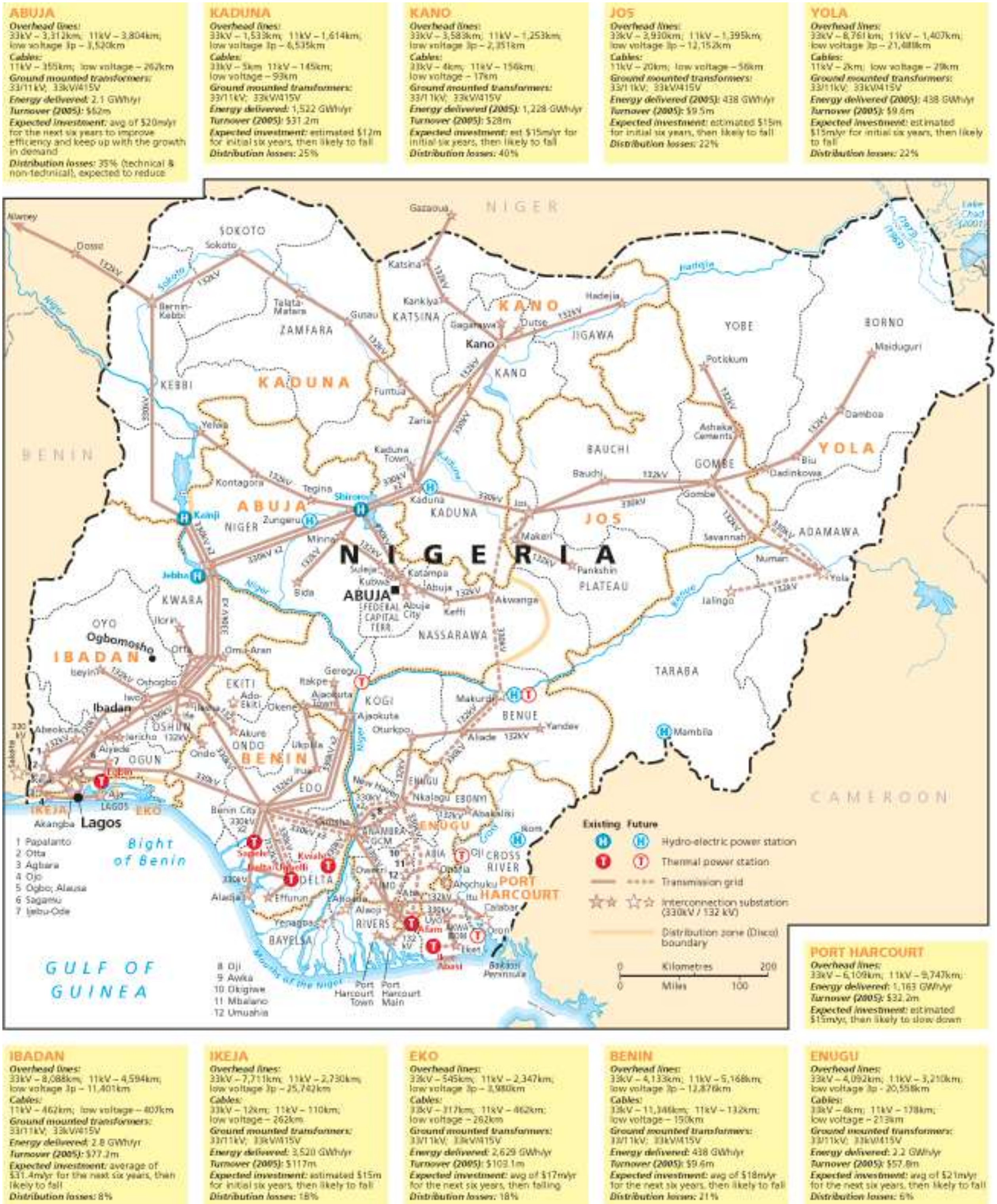

Figure 1.1. Transmission Grid in Nigeria (Updated on 30th June, 2016)

Source: Global Energy Network Institute (2016)

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Table 1.2. National Independent Power Projects and their Installed Capacity

S/N	Station	State	Turbine	Installed Capacity (MW)
1	Alaoji	Abia	Hydro	961
2	Calabar	Cross River	Gas	563
3	Egbema	Imo	Gas	338
4	Gbaran	Bayelsa	Gas	225
5	Ihorvbor	Edo	Gas	451
6	Olorunsogo II	Ogun	Gas	675
7	Omoku	Rivers	Gas	252
8	Omotosho II	Ondo	Gas	450
9	Sapele	Delta	Gas	451
	Total Power			**4,366**

Source: Omorogiuwa & Ogujor (2012)

This Electrical power is generated at specific location far from load centres before it is delivered to consumers through our transmission and distribution systems. The purpose is to generate and supply real and reactive power to consumers economically and reliably (Arabali *et al*., 2016).

Transmission lines are subjected to an unfriendly condition through thick forest from generation to control room and from control room for effective monitoring. On this lines fault cannot be neglected (Arabali *et al*., 2016). Location of faults on this line has been a studied for a long decade. Accuracy in locating of fault has a great impact for the economic operation of our power systems in Nigeria electricity markets. This has provided quick response to the repairs of our systems and availability over time, and has help in saving time, performance and effort to corrective maintenance. Hence, the reliability of the system is increased (Abdelaziz *et al*., 2011).

The lack of situation awareness is one of the major reasons for blackout in Nigeria power system as at today, because most of our systems are not remote base from my recent findings, and even Nigeria Independent Power Project (NIPP), there is no complete observability of the whole systems.

Modern power system has introduced a large number of Phasor measurement units to the grids to perform numerous tasks, such as protection, monitoring and controlling of the power system. A single or multiple line outage transmission lines

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disturbs the flow of the power system and changes the phase angles measured at the various buses where the PMUs are positioned (Awais *et al.,* 2016).

Due to the growing trend of remodelling of power system network for quality and uninterrupted power; the Phasor Measurement Unit can be brought into play for effective monitoring (Kumar *et al*., 2015). The phasor measurement units have the potential to revolutionize the way electric power system are monitored and controlled (Kumar *et al.,* 2015). This has significantly improved the methods to monitor and analyse power system dynamics (Abdelaziz *et al.,* 2011; Arabali *et al.,* 2016). Phasor measurement unit (PMU) is used to obtain magnitude and phasor values of voltage, current, power and their angles accurately. This has helped to estimate the system conditions (Srikumar *et al.,* 2015).

Phasor measurement units monitor power systems by providing near real time measurements of voltage magnitude and angles (Arabali *et al.,* 2016). The knowledge of the voltage magnitude and phase angle at each bus enables the performance of various crucial tasks, such as event detection, optimising power flows, maintaining system stability and reliability etc. PMU are very appropriate for online monitoring of angles thereby helping the operators during system restoration i.e., in determining when the system is over stressed up and putting some control measure in place (Srikumar *et al.,* 2015).

PMU report phasor measurement with high frequency, and changes in voltage due to topology changes of the power grid tend to be larger than the variation of voltage phasor during normal operation for example fluctuation during demand (Srikumar *et al.,* 2015). Accuracy and prompt identification of these line outages is mandatory and plays an important role in the system reliability and give a secure operation of our power grid.

1.2 Statement of Problem

It is a known fact that Electricity Power System in Nigeria is faced with so many challenges like, line overloading, epileptic power supply, losses on transmission and distribution lines, indiscriminate outages, system collapse, inadequate generation, and poor localise equipment which are no longer invoke; and cannot be integrated with most of our recently completed Independent Power Project stations. Therefore, there is the need to incorporate more intelligent system to aid

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in power profile analysis (real time measurement of voltage magnitudes and angles) for effective monitoring of power system dynamics using (PMUs), and a complete situation awareness of our entire grid which could been seen as improved method from the deficiencies from other monitoring devices like EMS/SCADA.

1.3 Aim of the Study

The aim of this study is to detect and analyse line outage in Nigeria 330kV transmission lines, using Phasor Measurement Units.

1.4 Objectives of the Study

The objectives of the study are to:

(a) collect and analyse data obtained from Transmission Company of Nigeria with the aid of PSAT 2.10.1/MATLAB SIMULINK using Newton-Raphson power flow algorithm;

(b) carry out load flow analysis on Nigeria Transmission line maintained at 330kV, considering 12 buses and 3 Generators system; and

(c) analyse the data obtained using PSAT / MATLAB software for pre-outage and post-outage considering the proposed network.

1.5 Research Methodology

The methodology to be adopted for this work would involve:

(a) Collection of relevant transmission parameters such as Generators-Transformer data, Generator ratings, number of 330kV buses, line impedance values from Transmission Company of Nigeria, Osogbo Osun State, Nigeria.

(b) Modelling of 330kV Nigeria transmission network, consisting of 12 buses and 3 generators on PSAT 2.10.1 and MATLAB 2015a using Newton-Raphson power flow algorithm.

(c) The admittance matrix for Y-bus and bus voltage for pre-outage via the power flow analysis and elimination of the row and column associated with slack bus and primary bus from the Generator were obtained.

(d) Converting the Admittance Y-Bus to Impedance value.

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(e) Selection of a one single line representing a possible outage.

(f) Calculation of the change in impedance ΔZ for the lines.

(g) Performing rank for the change in impedance matrix for step (f).

(h) Normalizing the first row of the matrix of the reduced row echelon form.

(i) Step (c) to (h) to be repeated for other possible single lines representing outages.

(j) Obtain the Phase Angle from online simulation from the PMU for Pre-Outage and also Post Outage for all the lines listed in (i).

(k) Calculation of change in voltage phase angle between Pre-Outage and Post Outages at all buses under consideration.

(l) Normalising the column matrix from the output of step (k).

(m) The normalised column matrix of change in voltage phase angle i.e., step (l) is compared with each normalized basic vector of transmission line outages (h) and (i).

(n) Finding the closest Vector to the Angle to determine the line outage.

(o) Plotting of the result of (n) on a graph using MATLAB software

1.6 Motivation of the Study

Due to recent advancement in technology globally in power system, failure rate of electrical component poses a challenge. Continuous and efficient supply of power is a hallmark of a developed economy, therefore any Nation whose energy need is epileptic in supply imperils its economic development (Obiaya, 2013). Therefore making our system smarter, reliable and more efficient should be our ultimate goal. PMU should be adopted to avert this menace in identifying potential risks and failure before a total system collapse will occurs. This is a way of combating this problem.

1.7 Scope of the Study

This study will be limited to a session of the Nigeria 330kV transmission network by identifying possible lines under outage within the south western region using PSAT/MATLAB Simulink software. Each line to be put under outage represents a typical outage lines when it occurs.

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CHAPTER TWO

LITERATURE REVIEW

2.1 Phasor Measurement Unit

Phasor Measurement Units (PMUs) or Synchronised Phasor was first invented in 1988 by Dr. Arun G. Phadke and Dr. James S. Thorp at Virgina tech (www.wikipedia.org). These instruments work with Global Positioning System (GPS) to synchronised measurements of positive sequence voltage phasors at various buses within the network and positive sequence current phasors in the lines connected to those buses. The positive sequence voltages at all network buses constitute the state vector of a power system.

2.1.1 Basic Definition of Phasor Measurement Unit

PMU is a device, which measures the electrical waves on an electricity grid, using a common time source for synchronisation. In a very clear term, PMU are devices used in measurement to measure the phasor angle between voltage and current and displays these results for analysis of power system.

The mathematical description of waveforms for an alternating current is a pure sinusoidal waveform can be represented by a unique complex number known as a phasor. Consider a sinusoidal signal

$$\mathrm{X(t) = X_m \cos(wt + \theta)} \quad (2.1)$$

The phasor representation of this sinusoid is given by

$$X = \frac{X_m}{\sqrt{2}} e^{j\theta} = X_m(\cos\theta + \sin\theta) \quad (2.2)$$

The magnitude of the phasor is the rms value of the sinusoid shown in (2.3) and its phase angle w is the frequency. Figure 2.1 shows a typical signal waveform and the phasor representation.

$$\frac{\mathrm{X_m}}{\sqrt{2}} \quad (2.3)$$

The positive phase angles (Figure 2.1) are measured in counter clockwise direction from the real axis. Phasor representation implies that the signal remains stationary at all times, leading to a constant phasor representation i.e., a constant phasor implies a stationary waveform. This PMU uses a frequency tracking step and thus estimates the period of the fundamental frequency component before the phasor

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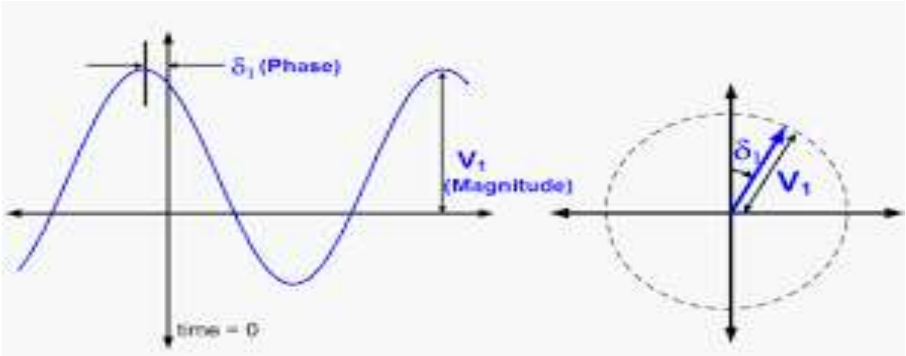
is estimated. The task of the phasor is to separate the fundamental frequency 50Hz component and find its phasor representation.



(a) (b)

Figure 2.1. (a) Sinusoidal waveform (b) Phasor Representation

2.1.2 Important of PMU in Line Outage Identification

The importance of PMU in line outage identification are, it:

(a) improves situation awareness using real-time synchro-phasor measurement;

(b) provides GPS-synchronised, more accurate and dense measurements of phasor voltage and phasor current;

(c) has the ability to provide geographical dispersed accurate synchronised measurements over the entire power grid (Srikumar *et al.,* 2015);

(d) gives a smaller error variances compared to other measurements; and

(e) gives an identification of line outages in power grids spread over vast geographical location (Awais *et al.,* 2016).

2.1.3 Working Principle of A PMU

Figure 2.2 represents the block diagram of working principle of a PMU, i.e., describing various functions that makes up the PMU while Figure 2.3 represents potential and current transformer channel serving as inputs to the PMU.

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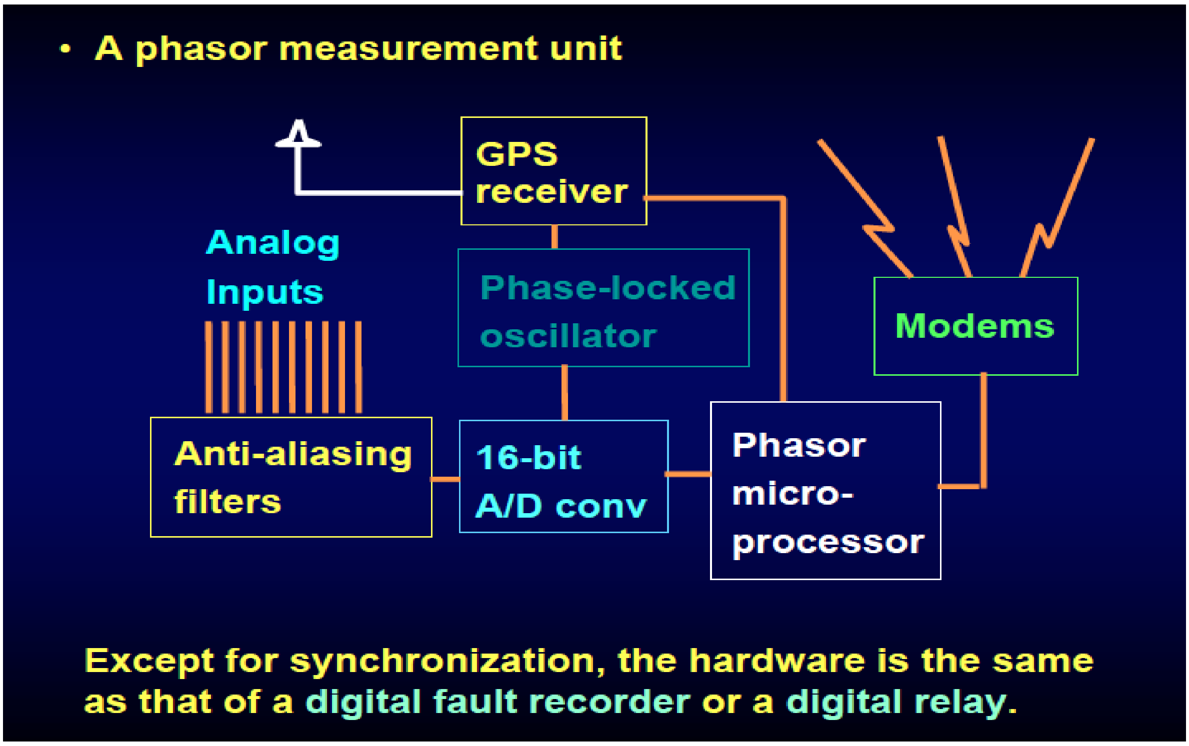

Figure 2.2. Block diagram of a PMU

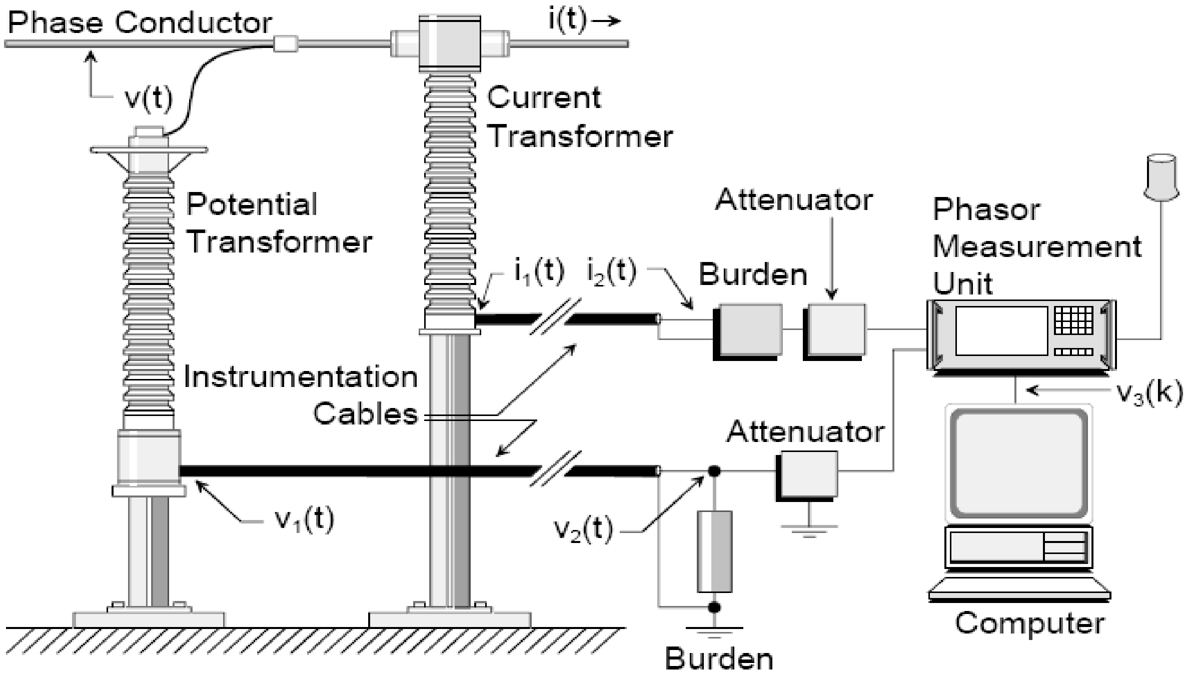

Figure 2.3. Potential and Current Instrumentation Channel

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2.2 Definition of Terms

2.2.1 Current and Potential Transformer

These help to connect the PMU to the grid as shown on Figure 2.3. They are connected through an electronic device called attenuator. The attenuator serves as the input to the PMU and helps to reduce the amplitude or power of the signal without appreciably distorting its waveform.

2.2.2 Anti-Aliasing Filter (AAF)

It receives the analogue voltages and current signals from the Secondary side of the current and potential transformers and also used to restrict the bandwidth of the signal also produces a delay which depends on the characteristics of the filter. This delay is a function of the signal frequency.

2.2.3 Global Positioning System (GPS)

This is a satellite based navigation system that gives accurate information about actual location and time irrespective of weather conditions. It consists of a network of 24 satellites orbiting in 6 geo-synchronous orbits such that at any given instant 4 satellites are visible from any point on the earth surface. It is capable of giving one pulse per seconds.

2.2.4 Phase Locked Oscillator (PLO)

This help to divide the pulse as received from the GPS into required number of pulses per second for sampling.

2.2.5 A/D Converter

This converts the analogue to digital (A/D) signals from AAF, at a sampling instants rate designed by the sampling time signals from the PLO. These digitized samples are then fed to the phasor microprocessor.

2.2.6 Phasor Microprocessor

This is programmed to calculate the positive sequence components at a timed rate, from the digitised sampled data by Discrete Fourier Transform algorithm. This measured data are transmitted to the remote location by using modems.

2.2.7 Optimal PMU Placement

This is defined as the finding the installation location of PMUs required for the complete observability of the power system such that the total investment cost is minimised.

2.2.8 Power System Analysis Toolbox (PSAT)

PSAT is a MATLAB tool box for electric power system analysis and control. This is used for power flow, continuation power flow, optimal power flow, small signal stability and time domain simulation. The core area is in power flow which also takes care of state variable initialization such as optimal PMU placement.

2.2.9 Power Outage

This is the condition of a component or power system when it is not available to properly perform its intended function. An outage may be scheduled or forced outages. Scheduled outage results when a component is consciously taken out of service at a selected time usually for purposes of maintenance and repairs. Forced outages may be temporary or permanent outages. Permanent forced outages require repairs or replacements before restoration of service continuity. Temporal (transient) outages imply no permanent damage and no need for repairs/replacement. The forced and momentary outages in transmission and distribution systems can be due to a number of reasons such as lightning, falling trees as a result of heavy wind, bird, vehicle accidents, over loading of the supply feeder leading to frequent breakdown of the feeder, earth fault, over current fault, system collapse at the source, poor generation of electricity leading to load shedding at the supply source etc.

2.3 PMU Utilisation in Power System

The phasor measurement units installed at various buses in the power system network provides with stored values of time-tagged phasor measurement data at various nodes in the network.

These data are gathered by the device called phasor data concentrator, which synchronises the measurement taken every time independent of when the data are fed to the advanced application software for the analysis of the power system as shown in Figure 2.4. Based on this analysis, system control, protection and

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various functions are well managed within the system (Mauryan & Ramkumar, 2014).

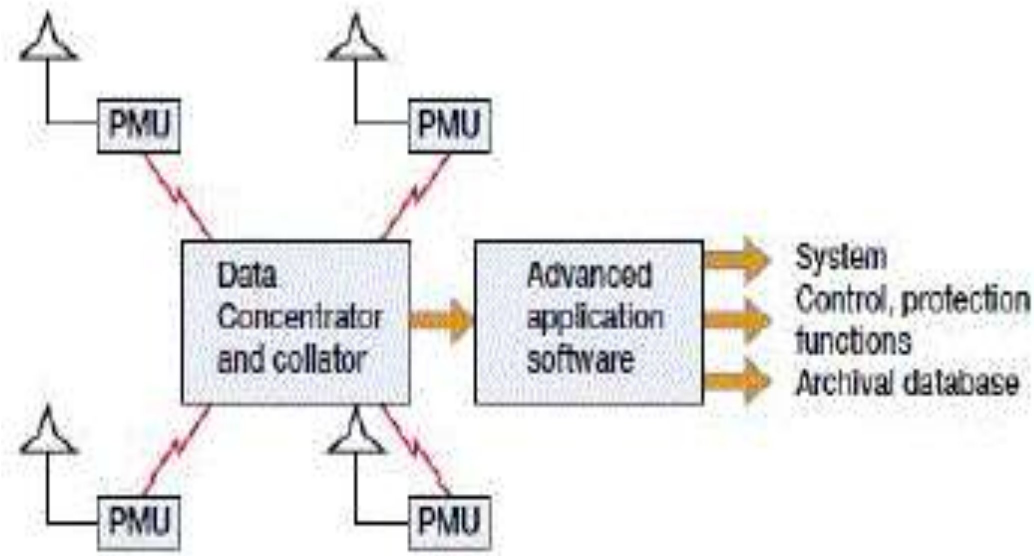

Figure 2.4. PMU Utilisation

2.4 Related Works

A proper methodology is required to analyse single line outage detection using Phasor Measurement Units. This chapter reviews the research work and studies that have been done in the area of Line outage detection, Applications and Optimal placement. The following are the list of researchers who have worked considering Phasor Measurement Units device.

Oduntan *et al.* (2016) proposed a method based on network connectivity information for the optimal placement of Phasor Measurement Unit (PMU), which minimize the cost of installation and provide the entire power system observability. The technique was based on hybridising the particle swarm optimisation and tabu-search (PSO-TS) algorithm. The lists from the tabu were used within the PSO algorithm which was tested in IEEE 14-Bus and IEEE 30-bus systems. There were two PSO algorithms; one was aims to differentiate the best solutions obtained by particles while the second prevent local optimal solutions without respect to the constraints. The scope of the work was limited to the optimal location of PMUs in power system and use of PMUs for state estimation.

Bindeshwar *et al.* (2011) proposed a review on different application of PMUs in electrical power system networks incorporated with FACTS controllers for

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advanced power system monitoring, protection, and control. It note the maximum research work carried out for optimal placement of PMUs in power system networks point of view in all the three decades. The paper addressed a survey on optimal placement of Phasor Measurement Units (PMUs) in power system for enhancement of power system stability such as rotor angle stability, frequency stability, voltage stability, power system oscillations, and voltage stability by using different FACTS controllers such as TCSC, SVC, SSSC, STATCOM, UPFC and IPFC in an integrated power system networks. The paper also discussed the current states of the research and development in the field of applications in PMUs in power system stability.

Awais *et al.* (2016) proposed a computational efficient technique based on Quantum Inspired Evolutionary Algorithm (QIEA) for the identification of multiple power line outages in smart power grids. A customised version of QIEA was also proposed, and it effectiveness was validated against various IEEE bus systems with multiple line outages used as an example. The simulation results gotten demonstrated the validity and accuracy of the proposed solution. In this work, A novel approach based on quantum inspired evolutionary algorithm (QIEA) to solve multiple line outage identification problem which is categorised as a probabilistic evolutionary algorithm. The proposed solution was capable to identify an (arbitrary) number of line outages with any possible combination and also avoid local optima. This solution is the first solution that falls into the category of variable MLOI solutions. The simulations was performed for various IEE reference bus system, it demonstrate that the proposed QIEA individual solution is more accurate as compared to various other met-heuristic approaches. In this work linear DC power flow model was defined, which assumes the conservation of power flow i.e., the power injected into bus "n" must be equal to power flowing out of it mathematically.

Huang *et al.* (2008) briefly summarised two documents: PMU testing guide and synchrophasor accuracy characterisation and also present methods for evaluating phasor performance in both steady-state and dynamic situations as well from PMU hardware to instrumentation channels. It was concluded that performing those procedures on PMUs to be deployed will help users to assure consistent PMU system performance and support interoperability of PMUs from various vendors.

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Mekhamer *et al.* (2012) introduces an important application of PMUs in power system protection which is the detection of single line outage. It main focus was on line outage problem and proposes an artificial intelligence based technique for outage detection. This was achieved base on the variations of phase angles measured at the system buses where the PMUs are located. A protection scheme against over loading leading to system collapse called support vector machine (SVM) classification tool was proposed. The effectiveness of the proposed approach was tested using offline simulation for both the IEEE 14-bus and the IEEE 30-bus systems and also in order to ensure the superiority of the SVM classification tool in the field of line outage detection. Several study cases was studied and noted including the complete observability principle. This was done by using SVM classification tool using either of polynomial kernel or radial basis function (RBF) kernel. The task of SVM is to utilize the output information from the PMUs to determine a status for each line if it is out of service or not. A mathematical model was applied to calculate the phasor angles. The above proposed approach uses the Rockfeller and Udren algorithm, which depends on successive three samples to calculate the power voltage magnitude and angle. Also the paper show the superiority of the RBF kernel compared with the polynomial kernel in the process of classification related to the line outage problem.

Rebiee *et al.* (2013) discussed some valuable experiences and view point associated with the practical aspects of PMU installation, among the points consider are: the required substation infrastructure and facilities, installation requirements, communication system preparation, and monitoring centre establishment and lessons learnt from the project implementation. It also stresses the practical aspects of a typical Wide Area Measurement System (WAMS) implementation project. This consist of generic specification of the project, substations defects and their associated solutions, and monitoring centre capabilities, amongst are the lack of CVTs in some substation bus-bars, missing communication active equipment in some cases, lack of connection to the optical fibre network associated with some substations, particular condition of distributed control system (DCS) substations, logic of line connectivity to bus-bars, determination of PMU to bus-bars, and determination of PMU locations in

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substations. The reviewed on this paper gave a convincing reason to initiate the WAMs development project.

Kumar *et al*. (2013) did a formulation of measurement by using WLS state estimation and PMU were incorporated with use of traditional technique. This was done by launching of PMUs on specific buses and their effect on accuracy to test cases of several parameters in different cases. Also the impact of PMU on bus voltage, bus current and real power flows were illustrated. The parameter assessment obtained on IEEE 6 bus system and IEEE 9 bus system was discussed. The problem of finding optimal placement of PMU devices a state estimation of power system was also investigated. This paper reproduces the accuracy of measurement with or without using PMU on state estimation parameters. For examinations of the system accuracy with or without PMU on system variables, some cases were tested with the aid of MATLAB simulated software. This was achieved by first testing the traditional method parameters without PMU and their performance was also tested in comparison with the PMU. From the comparison, the result shows that for effective installation of PMUs; it reduces the chances of error in measurement of estimated variables. In summary the study was carried out to ascertain the correlation between traditional technique and full weighted least square state estimation technique with the PMU.

Kumar *et al.* (2015) aimed to build a laboratory prototype of PMU that would estimate the phasor updating process of a commercial PMU at the benefit of improved measurement accuracy, reduced manufacturing cost and increased timely information. It also provides an experimentation regarding the behaviour of phasor updation in PMUs. This was done with the aid of MATLAB/Simulink program which was used to implement the idea of recursive and non-recursive algorithm. Simulation model for PMUs was developed for recursive and non-recursive algorithm. The phasor estimation algorithms are simulated and verified in MATLAB/Simulink. It was observed from the work that on application point of view for WAMS, recursive algorithm will prove to be a better method than non-recursive algorithm. The comparison of phase angle in between the different remote locations is easier and accurate because of constant phase angle differences.

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Bilik *et al.* (2015) developed system for PMU testing for the purpose of obtaining sample PMU test results. This article deals with procedure of tests for testing of static and dynamic properties of units for measurement of synchronous phasor (PMUs). The tests are performed by means of the use of a tester working on the basis of virtual working on the basis of virtual instrumentation. This paper also carried out some tests which were performed in the developed testing system. The PMU type SEL-351A was subjected to the tests and time synchronisation of the tested PMU was done using the IRIG-B protocol distributed from the central source of precise time information.

Sarri *et al.* (2016) assessed the performance of linear state estimation (LSE) processes of power systems relying on synchrophasor measurements. The performance assessment was conducted with respect to two different families of SE algorithms, i.e., static represented by weighted least square (WLS) and recursive represented by Kalman filter (KF). From the comparison of the performance of two different families of LSE processes, based on WLS (LWLS-SE) and KF (DKF-SE), that uses synchrophasor measurements. The theory predicts that DKF-SE provides a better accuracy as long as its process model is correct.

Goklani *et al.* (2014) presents various aspects of optimal phasor measurement unit placement problem in smart grid. In this work the cost of installation of PMUs was taken as the installation of PMUs, which was taken as the objective function to be minimised and the constraint being the observability of the power systems. The observability was defined using matrix containing ones and zeros.

For the TORA software, integer linear programming (ILP) was used for optional placement of the PMUs. The several methods of optional placement of PMU were compared using simulation Power System Analysis Toolbox (PSAT) and TORA software. The analysis of their merits and demerits was also carried out. This method was required to determine the minimum number of PMUs required making a power system observable.

Liang & Wen-Zhan (2014) proposes a distributed framework based on WAMS, the proposed approach allows multiple line outage identification using limited PMU measurements. A numerical tests was carried out which demonstrated the merits of the proposed schemes in coordinating the discovery of multiple line outages in a power grid. This was carried out in-network information processing and only shares estimates on boundaries with the neighbouring control areas. The novel framework was relied on the convex-relaxed formulation of the line outage detection problem and leverages the alternating direction method of multi-phasors (ADMM) for its distributed solution. The framework invokes a low computational complexity, requiring only linear and simple matrix-vector operations. The work was also extended to incorporate the sparse property of the measurement matrix and employ the LSQ R-algorithm to enable a warm start, which further accelerates the algorithms. An analysis and simulation test was done to validate the correctness and effectiveness of the proposed approach. The proposed algorithm was assumed to work in transmission networks. Due to the present challenge of unavailability of infrastructure of smart sensor network it was recommended that they can be applied for distribution networks theoretically.

Schwiil & Dobsan (2012) detect the location of line outages inside a specific area of the power system from synchrophasor measurement at the border of the area and inside the area. DC power flow model of the area was proposed in processing the area synchrophasor measurements. The method used extends the previous methods (Tate & Overbye's) that locate line trips in an entire network so that they work in a particular area and a case of islanding was dealt with. In this paper, an assumption was made; that a change in synchrophasor angles were made available using the detection and filtering methods and it also shown how to adapt line outage location method to an area within the interconnection with synchrophasor measurements inside the area and around border of the area. This work also confirms whether the line outage occurred inside the monitored area or not, giving useful discrimination of the source of changes in the power system. This work also converts a way to model the effect of line outages that island the area and also discriminate these islanding line outages with synchrophasor measurements.

Abdelaziz *et al.* (2013) present a modification on an existing algorithm, which presents a study for power oscillations with a laboratory model comprising a strong network, a transmission line and a generator, an algorithm tested for a three phase short circuit fault for a single machine infinite bus system: an approach to design power system transient stability assessment using direct methods for a multi-machine system that uses measured values of the currents and voltages of the three phases of two buses (equivalent to PMU data) was presented. The measured data was transformed from time domain into phasor domain using discrete Fourier Transform (DFT) to predict whether the swing is a stable or an unstable one. The performance of the method was tested on a simulated multi – machine system using PSCAD and MATLAB software. The proposed scheme can be used for the detection of out of step condition using an extension of the equal – area criterion. This proved that it is an efficient method for determining the transient stability of a power system and detecting the out of step condition for muilt-machine system as one machine against infinite bus or two machine systems.

Mousavian & Feizollahi (2015) proposed a new investment decision model to determine the optimal placement of PMUs that guarantees the full observability of the power grid. The new model utilises network observability rules and determines the optimal investment decision for the placement of PMUs in the power grid. Since genetic algorithm is well-known to have superior performance on solving discrete-binary optimisation problem – specific genetic algorithm was developed to solve the proposed model. Furthermore, a two phase PMU placement plan was also proposed which provides utility companies with flexibility of whether to install all PMUs in one or two phases and avoids unnecessary investment costs. In the first phase, PMUs were installed to make the power grid fully observable and postpone the N-1 observability placement to the second phase. The performance of the proposed algorithm was tested in several IEEE test systems. The experimental results were compared with the heuristic, meta-heuristic and integer linear programming based methods. Furthermore, the alternative optimal solutions provided by our GA were utilised to determine the optimal two phase investment. This gives flexibility to investors on where to install PMUs, which is advantageous to find the optimal-two phase investment plan as well that makes the power grid fully observable and resilient against single contingencies it two phases. The main disadvantage of this approach is that the optimality of the solution is not guaranteed, which is the common short coming of all heuristic and meta-heuristic methods compared to the ILP based methods. The analysis shows that the proposed approach is promising and verifies it efficacy.

Vignesh *et al.* (2015) present methodologies for modelling the loads under large as well as small disturbances using the measurements from phasor measurement units optimisation. A computationally efficient algorithm was developed to estimate the parameters under small disturbances and was presented using linearized model for the loads and eigen value sensitivity. A result was obtained from the simulation carried out on a small test system as well as on a practical larger power system. In this paper, a variable projection method which reduces the overall parameter space and ensures better convergence as compared to the existing algorithms, such as Gauss- Newton and levenberg-Marquardt and also proposes methodologies to determine the load models using PMU measurements under both large and small disturbances in a power system. The proposed load modelling can be implemented in practice to update the model parameters almost in real-time. A sensitivity analysis was performed to identify the most significant parameters of the load model. An efficient optimisation algorithm was then used to estimate only the significant model parameters i.e., for small disturbances, while for large disturbances, the accuracy and the speed of execution of the load modelling function are enhanced by using a variable projection based efficient optimisation algorithm to determine the model parameters.

Wen-Tai *et al.* (2015) developed a frame work for identifying multiple power line outages based on the PMUs measurements in the presence of bad data caused by communication errors or system malfunctions. This was done by designing an algorithm to identify locations of line outage and recover the faulty measurements simultaneously. The proposed algorithm does not require any prior information on the number of line outages and the noise variance. Some studies were carried out on test system of different sizes to validate the effectiveness and efficiency of the proposed approach. A computer simulation was used to demonstrate the effectiveness and efficiency of the proposed line outage identification algorithm.

Zhou *et al.* (2006) proposed an alternative approach, which leaves the traditional state estimation software in place, and discusses a novel method of incorporating the phasor measurement and the results of the traditional state estimator in a post processing linear estimator. The paper presents the basic theory and provides verification through simulations of the two alternative strategies. It was shown that the new technique provide non-linear state estimator and does not require modification of the existing EMS software. The approach proposed in this paper is such that it should be possible to continue with all other application functions exactly as before. The output of the traditional state estimator was processed by the proposed algorithm to incorporate PMU data and was put back in the same format as that produced by the traditional state estimator. In summary, the paper considered alternative techniques for using synchronised phasor measurements as additional data in traditional state estimator software in modern EMS and simply shows that by increasing the number of phasor measurements on a power system, the quality of the estimated state is progressively improved.

Darvishi & Dobson (2015) demonstrated how to combine synchrophasor measurements around the border of an area to quickly monitor the severity of multiple outages inside the area. In order to achieve this, voltage angles around the border of an area of the power system was combine into a bulk angle across the area. The area angle concept is a generalisation of the angle across a cut set area concept developed and proposed for stress monitoring. DC load flow model was used for the analysis and it was observed that synchrophasor measurements around the border of an area can be advantageous for other applications such as combining AC voltage measurements in a transmission corridor to monitor voltage collapse or locating line outages in the area.

Kesherwani *et al.* (2012) present the assessment methodology for voltage stability using PMU with complete system observability. The data obtained by PMU's were used for voltage stability assessment with the help of L-index. In this paper a similar formulation of optimal PMU placement problem was also done by integer linear programming with and without conventional power flow and power injection measurement i.e., the OPP problem was formulated using topology based algorithm and solved using integer linear programming on MATLAB.

Pinte *et al.* (2014) describes the steps, challenges and reasoning involved in building a single-phase, distribution – level PMU using National instruments products.

Theodorakatos *et al*. (2014) formulated Optimal Placement (OPP) problem by using a non-linear programming (NLP) problem and a sequential quadratic programming (SQP) method. Simulations were carried out on IEEE standard test systems, using MATLAB. The numerical results were compared to those obtained

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by a binary integer programming (BIP) model, also implemented in MATLAB. The comparative study shows that the proposed formulation yields the same number of PMUs as the BIP model. This was done by minimising the quadratic objective function which was subject to equality non-linear bus constraints, where the decision variables are defined on the bounded set. The quadratic function represents the total PMU installation cost, whereas the non-linear constraints express the network observability conditions. The main contribution of this paper lies in investigating the feasibility of using NLP for the OPP problem, despite the fact that this problem is discrete in nature. Hence, Binary integer programming model was developed, which guarantees convergence to the optimum solution using existing optimisation software. The BIP model was used as a comparative reference to demonstrate the efficiency and accuracy of the proposed model.

Pereira *et al.* (2006) present a technique for fault location on overhead distribution feeders using measurements of pre – and during fault voltage and current phasors at the sending node of a substation along with during – fault voltage measurement at the nodes along the feeder and a data base containing electrical, operational and topological parameters of the distribution networks, and fault simulation. The proposed technique was tested on an overhead line feeder and the results show that the technique is robust and efficient for carrying out fault location in a fast and accurate way.

Srikumar *et al.* (2015) discussed on algorithm to detect line outages on the transmission system using the bus voltage phasor measurement available from PMUs in conjunction with change in the system topology arising due to line outage. The algorithm also suggests the minimum number of PMUs required for effective line outage detection for a given system. This was simulated in Mi Power ™ software to obtain the bus voltage angle and the algorithm to detect effective line outage was programmed using MATLAB. The problem addressed in this paper is the detection of single line outage using only the data provided by the PMU and system topology information. The problem is formulated on the basis that "n" bus system is connected by single lines and only "n" single transmission line outage occurs. It is based upon the voltage phasor angles measured by the PMUs for the buses. These angles are obtained by simulating the "n" system and carrying out load flow studies on it. Later, the algorithm to detect line outage is implemented

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on IEEE power systems using MATLAB. The systems were simulated and analysed using Mi Power ™ software package. The paper also discusses the important role of PMU in line outage detection and show cases a methodology to detect single line outages with available date from PMU in conjunction with system topology information.

Arabali *et al.* (2016) proposed a new state estimation methodology based on the concepts of sparse vector recovery and line outage modelling i.e., it introduces a new line outage model based on voltage angle measurements that determines the changes in network topology after contingencies using sparse vector recovery since reporting rates of PMUs are faster than those of conventional PQ meters. This proposed method uses the estimated transmission line flows, PMU data and new network topology to provide system estimates until the conventional PQ measurement become available. The method make use of the PMU data, PQ measurements and new network topology to provide state estimates for post contingency networks. The proposed state estimation method overcomes the post – contingencies issues of change in topology and loss of measurements and the optimisation problem in convex. The performance and accuracy of the proposed methods were evaluated for the various IEEE bus systems. The simulation results show that the method provides good results for the three networks.

Abdelaziz *et al.* (2011) generate a method using only voltage measurements and also proposed a new algorithm using both voltage and current measurement with higher degree of accuracy. A comparison between the two algorithms in terms of accuracy and reliability was carried out to show the validity of the new algorithm over others. The two methods were tested using results of an off-line simulation program PSCAD (Power System Computer Aided Design) and the mathematical analysis with the aid of MATLAB. Comparison between the proposed PMU based fault location algorithms and some other conventional and new techniques was also presented. The method also considers the transmission line parameters such as surge impedance and propagation constant; which is also dependent on the primitive parameters of the transmission line (the line resistance, inductance and capacitance per unit length). The work on this paper also clarifies that, the algorithm based only on the voltages measurements has an advantage and that it is free from the CTs errors and it doesn't require current measurements. The

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second proposed method has more advantages because; it has more accurate results as it deals with more details about the system (Voltages and Currents).

Dotta *et al.* (2014) discuss the design and usage of a Simulink-based PMU simulator package. This can be used for teaching and research to explore the algorithms involved in the phasor measurement process. It replicates the device architecture and other conventional algorithms.

Satyendra & Singh (2014): in this paper, integer programming based methodology was presented for the optimal placement of PMU in order to minimise the cost of installation and provides the entire system observability. The concepts of zero injection buses were used in this paper for further reduction in number of PMUs. A criterion was also proposed to select the appropriate location of PMU and to deal with problem of having multiple results which might create confusion. The proposed algorithm was tested on IEEE 14-bus, IEEE 24-bus and IEEEE 30-bus systems. In addition, multiple choices of locations were eliminated by selecting the combination of buses having maximum redundancy. Simulation results on the following IEEE buses 14-, 24-, and 30- test systems indicate that the proposed placement method satisfactorily and provides full observable system measurements with minimum number of PMUs.

Abood & Sreeram (2014) present the main categories for PMUs placement strategies according to the objective of PMUs employment. The paper focuses on the objectives because PMUs can be installed for many objectives and optimal PMUs placement problem is a multi-dimensional and multi-functional problem.

Liang *et al.* (2016) developed a hybrid filter algorithm to deal with the state estimation (SE) problem for power systems by taking into account the impact from the PMUs. The proposed algorithm was applied to give an estimate of the states of the power systems with both traditional and PMU parameters in the presence of probabilistic data missing phenomenon. An extensive simulation was carried out on the 14 bus standard IEE test system and it was shown that the proposed algorithm gives much improved estimation performances over the traditional extended Kalman filter algorithm method.

Martin *et al.* (2006) describes a set of test used to determine PMU measurement characteristics under steady and dynamic conditions. The methodology was based

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on the use of test signals that are mathematically generated from a signal model and played into the PMU with precise GPS synchronisation.

Mauryan & Ramkumar (2014) present a brief review on the phasor measurement unit and its application in the power system such as state estimation, power system protection, and power system control.

Anil kumar & Lakshmi (2014) present the fault detection and classification in power system using PMU. The proposed technique is based mainly on two components to identify the faults on the transmission lines. The first component is the voltage reduction due to fault occurrence. The second component is the power flow detection after fault occurrence. The phase angle was used to determine the direction of fault current with respect to a reference quantity. In summary it presents a new protection technique for transmission grids using Phasor Synchronised measuring techniques in a wide area system.

Tate & Overbye (2007) proposed an algorithm which uses known system topology information together with PMU phasor angle measurements, to detect system line outages. The algorithm also provides an estimate of the pre-outage flow on the outage line. This was done by using simulated and real PMU data from two systems: a 37-bus study case and TVA control area. The problem addressed was the detection of system events using only PMU data, transmission line and transformer parameter data, and system topology information.

Garcia *et al.* (2016), a statistical classifier that localises line outages using time series PMU data that is sampled during the transient response of the system. The classifier is a linear multinomial regression model that is trained by solving a maximum likelihood problem. 57 bus systems were used to compare the results to existing quasi – steady state and to illustrate the ability of the classifier to quickly identify line outages before a steady state is reached.

Ali *et al.* (2014) proposed a neural network based voltage instability detector which utilising wide area monitoring system and measured angle of the installed PMUs. The detector depends on the bus voltage angle which is measured by the installed PMUs. Furthermore, the effect of different loading conditions was applied to the simulation system to get their corresponding bus angles values. The work done on this paper was developed through three stages. The first stage was the simulation of the power system using MATLAB to get the system load flow results. The second stage was the normalisation of the output of the first stage. The third stage was the design and training of a feed-forward neural network which utilise thirty percent of the studied cases. The network was programmed to give the voltage stability status of the power system buses based on bus voltage angles. The newly developed ANN based voltage detector was designed to study the voltage stability status of the whole system buses as one unit. The smart developed method was applied to IEEE 14-bus standard system. The system was later simulated and about one thousand studied cases were obtained i.e., Four hundred studied cases of them were used for training of the ANN and the rest were used for testing stage. It was found that the accuracy of ANN was about 90%.

Oshevire *et al.* (2013) examined the prospects and possible application of Smart Grid Technology (SGT) to the Nigeria power system. The study shows that the smart grid system will make the present network more efficient and reliable by connecting different sources of distributed generators into the existing grid. Basic requirements necessary for the application of SGT using the Nigeria power system as a case study were discussed. The paper proposed a method of supply reliability evaluation for micro grids, including renewable energy sources, installation of electric energy storage systems etc.

Nafeena & Seralathan (2014) present a novel approach to optimal placement of PMUs for state estimation. This was done by determining the optimal measurement set in order to achieve full network observability using heuristic approach during normal conditions. Artificial Bee Colony algorithm was used as the tool for optimisation to obtain the minimal number of PMUs and their corresponding locations while satisfying the associated constraint. The integer based artificial bee colony optimisation method was tested on various standards of IEEE bus system such as 14-bus, 30-bus, 57-bus and 118-bus. The proposed two stage algorithm on the paper determines the minimum number of strategic bus locations where PMU must be placed for complete observability. The first stage of the algorithm determines the important bus locations for allocating PMUs. The second stage is pruning stage which is checks the possible ways to further reduce any PMUs minimum number of strategic bus locations where PMU must be placed

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for complete observability. Measurement redundancy was also checked. Simulation results for different networks show the effectiveness of the proposed method in obtaining the minimum number of PMU required for complete observability of power systems. A drawback was noted for heuristic method which is the time to execute and it was mitigated using Artificial Bee Colony Approach.

Marwa & Noha (2013), a new approach for Artificial Immunity system (AIS) based voltage instability detection during transient period was developed. The AIS technique was developed to predict the system behaviour and determine voltage instability occurrence. The voltage instability was analysed and studied using the concept of Wide Area Measurement Protection and Control (WAMPAC). The newly developed voltage instability detector was applied to the IEEE 14 bus system. This gave an acceptable result in the expected system behaviour. The work was progressed through three main stages. First stage is simulating power system using PSAF. Second stage is handling and processing data, before using it by the AIS technique. Third stage is the use of the developed AIS technique to detect system stability, and inform system protection centre (SPC) in case of voltage instability.

Ganga *et al.* (2012), deals with a study to determine the optimal locations of PMUs for a given power system. This paper focuses on the use of PMU measurements in state estimators. The principle objective was the investigation of various methods of determining optimal locations for PMUs so that the entire power system is observable. The recently developed artificial intelligence (AI) techniques, like Genetic Algorithm and artificial bee colony techniques were applied to find out the optimal placement of PMUs for various systems. The artificial bee colony approval for solving a binary mode of optimization gives the desired optimised results successfully. The ABC approach guarantees a global or near global solution with a properly chosen colony parameters like maximum number of iterations, population size, on looker bees, employed bees and threshold limit.

Gunjker *et al.* (2015) present an extensive simulation studies on fault location carried out using MATLAB. A brand-new adaptive PMU based protection scheme for both transposed and un-transposed parallel transmission lines was also presented. The development of the scheme was based on the distributed line model and the synchronised phasor measurement at both ends of line by means of eigen value/eigen vector theory to decouple the mutual coupling effects between the parallel lines, the fault detection and location indices. The extensive simulation studies show that the performance of the proposed algorithm is very excellent and the average error of fault location was well less than 1 % under various system operations with a consideration on fault factors. The simulation results also demonstrate the feasibility and effectiveness of the proposed fault location technique for multi-terminal transmission lines with arbitrary configurations. The proposed fault location technique was an accurate method and its performance is almost unaffected by system operation conditions and fault events.

Chakrapani & Dushmanta (2015) gave an insight of the importance and application of Phasor Measurement unit in power system. It also presents the modelling of phasor measurement unit in MATLAB as well as realization of Phasor data considering only a two bus system as against my work, which intend to consider 16 bus systems on Nigeria Transmission line. The work on the paper was done with the aid of Simulink model of 2-bus system comprising of PMU block in MATLAB. The real data were obtained to understand the dynamic behaviour or change in the system irrespective of the state.

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CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Research Data

Data collection is the process of gathering and measuring information on targeted variables such as lines and Generators parameters in an established systematic fashion, which then enables one to perform analysis and evaluate outcomes. The various data (Generator Data, Generator-Transformer Data, Transmission Line Data, and Load Data) that was used for the network proposed in this research are tabulated on Appendix A - A typical Generator Data as collected, Appendix B – A typical Generator Transformer Data, Appendix C – Transmission line parameter, Appendix D – A typical Load Data as collected and Appendix E – Data for Generating stations from January to April, 2017.

3.2 Data Preparation

The data to be used are summarised by taking the average of the power on the load bus and the generators data within a period of four months; alongside the transmission lines parameters and the Generators-Transformers data were also considered. These were managed in Microsoft Excel format and were entered as input to the 330kV transmission network drawn on PSAT/MATLAB Simulink 2015a (Figure 3.1), with the aid of the prototype received from Transmission Company of Nigeria (TCN).

The network to be considered represents the South – West region (Figure 3.2). It has twelve (12) buses maintained at 330kV, three (3) Generators and six (6) numbers of PMU as determined from PSAT optimal placement. Ikeja-West to Osogbo, Ikeja-West to Sakete, and Ayede to Olorunsogo lines representing a single circuit network were considered as the lines under outage and were analysed following the algorithm on session (3.3).

3.3 Method of Data Analysis

The methodology used for this work involved collection of relevant transmission parameters such as Generators-Transformer data, Generator ratings, number of 330kV buses, and line impedance values from Transmission Company of Nigeria, Osogbo, Osun state, Nigeria. The entire 330kV transmission line diagram was modelled and simulated on PSAT 2.10.1 and MATLAB 2015a as shown on Figure 3.1. The south western region was then considered for this work due to the complexity involved considering the entire network during power flow analysis.

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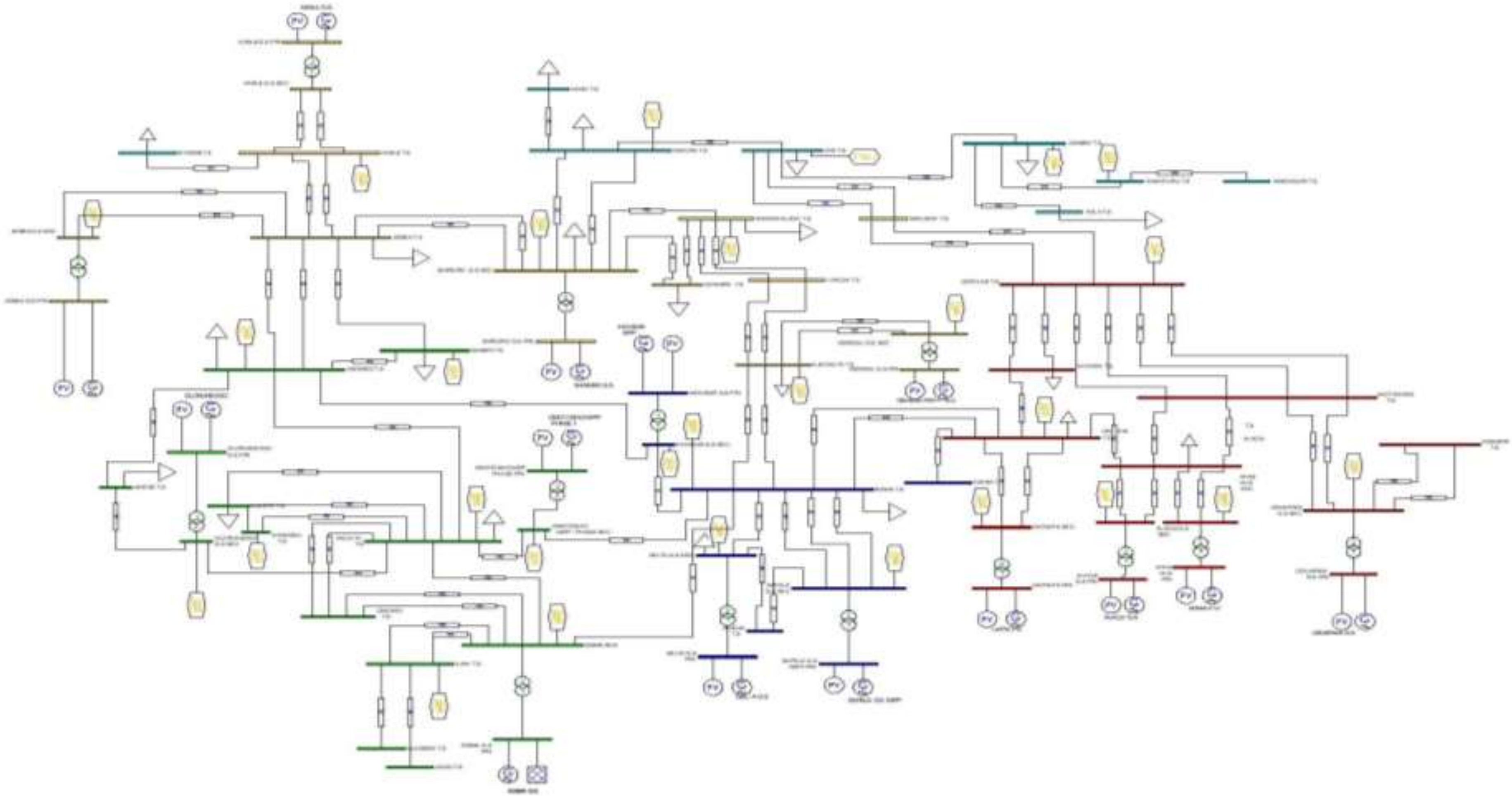

Figure 3.1. 330kV Transmission National Grid of Nigeria drawn on PSAT/MATLAB Simulink

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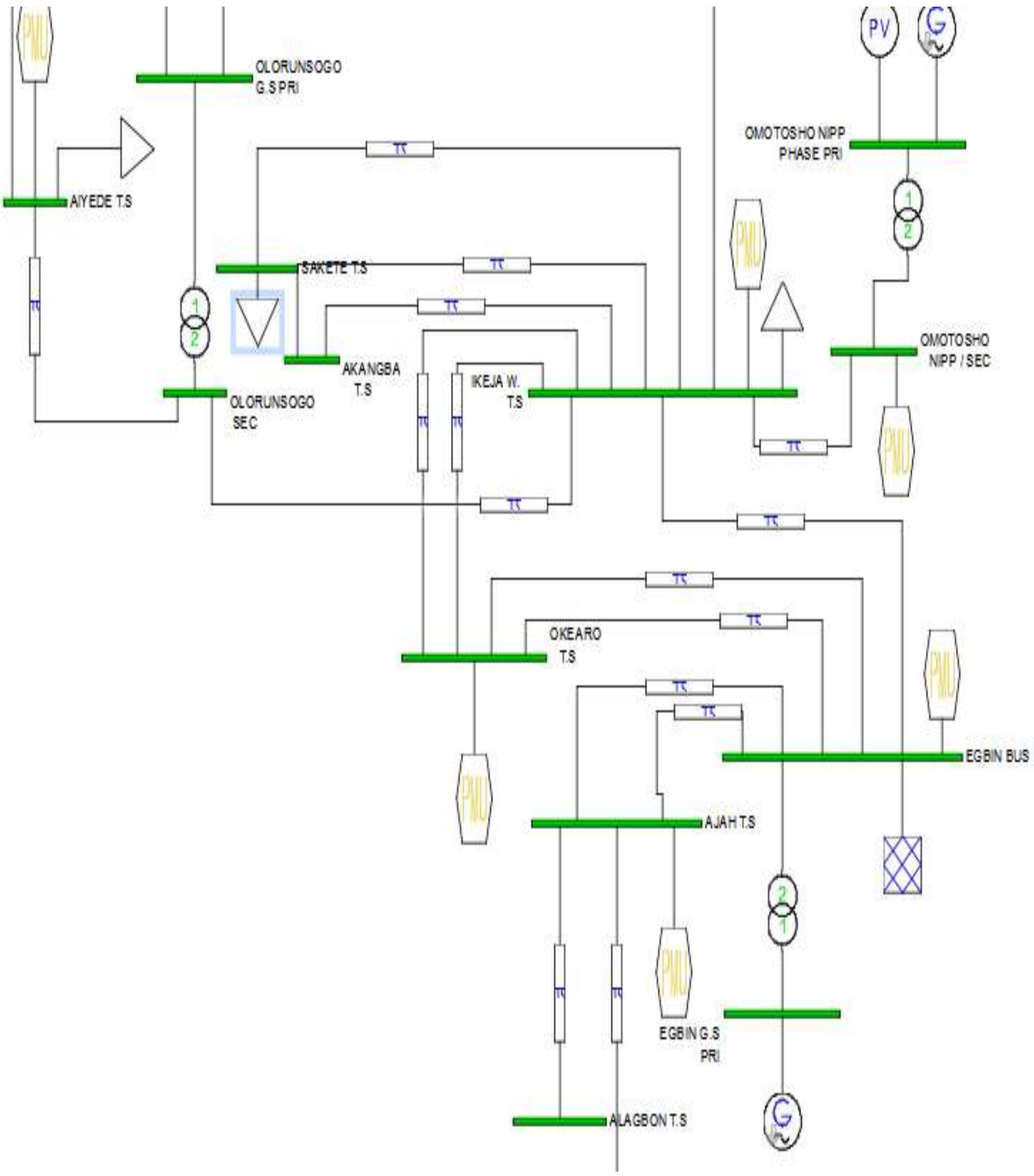

Figure 3.2. A session of the 330kV Transmission Grid Representing the South West Region of Nigeria

The network for this study consists of 12 buses at 330kV, with 3 generators and 6 PMUs device. Egbin power station was used as the slack bus among other power generating stations; this is as a result of having the largest generating power and would be suitable as the slack bus in the system. In order to determine the following: Voltage magnitudes, Phase angles, active and reactive power etc., throughout the network, buses were maintained at 330kV. The method was then divided into offline analysis and online analysis. For the offline analysis, the following steps were carried out to achieve the normalised values of change in admittance:

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(a) the admittance matrix for Y-bus and bus voltage for pre-outage was obtained via the power flow analysis;

(b) then the row and column of the primary bus bar of Generator and the row and column associated with slack bus was eliminated i.e., since the angle change at slack bus is always zero;

(c) converting the Admittance Y-Bus to Impedance values;

(d) selection of a single line linking Ikeja to Osogbo representing a possible outage;

(e) calculation of the change in impedance ΔZ for line (Ikeja-West to Osogbo);

(f) performing rank for the change in impedance matrix for step g (i.e.) finding a single vector. This was done by performing reduced row echelon form (rref) on the transpose of the change in impedance;

(g) normalising the first row of the matrix of the reduced row echelon form;

(h) step (c) to (g) was repeated for other single lines such as Sakete to Ikeja-West, and Olorunsogo to Ayede to obtain the normalised values of change in impedance; and

(i) recursive N-1 method on PSAT for optimal placement of PMU was used to obtain the number of PMU for total observability of the system and the Phasor voltage and angle at all the buses.

While for the online analysis, the following steps were carried out to achieve the normalised values of change in angle.

(i) The Phase Angle from online simulation for the Pre-Outage and also Post Outage was obtained for all the lines listed in (h)

(ii) Calculation of change in voltage phase angle between Pre-Outage and Post Outages at buses.

(iii) Normalising the column matrix from the output of step (ii).

(iv) The normalised column matrix of change in voltage phase angle (iii) is compared with each normalised basic vector of transmission line outages (g) and (h).

(v) Finding the closest Vector to the Angle to determine the line outage.

(vi) Plotting of the result of (iv) on a graph using MATLAB software.

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3.4 Equation of Power Flow and Line Outage Detection

In general, the flow of power in a power system is governed by basic electric circuit theory. A power flow study is performed in order to determine where and to what degree the active and reactive powers flow (Mahoney, 2011). Beginning from Ohm's law and the definition of complex electric power, the following power flow equations are derived:

$$P_i = \sum_{n=1}^{N} \left(|Y_i||V_i||V_n|\cos(\delta_{in} + \theta_n - \theta_i) \right) \quad (3.1)$$

$$Q_i = \sum_{n=1}^{N} -\left(|Y_i||V_i||V_n|\sin(\delta_{in} + \theta_n - \theta_i) \right) \quad (3.2)$$

Where N is the number of buses, i is the Bus identity, P_i is the real power and Q_i is the reactive power injected.

The admittance of a branch element in the power system i defined as:

$$|Y_{in}|\angle\delta_{in} \quad (3.3)$$

And the bus voltage and magnitude at bus i

$$|V_{in}|\angle\theta_{in} \quad (3.4)$$

The power flow solution is a process of solving the power flow equations such that the active power generated equals the active power loss plus the real powers of the loads. Similarly, the reactive power generated must equal the reactive powers of the connected loads. Since the power flow problem is non-linear in nature, most solution methods use an iterative approach to arrive at a solution. In an attempt to provide a faster, though less accurate solution, the DC power-flow was created. A DC power flow represents an entirely linear set of equations which do not require iteration. Some assumptions are made to arrive at the DC power flow solution.

First, many large systems have branch impedances whose real part is in significant compared to the imaginary part:

$$z = r + jx \quad (3.5)$$

Where $r \ll x \Rightarrow z \approx jx$

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It is important to note that since the impedance is approximately equal to the reactance, the *j* can be dropped as long as it is known that all calculations are performed on the imaginary components only. Also, in general, if an angle is represented in radians, the sine of that angle is approximately equal to the angle itself (Mahoney, 2011):

$$\text{Sin}(\theta) \approx \theta \tag{3.6}$$

Lastly, when expressed using the per-unit system, the voltages at every bus are approximately equal to 1. With only the real part of the impedance remaining and since the angle δ_{ij} of each impedance is 90^0. Thus, the power flow equations become:

$$P_i = \sum_{n=1}^{N} \left(|Y_{in}| (\theta_n - \theta_i) \right) \tag{3.7}$$

$$Q_i = 0 \tag{3.8}$$

Additionally, the power flowing through a single branch from bus I to bus j can then be approximated as:

$$P_{ij} \cong \frac{|V_i||V_j|}{|X_{ij}|} \sin(\theta_{ij}) \tag{3.9}$$

The real power injected at any bus can then be expressed as a sum of the incident branch flows which consist of admittances and bus voltage angles. Therefore, a relation between bus power injections and bus voltage angles can be written in matrix form:

$$P = Y\theta \tag{3.10}$$

More often, the quantity of interest is the bus voltage angle, since it can be used to determine the line flows as in (3.10). For this reason, the DC power flow equations can be expressed in terms of an admittance matrix, **Y**, or an impedance matrix **X**:

$$\theta = Y^{-1}P \tag{3.11}$$

$$\theta = XP \tag{3.12}$$

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Due to their linear nature, the DC power flow (3.11) and (3.12) are useful in many applications. One particularly important application is in the area of contingency analysis. During normal operation, it is often unrealistic to solve a full power flow in the case of some system contingency. Instead, a set of so-called linear distribution factors is used to quickly calculate the change in line flows or bus voltage angles when system contingencies occur. Using the DC power flow assumption as stated earlier, it is possible to view the system impedance matrix **X** as a linear transformation. Since **X** is a mapping from vectors in the space of injected powers to the space of bus voltage angles, it can be viewed as the matrix representation of a linear transformation between two finite dimensional vector spaces. Thus, in order to detect line outages, there must be some way to characterise the vectors in the range of **X** as belonging to a specific subset.

Each subset represents the possible bus voltage angles which may occur due to an individual line outage. Before a line outage occurs, it is assumed that the linear transformation matrix **X** has been calculated. During and after the outage itself, it is also assumed that a certain number of bus voltage angles are measurable via PMUs. The only unknown quantities then are the injected real powers at each bus.

Since bus voltage magnitudes have been shown to provide the most telling information about power system events, it can be reasoned that their difference before an event and after an event describes the true character of said event. The model of a power system before an outage:

$$\theta_{Pre} = XP$$

and the same system after a line outage is as follows:

$$\theta_{post} = [X + \Delta X]P \tag{3.13}$$

Due to the line outage, the impedance matrix is modified. The character of this modification is well known, but may be easier to visualise in terms of admittance. Recall that $Y = X^{-1}$. Therefore

$$Y = X^{-1} \Rightarrow [X + \Delta X] = [Y + \Delta Y]^{-1} \tag{3.14}$$

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The line between bus *i* and bus *j* whose admittance is y_{ij} can be removed from the original admittance matrix **Y** to yield the new admittance matrix $\hat{\mathbf{Y}}$ as follows:

$$\hat{Y} = Y + \begin{array}{c} \\ (i) \\ \\ (j) \end{array}\begin{array}{c} \begin{array}{ccc} (i) & & (j) \end{array} \\ \begin{bmatrix} -y_{ij} & \cdots & y_{ij} \\ \vdots & \ddots & \vdots \\ y_{ij} & \cdots & -y_{ij} \end{bmatrix} \end{array} \tag{3.15}$$

Typically, this same operation can be modelled with impedances by adding another artificial line of negative impedance equal to the original in parallel with the original line. To remove the effect of the artificial line Kron Reduction is then performed (Mahoney, 2011). In (3.15), the negative of the admittance is on the main diagonal, but the actual admittances are in row *i*, column *j* and row *j*, column *i*. For a 3 x 3 admittance matrix, when removing a line between bus 1 and bus 3, the above equation could be written as:

$$Y = \begin{bmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{bmatrix} + \begin{bmatrix} -y_{13} & 0 & y_{13} \\ 0 & 0 & 0 \\ y_{13} & 0 & -y_{13} \end{bmatrix} \tag{3.16}$$

Using the Sherman-Morrison-Woodbury (SMW) matrix identity, it is possible to determine the impedance matrix form of this equivalent admittance matrix form. The SMW matrix identity is simply a method for finding the inverse of a matrix when the matrix is updated with a rank *k* update:

$$(A + UCV)^{-1} = A^{-1} - A^{-1}U(C^{-1} + VA^{-1}U)^{-1}VA^{-1} \tag{3.17}$$

Rewriting the (3.17), it is possible to arrive at a form similar to the Woodbury identity. Again, assuming a three bus system:

$$\hat{Y} = \begin{bmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{bmatrix} + \begin{bmatrix} -y_{13} & 0 & y_{13} \\ 0 & 0 & 0 \\ y_{13} & 0 & -y_{13} \end{bmatrix} \tag{3.18}$$

$$= Y + \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}\begin{bmatrix} -y_{13} & 0 & y_{13} \end{bmatrix}$$

$$= Y - \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}[-y_{13}]\begin{bmatrix} 1 & 0 & -1 \end{bmatrix} \tag{3.19}$$

Now, (3.19) can be inverted using the SMW identity as follow

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$$= \overset{y_{aa}}{\widehat{Y}} - \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix} \underbrace{[-y_{13}]}_{y_{bb}} \underbrace{[1 \quad 0 \quad -1]}_{y_{ab}{}^T} \tag{3.20}$$

The expression above is made up of four separate pieces which can be rewritten as follows:

$$(y_{aa} - y_{ab} y_{bb} y_{ab}{}^T)^{-1} = y_{aa}{}^{-1} - y_{aa}{}^{-1} y_{ab} (y_{bb}{}^{-1} + y_{ab} y_{aa}{}^{-1} y_{ab}{}^T)^{-1} y_{aa}{}^{-1} y_{ab}{}^T \tag{3.21}$$

Equivalently, the original admittance matrix is simply the inverse of the original impedance matrix:

$$(y_{aa} - y_{ab} y_{bb} y_{ab}{}^T)^{-1} = X - X \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \left([-y_{13}]^{-1} + [1 \quad 0 \quad -1] X \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \right)^{-1} [1 \quad 0 \quad -1] X \tag{3.22}$$

The second term which is subtracted from the original impedance matrix is made up of three separate pieces. The first piece on the left can be rewritten as follows:

$$X = \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix} = \begin{bmatrix} X_{11} & -X_{13} \\ X_{21} & -X_{23} \\ X_{31} & -X_{33} \end{bmatrix} = [\mathrm{Col}_i - \mathrm{Col}_j] \tag{3.23}$$

The right most piece is simply the transpose of the leftmost piece and can be rewritten similarly:

$$[1 \quad 0 \quad -1] X = [X_{11} - X_{31} \quad X_{12} - X_{32} \quad X_{13} - X_{33}] = [\mathrm{Row}_i - \mathrm{Row}_j] \tag{3.24}$$

and

$$[-y_{13}]^{-1} + [1 \quad 0 \quad -1] X \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}$$

When line impedance is removed from the system the equation becomes:

$$[-y_{13}]^{-1} + [X_{11} - X_{31} \quad X_{12} - X_{32} \quad X_{13} - X_{33}] \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix} \tag{3.25}$$

$$[-y_{13}]^{-1} + [X_{11} - X_{31} \quad -(X_{13} - X_{33})] \leftarrow X_{13} = X_{31}$$

$$= X_{13} + X_{11} + X_{33} - 2(X_{13})$$

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Taking the inverse of the result above simply yields a scalar in the case of a single line removal:

$$(x_{13} + X_{11} + X_{33} - 2(X_{13}))^{-1} = \frac{1}{x_{13} + X_{11} + X_{33} - 2(X_{13})} \tag{3.26}$$

With each of the rewritten pieces, it is easy to see how line impedance is removed from a system impedance matrix:

$$[\mathrm{Col}_i - \mathrm{Col}_j]\left[\frac{1}{Z_{ii} + Z_{ij} - 2Z_{ij} + Z_{13}}\right][\mathrm{Row}_i - \mathrm{Row}_j] =$$

$$= X\begin{bmatrix}1\\0\\-1\end{bmatrix}\left(([-y_{13}]^{-1}) + [1 \quad 0 \quad -1]X\begin{bmatrix}1\\0\\-1\end{bmatrix}\right)^{-1}[1 \quad 0 \quad -1]X \tag{3.27}$$

Thus, the Kron Reduction which is typically used to add a new loop element to an impedance matrix is nothing more than an application of the SMW matrix identity. The typical form of Kron Reduction K is:

$$K = X - \Delta X \tag{3.28}$$

Now, with the ability to model the change in the power system due to a line removal, it is possible to determine analytically the effect of a line outage on bus voltage angles. In the equation above, the term **ΔX** is the representation of the line removal. The question however, is how to isolate this portion so that, when PMU measurements are used, only the change in the impedance matrix is characterised. To accomplish this, the difference in pre and post outage angles must be used. In order to examine the difference in pre and post outage angles, the power system can be modelled using the DC power flow assumptions. As shown above the models before and after an outage is:

$$\theta_{Pre} = XP \tag{3.29}$$

$$\theta_{Post} = [X + \Delta X]\,P \tag{3.30}$$

However, as was shown above, the model after the outage can also be written as (3.30). To characterise their difference (the impedance change), the post outage angles are subtracted from their pre outages angles:

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$$\theta_{Pre} - \theta_{Post} = \Delta\theta = [\Delta X]\, P \tag{3.31}$$

The vector **Δθ** is the image of the line outage in terms of bus voltage angles. Here, as before, the assumption is that an angle measurement is available at every bus. Also, as before, this assumption can be relaxed without loss of generality. The vector **Δθ** can be found off-line, for every line outage since the matrix **ΔX** can be calculated from the topology and the list of branch impedances. The impedance change can be shown to be a rank one matrix. Normalising a vector:

$$\Delta\theta_{norm} = \frac{\Delta\theta}{|\Delta\theta|} \tag{3.32}$$

With these equations above, when the measured **Δθ** vector is also normalised to rank one, the vectors will be identical, i.e., using DC power flow assumptions.

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CHAPTER FOUR

DATA ANALYSIS AND DISCUSSION

4.1 Simulation

The data used in this study was based on what was collected from TCN, Control Centre Osogbo and the equation used in achieving these have been presented in chapters 3; i.e., (3.23) to (3.32). Figure 4.1 shows the estimated voltage in Per Units and the estimated angles in radian using Recursive N-1 spanning method for selection of the best suitable location that will give a total system observability using PMU at the stipulated position within the network; without leaving any bus un-observed. This figure represents when the system is in a stable state.

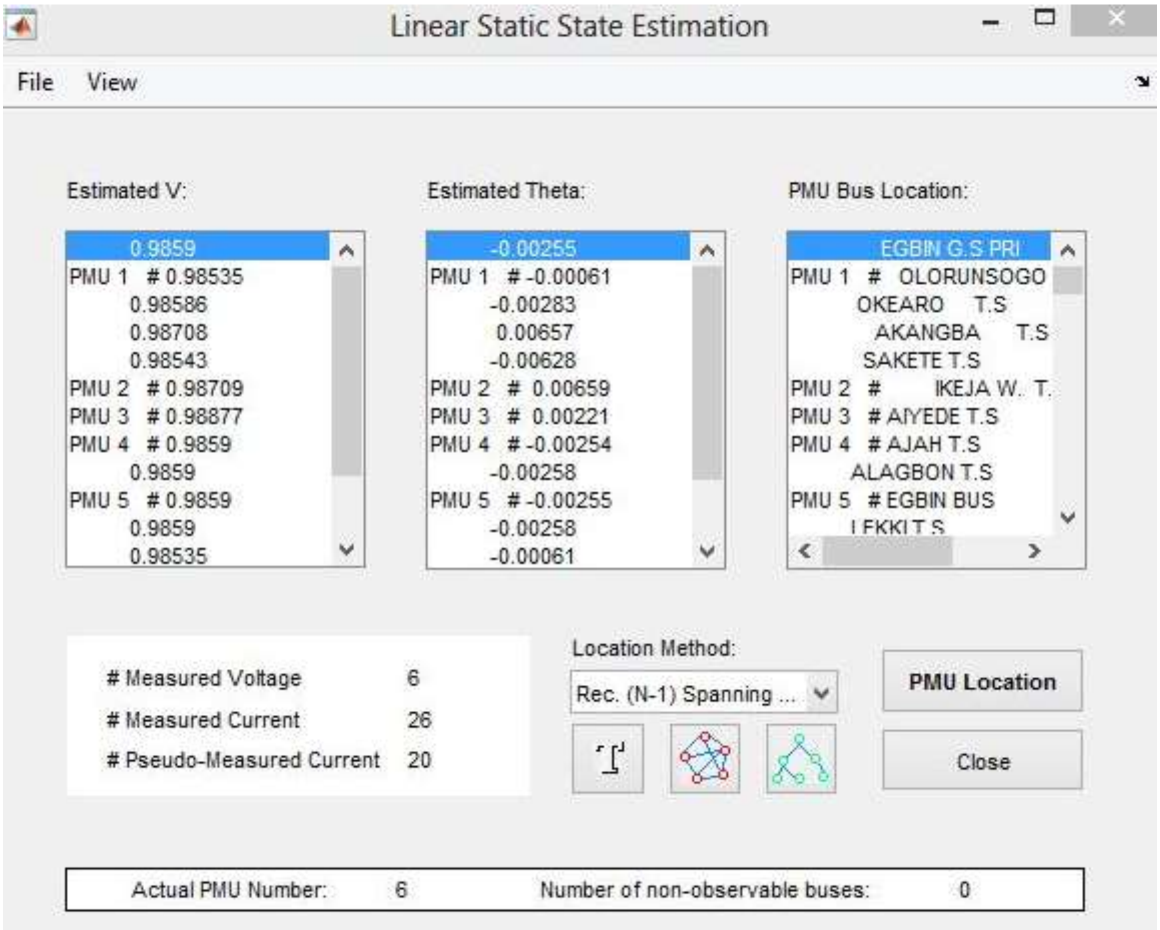

Figure 4.1. PMU reading for Pre-Outage

Figure 4.2 shows the estimated voltage in per units and the estimated angles in radian using recursive N-1 spanning method for selection of the best suitable location that will give a total system observability using PMU at the stipulated position within the network; without leaving any bus un-observed. This figure represent when the system is in an unstable state and the values gotten from the simulation; i.e., when Ikeja-Osogbo line

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is taking out of the system before running simulation on PSAT. While Table 4.1 represents the various angles at each bus and their changes in degree.

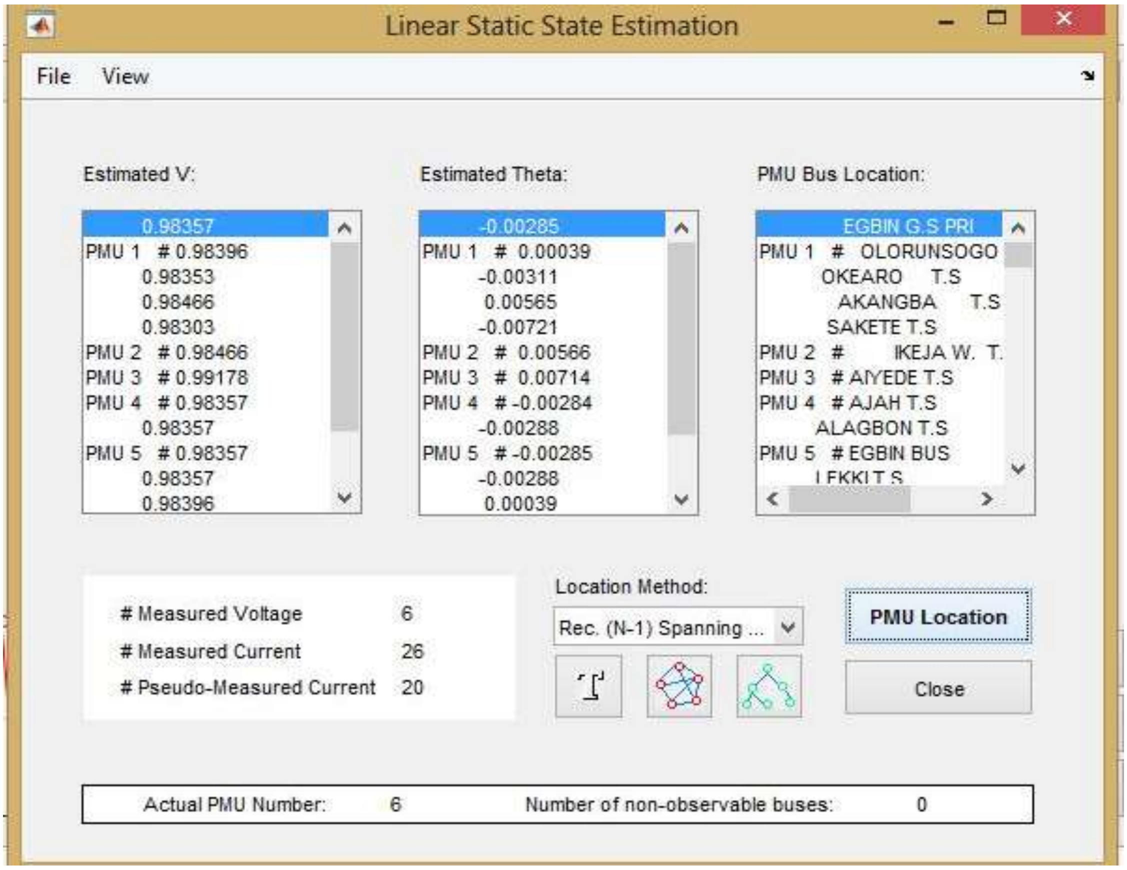

Figure 4.2. PMU reading for Ikeja-Osogbo Outage line

Table 4.1. Change in Angle reading for Ikeja -Osogbo

Bus	Pre-Outage	Post-Outage	ΔΘ in Degree
Egbin GS Pri	0.984586561	-0.163271801	1.147858362
Olorunsogo Sec	-3.281955203	0.022342457	-3.30429766
Okearo TS	0.918947457	-0.178166773	1.097114229
Akangba TS	3.019398786	0.323679185	2.695719601
Sakete TS	3.052218338	-0.413049013	3.465267352
Ikeja West TS	3.052218338	0.324252069	2.72796627
Aiyede TS	-16.18003915	0.409038829	-16.58907798
Ajah TS	0.984586561	-0.162698918	1.147285479
Alagbon TS	0.984586561	-0.164990452	1.149577013
Egbin Bus	0.984586561	-0.163271801	1.147858362
Lekki TS	0.984586561	-0.164990452	1.149577013
Olorunsogo GS Pri	-3.281955203	0.022342457	-3.30429766
Omotosho NIPP / Sec	3.183496546	0.889115213	2.294381333
Omotosho NIPP Phase Pri	3.183496546	0.889115213	2.294381333
Osogbo TS	-19.36353569	0.409038829	-19.77257452

GS: Generation Station; TS: Transmission Station

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Figure 4.3 simply shows the estimated Voltage in Per Units and the estimated angles in radian using recursive N-1 spanning method for selection of the best suitable location that will give a total system observability using PMU at the stipulated position within the network; without leaving any bus un-observed. This figure represent when the system is in an unstable state and the values gotten from the simulation; i.e., when Ayede-Olorunsogo line is taking out of the system before running simulation on PSAT. Table 4.2 represents the various angles at each bus and their changes in degree.

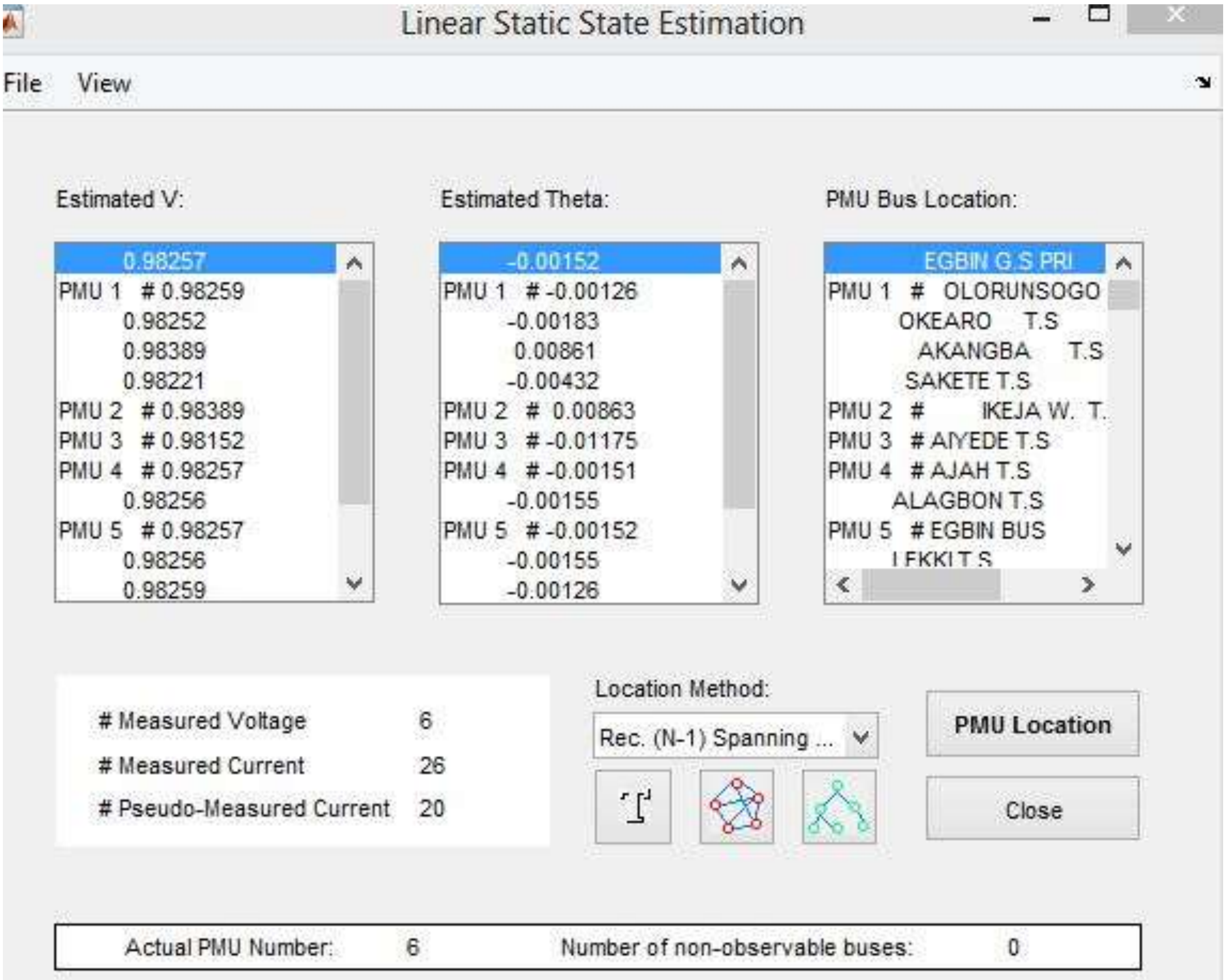

Figure 4.3. PMU reading for Ayede-Olorunsogo Outage line

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Table 4.2. Change in Angle reading for Ayede -Olorunsogo

Bus	Pre-Outage	Post-Outage	ΔΘ in Degree
Egbin GS Pri	0.984586561	-0.087078294	1.071664855
Olorunsogo Sec	-3.281955203	-0.072183323	-3.20977188
Okearo TS	0.918947457	-0.104837683	1.02378514
Akangba TS	3.019398786	0.493252705	2.526146081
Sakete TS	3.052218338	-0.247485678	3.299704016
Ikeja West TS	3.052218338	0.494398472	2.557819866
Aiyede TS	-16.18003915	-0.673138129	-15.50690102
Ajah TS	0.984586561	-0.086505411	1.071091971
Alagbon TS	0.984586561	-0.088796945	1.073383505
Egbin Bus	0.984586561	-0.087078294	1.071664855
Lekki TS	0.984586561	-0.088796945	1.073383505
Olorunsogo GS Pri	-3.281955203	-0.072183323	-3.20977188
Omotosho NIPP / Sec	3.183496546	1.071292171	2.112204376
Omotosho NIPP Phase Pri	3.183496546	1.071292171	2.112204376
Osogbo TS	-19.36353569	-0.673138129	-18.69039757

GS: Generation Station; TS: Transmission Station

Figure 4.4 simply shows the estimated Voltage in PU and the estimated angles in radian using recursive N-1 spanning method for selection of the best suitable location that will give a total observability using PMU at the stipulated position within the network; without leaving any bus un-observed.

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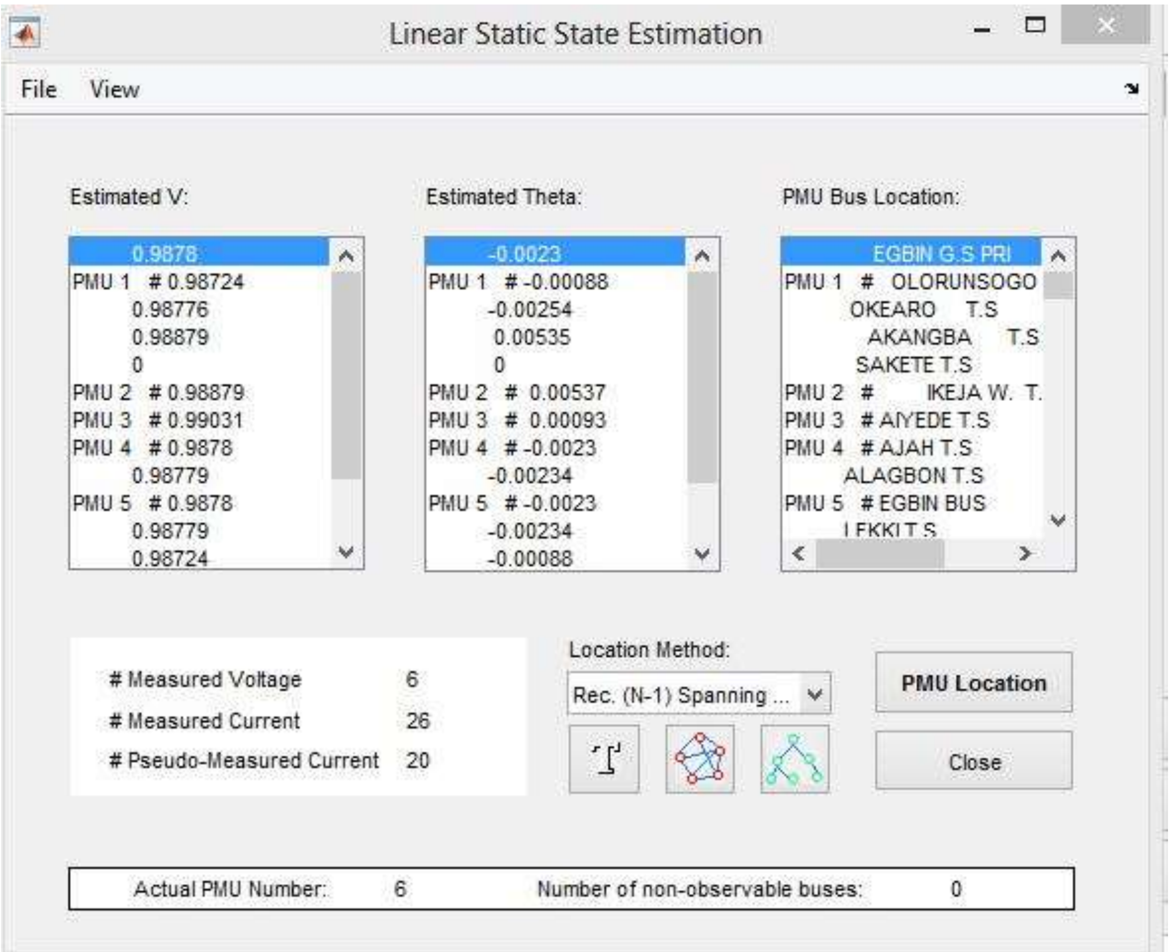

Figure 4.4. PMU reading for Sakete-Ikeja Outage line

This figure represent when the system is in an unstable state and the values gotten from the simulation; i.e., when Sakete-Ikeja line is taking out of the system before running simulation on PSAT.

Table 4.3. Change in Angle reading for Sakete-Ikeja

Bus	Pre-Outage	Post-Outage	ΔΘ in Degree
Egbin GS Pri	0.984586561	-0.163271801	1.147858362
Olorunsogo Sec	-3.281955203	0.022342457	-3.30429766
Okearo TS	0.918947457	-0.178166773	1.097114229
Akangba TS	3.019398786	0.323679185	2.695719601
Sakete TS	3.052218338	-0.413049013	3.465267352
Ikeja West TS	3.052218338	0.324252069	2.72796627
Aiyede TS	-16.18003915	0.409038829	-16.58907798
Ajah TS	0.984586561	-0.162698918	1.147285479
Alagbon TS	0.984586561	-0.164990452	1.149577013
Egbin Bus	0.984586561	-0.163271801	1.147858362
Lekki TS	0.984586561	-0.164990452	1.149577013
Olorunsogo GS Pri	-3.281955203	0.022342457	-3.30429766
Omotosho NIPP / Sec	3.183496546	0.889115213	2.294381333
Omotosho NIPP Phase Pri	3.183496546	0.889115213	2.294381333
Osogbo TS	-19.36353569	0.409038829	-19.77257452

GS: Generation Station; TS: Transmission Station

Table 4.3 represents the various angles at each bus and their changes in degree. Table 4.4 presents the summary of the results gotten from PSAT/MATLAB simulation considering five numbers of line outages which shows abrupt change in angles. Appendix F represents Matlab script used in achieving the results. Enorm represent the normalised echeleon reduce ranking form of change in impedance value, while Theta represent the normalised angles in degrees. Figures 4.5 to 4.7 show the graphical representation of results for effective line outage detection in south west region of Nigeria 330kV transmission lines. Appendixes G and H show the load flow result and signal profiles when the system was stable while Appendix I shows the graphical representation of the network considered for optimal placement of PMU.

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Table 4.4. MALTAB Simulation Result

Ikeja-Osogbo												
Echeleon Normalised		0.0746	0.0562	0.1522	0.1522	0.1522	0.7515	0.0424	0.0424	0.0424	0.0827	0.6051
Theta		0.1251	0.035	0.1151	0.1164	0.1164	0.6169	0.0375	0.0375	0.0375	0.1214	0.737
Olorunsogo-Ayede												
Echeleon Normalised		0.0445	0.4297	0.0445	0.0445	0.0445	0.0445	0.695	0.0445	0.0445	0.0445	0.4297
Theta		0.0366	0.128	0.0347	0.0933	0.1222	0.0945	-0.6211	0.0365	0.0366	0.0366	0.128
Sakete-Ikeja												
Echeleon Normalised		0.0558	0.0399	0.1079	0.7579	0.1079	0.5689	0.0301	0.0301	0.0301	0.0587	0.2603
Theta		0.0367	0.0394	0.1659	0.854	0.1659	0.1741	0.0326	0.0326	0.0326	0.3671	0.2108

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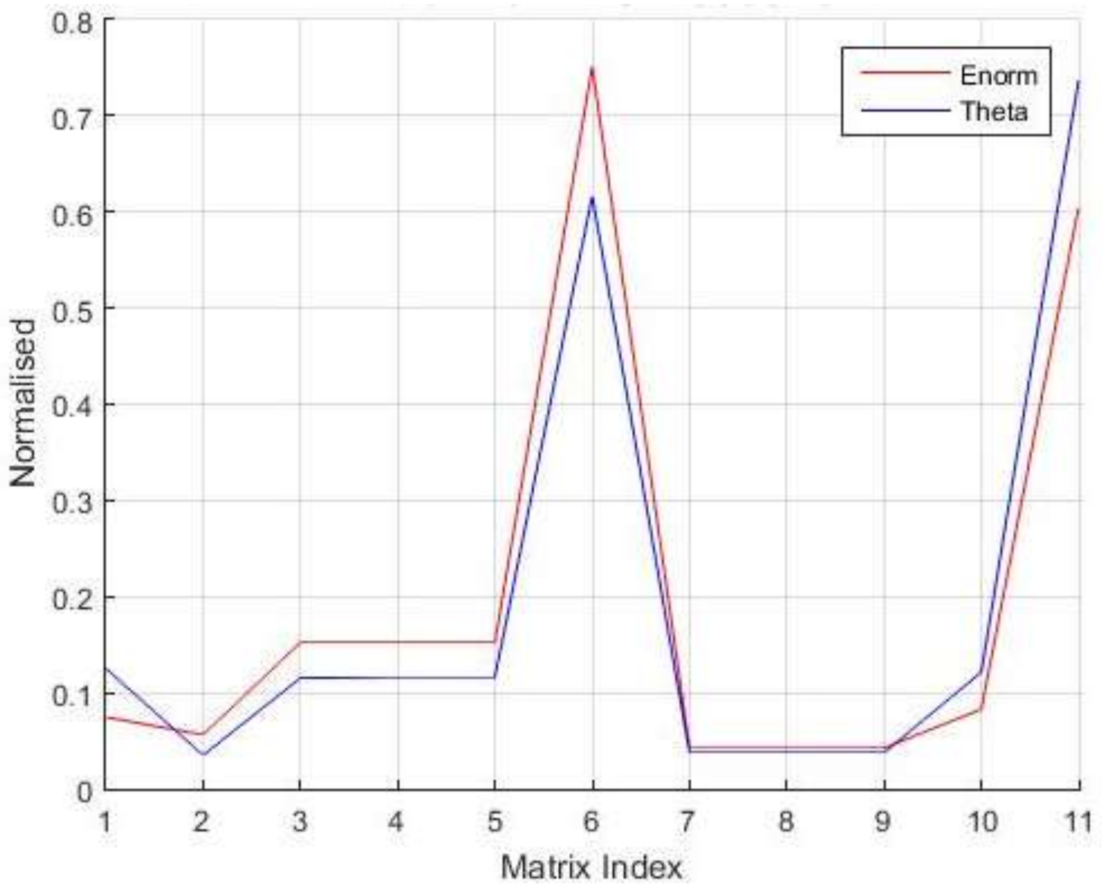

Figure 4.5. Plot of E-Normalised (Change in Impedance) and Normalised Theta (change in angle) against Matrix index representing Ikeja West – Osogbo line

4.2 Discussion

Based on the plot of various lines outages considered for this study, the blue graph gotten from the online analysis almost matches closely with the echeleon normalised red graph (i.e., off line analysis), which shows the effective line outage detection when PMU is placed at various buses within the south west region.

Figure 4.5 represents the modelled line outage for Ikeja-Osogbo. The red line almost matches closely with the blue lines. At buses 7, 8, and 9 the line experience the closes match. This signifies that PMU has the ability to identify the change in line flows or bus voltage angles when there is a disturbance or contingencies in the system.

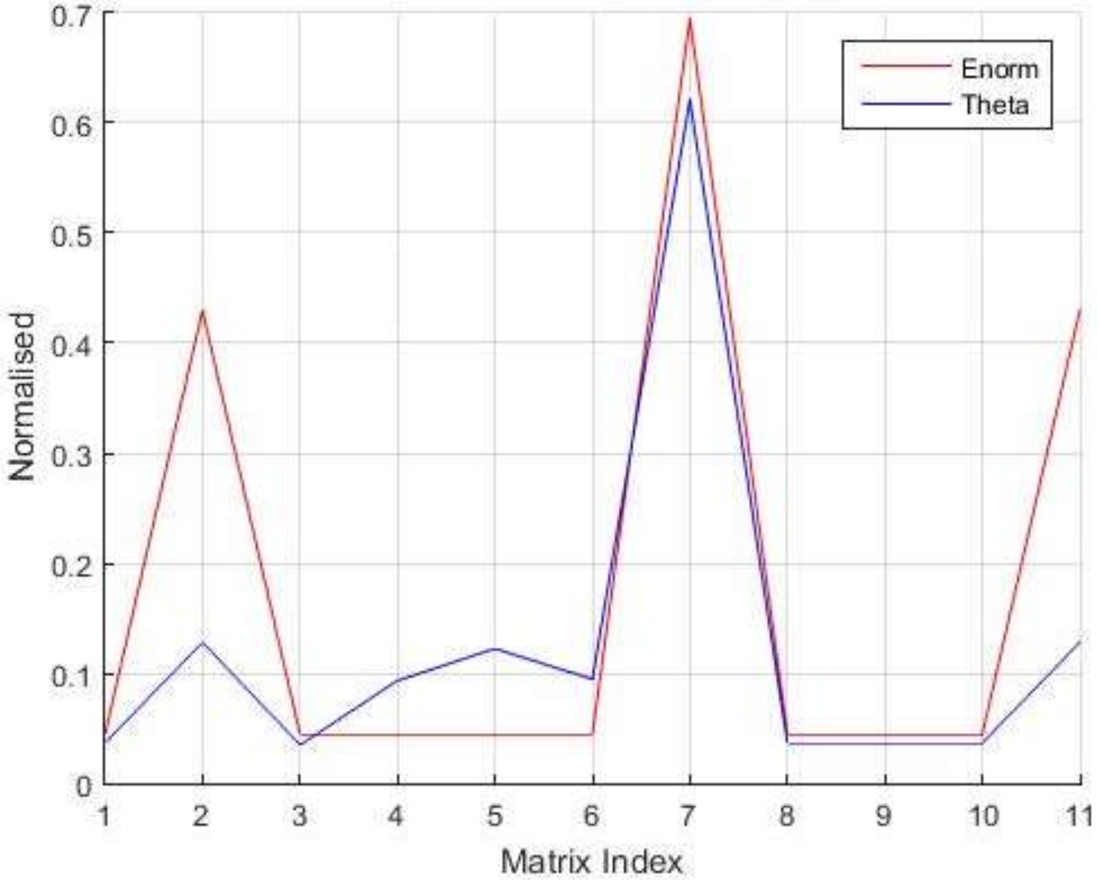

Figure 4.6. Plot of E-Normalised (Change in Impedance) and Normalised Theta (change in angle) against Matrix index representing Ayede-Olorunsogo line

Figure 4.6 represent the modelled line outage for Ayede to Olorunsogo. The red line also follows the same pattern with the blue line and has the greatest match at bus 1, 8, 9 and 10.

Figure 4.7 representing Ikeja to Sakete line has a close match at bus 2, 7, 8, and 9. From analysis the various lines that were on outage can be observed by more than one bus having PMU, this also proved that there is a complete observabilty when a line is on outage. Other lines like Akangba to Ikeja been a double circuit did not converge due to zero change in angle.

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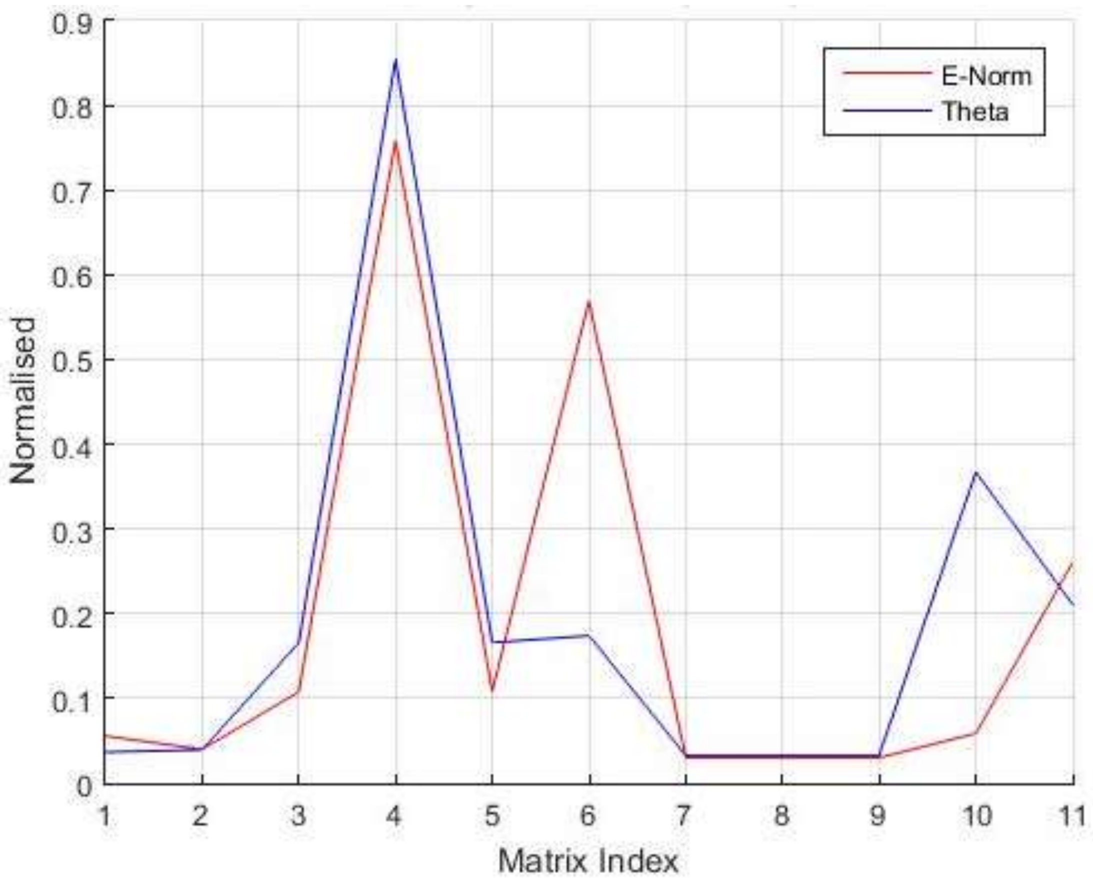

Figure 4.7. Plot of E-Normalised (Change in Impedance) and Normalised Theta (change in angle) against Matrix index representing Sakete-Ikeja West line

The theta-norm is simply the normalised vector of change in bus voltage angles obtained from PMUs installed in the system and e-norm is the normalised vector of change in impedance matrix. The X-axis of the graph represents the normalised values of vectors corresponding to offline and online analysis and Y-axis represents the index value of these vectors

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CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This thesis discusses the analysis of single line outages using PMU data's considering south west region of Nigeria as a case study. With the analysis done so far it can been seen that PMU has the ability to identify single line outages when introduced in our National Grid. Figures 4.5, 4.6 and 4.7 represent the various line outage model; the red lines almost lapped with the blue lines in the entire sample carried out. They all followed repeated pattern i.e., the red and the blue line for their respective model. This clearly shows that PMU has the ability to identify the change in line flows or bus voltage angles when there is a disturbance or contingencies in the system. This work has also presented the important role of PMU in line outage detection compared to other existing systems such like SCADA which does not provide complete situational awareness such as detection of line outage. But with deployment of PMUs in the system, even with incomplete observability, applications using PMU data can be created to detect the line outage.

In order to identify a line outage correctly, a simulation of loading and generation condition must have already been simulated to correlate the line outage with peculiar changes i.e. difference in bus voltage angle and change in impedance matrix. The methodology discussed did not consider transmission line power flow due to the complexity involved in calculation but requires only the bus voltage angle and system topology for single line outage detection.

To this end, it can be said that the objectives and aim of this study have been achieved. For a better, improved reliability and efficiency, introducing PMU into the national grid will reduce the number of outages to minimal and mean time to failure, because with the known.

5.2 Recommendations

Based on the deductions from the analysis of data collected from TCN, Osogbo over the period of this study, the following recommendations are made.

(a) The present data recording system should be improved from manual to automated form. An improvement needs to be made in this area, because a wrong data will surely give a deviation from the expected result.

(b) More research work needs to be done in this area, because it seems (Nigerian's) are lagging behind from the numbers of literature reviewed on in this study.

5.3 Further Studies

As it is well known in many research works especially a new area such as this that every aspect cannot be fully covered, there are still more that can be done hence the future work could include:

(a) multiple lines outages on Nigeria 330kV lines and also on our Distribution Network which are very prone to unplanned outages;

(b) modernising Nigerian Transmission Grid using PMU; and

(c) two or more sophisticated software such as MATPOWER and POWER WORLD should be used to compare and verify results from the lead software in the near future.

5.4 Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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APPENDIX

Appendix A. A Typical Generator Data as Collected`

Station	Nomenclature	Type	Rating (MVA)	Terminal Voltage (kV)	Rated PF (PU)
Okpai	GT1	Gas	210	15.75+/-5%	0.85
	GT2	Gas	210	15.75+/-5%	0.85
	ST1	Steam	210	15.75+/-5%	0.85
Delta I	GT1	Gas	45		
	GT2	Gas	45		
Delta II	GT3	Gas	29.725	11.5 +/-5%	0.8
	GT4	Gas	29.725	11.5 +/-5%	0.8
	GT5	Gas	29.725	11.5 +/-5%	0.8
	GT6	Gas	29.725	11.5 +/-5%	0.8
	GT7	Gas	29.725	11.5 +/-5%	0.8
	GT78	Gas	29.725	11.5 +/-5%	0.8
Delta III	GT9	Gas	29.725	11.5 +/-5%	0.8
	GT10	Gas	29.725	11.5 +/-5%	0.8
	GT11	Gas	29.725	11.5 +/-5%	0.8
	GT12	Gas	29.725	11.5 +/-5%	0.8
	GT13	Gas	29.725	11.5 +/-5%	0.8
	GT14	Gas	29.725	11.5 +/-5%	0.8
Delta IV	GT15	Gas	133.75	11.5 +/-5%	0.85
	GT16	Gas	133.75	11.5 +/-5%	0.85
	GT17	Gas	133.75	11.5 +/-5%	0.85
	GT18	Gas	133.75	11.5 +/-5%	0.85
	GT19	Gas	133.75	11.5 +/-5%	0.85
	GT20	Gas	133.75	11.5 +/-5%	0.85
Sapele	ST1	Steam	133.97	15.75+/-5%	0.9
	ST2	Steam	133.97	15.75+/-5%	0.9
	ST3	Steam	133.97	15.75+/-5%	0.9
	ST4	Steam	133.97	15.75+/-5%	0.9
	ST5	Steam	133.97	15.75+/-5%	0.9
	ST6	Steam	133.97	15.75+/-5%	0.9
	GT1	Gas	110	10.5+/-7.5%	0.8
	GT2	Gas	110	10.5+/-7.5%	0.8
	GT3	Gas	110	10.5+/-7.5%	0.8
	GT4	Gas	110	10.5+/-7.5%	0.8
Egbin	ST1	Steam	245.8	16	0.9
	ST2	Steam	245.8	16	0.9
	ST3	Steam	245.8	16	0.9
	ST4	Steam	245.8	16	0.9
	ST5	Steam	245.8	16	0.9
	ST6	Steam	245.8	16	0.9

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Appendix A. A Typical Generator Data as Collected (Continuation)

Station	Nomenclature	Type	Rating (MVA)	Terminal Voltage (kV)	Rated PF (PU)
Aes	GT 1	Gas	38.6	10.5	0.8
	GT 2	Gas	38.6	10.5	0.8
	GT 3	Gas	38.6	10.5	0.8
	GT 4	Gas	39.54	10.5	0.8
	GT 5	Gas	39.54	10.5	0.8
	GT 6	Gas	39.54	10.5	0.8
	GT 7	Gas	40.5	10.5	0.9
	GT 8	Gas	40.5	10.5	0.9
	GT 9	Gas	40.5	10.5	0.9
Jebba	2G1	Hydro	119	16	0.85
	2G2	Hydro	119	16	0.85
	2G3	Hydro	119	16	0.85
	2G4	Hydro	119	16	0.85
	2G5	Hydro	119	16	0.85
	2G6	Hydro	119	16	0.85
Kainji	1G5	Hydro	126	16	0.95
	1G6	Hydro	126	16	0.95
	1G7	Hydro	85	16	0.95
	1G8	Hydro	85	16	0.95
	1G9	Hydro	85	16	0.95
	1G10	Hydro	85	16	0.95
	1G11	Hydro	115	16	0.95
	1G12	Hydro	115	16	0.95
Shiroro	UNIT1	Hydro	176.5	15.65	0.85
	UNIT2	Hydro	176.5	15.65	0.85
	UNIT3	Hydro	176.5	15.65	0.85
	UNIT4	Hydro	176.5	15.65	0.85
Afam I	GT1	Gas	16	10.5 ±7.5	0.8
	GT2	Gas	16	10.5 ±7.5	0.8
	GT3	Gas	25	10.5 ±7.5	0.8
	GT4	Gas	25	10.5 ±7.5	0.8
Afam II	GT5	Gas	30	10.5 ±7.5	0.8
	GT6	Gas	30	10.5 ±7.5	0.8
	GT7	Gas	30	10.5 ±7.5	0.8
	GT8	Gas	30	10.5 ±7.5	0.8
Afam III	GT9	Gas	34	10.5 ±7.5	0.8
	GT10	Gas	34	10.5 ±7.5	0.8
	GT11	Gas	34	10.5 ±7.5	0.8
	GT12	Gas	34	10.5 ±7.5	0.8

Appendix A. A Typical Generator Data as Collected (Continuation)

Station	Nomenclature	Type	Rating (MVA)	Terminal Voltage (kV)	Rated PF (PU)
Afam IV	GT13	Gas	110	10.5 ±7.5	0.8
	GT14	Gas	110	10.5 ±7.5	0.8
	GT15	Gas	110	11.5± 5	0.8
	GT16	Gas	110	11.5± 5	0.8
	GT17	Gas	110	11.5± 5	0.8
	GT18	Gas	110	11.5± 5	0.8
Afam V	GT19	Gas	162.69	15.75± 5	0.85
	GT20	Gas	162.69	15.75± 5	0.85
Papalanto	GT1	Gas	48	10.5	0.8
	GT2	Gas	48	10.5	0.8
	GT3	Gas	48	10.5	0.8
	GT4	Gas	48	10.5	0.8
	GT5	Gas	48	10.5	0.8
	GT6	Gas	48	10.5	0.8
	GT7	Gas	48	10.5	0.8
	GT8	Gas	48	10.5	0.8
Omotoso	GT1	Gas	47.5	10.5+/-5%	0.8
	GT2	Gas	47.5	10.5+/-5%	0.8
	GT3	Gas	47.5	10.5+/-5%	0.8
	GT4	Gas	47.5	10.5+/-5%	0.8
	GT5	Gas	47.5	10.5+/-5%	0.8
	GT6	Gas	47.5	10.5+/-5%	0.8
	GT7	Gas	47.5	10.5+/-5%	0.8
	GT8	Gas	47.5	10.5+/-5%	0.8
Geregu	GT1	Gas	174	15.75+/-5%	0.85
	GT2	Gas	174	15.75+/-5%	0.85
	GT3	Gas	174	15.75+/-5%	0.85
Alaoji	GT1	Gas	141.25	15	0.85
	GT2	Gas	141.25	15	0.85
	GT3	Gas	141.25	15	0.8
Calabar	Unit1	Gas	141.25	15	0.8
	Unit2	Gas	141.25	15	0.8
	Unit3	Gas	141.25	15	0.8
	Unit4	Gas	141.25	15	0.8
	Unit5	Gas	141.25	15	0.8
Egbema	Unit1	Gas	141.25	15	0.8
	Unit2	Gas	141.25	15	0.8
	Unit3	Gas	141.25	15	0.8

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Appendix A. A Typical Generator Data as Collected (Continuation)

Station	Nomenclature	Type	Rating (MVA)	Terminal Voltage (kV)	Rated PF (PU)
Eyaen	Unit1	Gas	141.25	15	0.8
	Unit2	Gas	141.25	15	0.8
	Unit3	Gas	141.25	15	0.8
	Unit4	Gas	141.25	15	0.8
Gbaran	Unit1	Gas	141.25	15	0.8
	Unit2	Gas	141.25	15	0.8
Ikot Abasi	Unit1	Gas	141.25	15	0.8
	Unit2	Gas	141.25	15	0.8
	Unit3	Gas	141.25	15	0.8
Sapele	Unit1	Gas	141.25	15	0.8
	Unit2	Gas	141.25	15	0.8
	Unit3	Gas	141.25	15	0.8
	Unit4	Gas	141.25	15	0.8
Omoku	Unit1	Gas	141.25	15	0.8
	Unit2	Gas	141.25	15	0.8
Alaoji	Gt4	Gas	126 MW	15	0.8
	St1	Steam	285 MW	17	0.85
	St2	Steam	285 MW	17	0.85
Geregu			148 MW		
			148 MW		
			148 MW		
Omotoso			126 MW		
			126 MW		
			126 MW		
			126 MW		
Papalanto			126 MW		
			126 MW		
			126 MW		
			126 MW		
Afam Vi (Shell)			150 MW		
			150 MW		
			150 MW		
			150 MW		
			150 MW		
Bonny (Mobil)			130 MW		
			130 MW		
			130 MW		
Chevron-Texaco			250 MW		
			250 MW		
			250 MW		

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Appendix A. A Typical Generator Data as Collected (Continuation)

Station	Nomenclature	Type	Rating (MVA)	Terminal Voltage (kV)	Rated PF (PU)
TotalFinaelf (1&2)			125 MW		
			125 MW		
			125 MW		
			125 MW		
Ethiope			2800 MW		
Farm Electric			150 MW		
ICS Power			600 MW		
Supertek			1000 MW		
Alscon			90 MW		
			90 MW		
			90 MW		
			90 MW		
			90 MW		
			90 MW		
Ibom Power I			38 MW		
			38 MW		
			112 MW		
Ibom Power Ii			500 MW		
Omoku (Rivers State)			100 MW		

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Appendix B. A Typical Generator Transformer Data as Collected

Station	**Ratings(MVA)**	**V_{rated}(kV)**
Delta	54/72/81	138/11.5/11.5/11.5
	45/81	138/11.5/11.5/11.5
	54/72/81	138/11.5/11.5/11.5
	54/72/81	138/11.5/11.5/11.5
	45/81	138/11.5/11.5/11.5
	54/72/81	138/11.5/11.5/11.5
Delta IV	72/96/120	345/11.5
	72/96/120	345/11.5
	72/96/120	345/11.5
	72/96/120	345/11.5
	72/96/120	345/11.5
	72/96/120	345/11.5
Delta	90/120/150	330/132
Sapele	90/140	345/15.75
	90/140	345/15.75
	90/140	345/15.75
	90/140	345/15.75
	105/14O	345/15.75
	105/14O	345/15.75
	126/168.5	345/10.5
	126/168.5	345/10.5
Okpai	140/205	330/15.75
	140/205	330/15.75
	140/205	330/15.75
	140/205	330/15.75
Afam PS	109/168	10.5/345
	109/168	10.5/345
	109/168	10.5/345
	109/168	10.5/345
	109/168	10.5/345
	109/168	10.5/345
	163	15.7/345
	163	15.7/345
	162	330/132
Jebba GS	119	16/330
	119	16/330
	119	16/330
	119	16/330
	119	16/330
	119	16/330
Kainji GS	145	16/330
	145	16/330
	184	16/330
	183.6	16/330
	115	16/330
	115	16/330
Shiroro GS	200	15.2/330
	200	15.2/330
	200	15.2/330
	200	15.2/330

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Appendix B. A Typical Generator Transformer Data as Collected (Continuation)

Station	Ratings(MVA)	V_{rated}(kV)
Egbin GS	270	16/330
	270	16/330
	270	16/330
	270	16/330
	270	16/330
	270	16/330
AES	60	10.5/132
	40	11.5/132
	40	11.5/132
	40	11.5/132
Egbin GS	150	330/132/33
Geregu	168	345/15.75
	168	345/15.75
	168	345/15.75
Omotosho	105	346.5/10.5
	105	346.5/10.5
	105	346.5/10.5
	105	346.5/10.5
	150	330/132/33
Papalanto	346.5	10.5/330
	346.5	10.5/330
	346.5	10.5/330
	346.5	10.5/330
Alaoji	102/136/170	15/330kV
Gbaran NIPP	90/143	139/15
	90/143	139/15
Calabar	90/143	343/15
	90/143	343/15
	90/143	343/15
	90/143	343/15
	90/143	343/15
Egbema	90/143	343/15
	90/143	343/15
	90/143	343/15
Ihovbor	90/143	343/15
	90/143	343/15
	90/143	343/15
	90/143	343/15
Ikot Abasi	90/143	343/15
	90/143	343/15
	90/143	343/15
Sapele	90/143	343/15
	90/143	343/15
	90/143	343/15
	90/143	343/15
Omoku	90/143	343/15
	90/143	343/15

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APPENDIX C. Transmission Line Parameter Data as collected

kV	Name	Length (km)	Type (DC/SC)	Conductor Name	Conductors Per Phase	Conductor Cross-Section (mm^2)	Zc (Ω)	R_1		X_1	
								(Ω/km)	pu	(Ω/km)	pu
330	Afam – Alaoji	25	DC	Bison	2	2x350	300	*0.392*	*0.009*	0.3049	0.007
330	Afam - Ikot Ekpene	90	DC	Bison	2	2x350	300	0.0394		0.303	
330	Aja – Alagbon	26	DC	Bison	2	2x350	300	0.0394		0.303	
330	Aja – Egbin	14	DC	Bison	2	2x350	300	0.17113	0.0022	1.3379	0.0172
330	Ajaokuta - Geregu	5	DC	Bison	2	2x350	300	0.0394		0.303	
330	Ajaokuta - Lokoja	38	DC	Bison	2	2x350	300	0.0394		0.303	
330	Alagbon – Aja	26	DC	Bison	2	2x350	300	0.0394		0.303	
330	Alaoji - Ikot Ekpene	38	DC	Bison	2	2x350	300	0.0394		0.303	
330	Alaoji – Afam	25	DC	Bison	2	2x350	300	*0.392*	*0.009*	0.303	0.007
330	Makurdi -Ugwuaji	150	DC	Bison	2	2x350	300	0.0394		0.303	
330	Benin – Sapele	50	DC	Bison	2	2x350	300	0.0392	0.0018	0.3027	0.0139
330	Egbin – Aja	14	DC	Bison	2	2x350	300	0.17113	0.0022	1.3379	0.0172
330	Egbin - Ikeja West	62	DC	Bison	2	2x350	300	0.03864	0.0022	0.3021	0.0172
330	Gwagwalada – Katampe	30	DC	Bison	2	2x350	300	0.0394		0.303	
330	Gwagwalada – Lokoja	140	DC	Bison	2	2x350	300	0.0394		0.303	
330	Gwagwalada - Shiroro	114	SC	Bison	2	2x350	300	0.0394		0.303	
330	Ikeja West - Egbin	62	DC	Bison	2	2x350	300	0.03864	0.0022	0.3021	0.0172
330	Ikot Ekpene –Ugwuaji	143	DC	Bison	2	2x350	300	0.0394		0.303	
330	Ikot Ekpene –Ugwuaji	143	DC	Bison	2	2x350	300	0.0394		0.303	
330	Jebba – Kainji	81	DC	Bison	2	2x350	300	0.03899	0.0029	0.3307	0.0246
330	Jebba Ts - Jebba Gs	8	DC	Bison	2	2x350	300	0.04084	0.0003	0.2995	0.0022
330	Jos – Makurdi	230	DC	Bison	2	2x350	300	0.0394		0.303	

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APPENDIX C. Transmission Line Parameter Data as collected (Continuation)

kV	Name	Length (km)	Type (DC/SC)	Conductor Name	Conductors Per Phase	Conductor Cross-Section (mm^2)	Zc (Ω)	R_1		X_1	
								(Ω/km)	pu	(Ω/km)	pu
330	Kainji – Jebba	81	DC	Bison	2	2x350	300	0.03899	0.0029	0.3307	0.0246
330	Katampe - Gwagwalada	30	DC	Bison	2	2x350	300	0.0394		0.303	
330	Katampe - Shiroro*	144	DC	Bison	2	2x350	300	0.0394		0.303	
330	Lokoja - Ajaokuta	38	DC	Bison	2	2x350	300	0.0394		0.303	
330	Lokoja – Gwagwalada	140	DC	Bison	2	2x350	300	0.0394		0.303	
330	Makurdi - Aliade	50	DC	Bison	2	2x350	300	0.0394		0.303	
330	Makurdi – Jos	230	DC	Bison	2	2x350	300	0.0394		0.303	
330	New Haven – Ugwuaji	5	DC	Bison	2	2x350	300	0.0394		0.303	
330	Ugwuaji - Aliade	150	DC	Bison	2	2x350	300	0.0394		0.303	
330	Ugwuaji - Ikot Ekpene	143	DC	Bison	2	2x350	300	0.0394		0.303	
330	Ugwuaji - Ikot Ekpene	143	DC	Bison	2	2x350	300	0.0394		0.303	
330	Okpai - Onitsha	80	DC	Bison	2	2x350	300	0.12251	0.009	0.0953	0.007
330	Sapele – Benin	50	DC	Bison	2	2x350	300	0.0392	0.0018	0.3027	0.0139
330	Shiroro – Gwagwalada	114	DC	Bison	2	2x350	300	0.0394		0.303	
330	Shiroro - Katampe*	144	DC	Bison	2	2x350	300	0.0394		0.303	
330	Ajaokuta - Benin North	195	SC	Bison	2	2x350	300	0.039		0.331	
330	Ajaokuta - Benin North	195	SC	Bison	2	2x350	300	0.039		0.331	
330	Shiroro - Jebba	244	SC	Bison	2	2x350	300	0.0299	0.0067	0.3133	0.0702
330	Shiroro - Jebba	244	SC	Bison	2	2x350	300	0.0299	0.0067	0.3133	0.0702
330	Ajaokuta - Benin	195	SC	Bison	2	2x350	300	0.03909	0.007	0.3127	0.056
330	Ajaookuta - Benin	195	SC	Bison	2	2x350	300	0.03909	0.007	0.3127	0.056
330	Akangba - Ikeja West	18	SC	Bison	2	2x350	300	0.1331	0.0022	1.0406	0.0172

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APPENDIX C. Transmission Line Parameter Data as collected (Continuation)

kV	Name	Length (km)	Type (DC/SC)	Conductor Name	Conductors Per Phase	Conductor Cross-Section (mm^2)	Zc (Ω)	R_1		X_1	
								(Ω/km)	pu	(Ω/km)	pu
330	Akangba - Ikeja West	18	SC	Bison	2	2x350	300	0.1331	0.0022	1.0406	0.0172
330	Aladja - Delta*	32	SC	Bison	2	2x350	300	0.07827	0.0023	0.6466	0.019
330	Aladja – Sapele	63	SC	Bison	2	2x350	300	0.03976	0.0023	0.3384	0.019
330	Alaoji - Onitsha	138	SC	Bison	2	2x350	300	*0.3867*	*0.049*	0.3306	0.0419
330	Ayede - Ikeja West	137	SC	Bison	2	2x350	300	0.03895	0.0049	0.3307	0.0416
330	Ayede – Osogbo	115	SC	Bison	2	2x350	300	0.03883	0.0041	0.3305	0.0349
330	Benin - Ajaokuta	195	SC	Bison	2	2x350	300	0.03909	0.007	0.3127	0.056
330	Benin - Ajaokuta	195	SC	Bison	2	2x350	300	0.03909	0.007	0.3127	0.056
330	Benin – Delta	107	SC	Bison	2	2x350	300	0.02341	0.0023	0.1934	0.019
330	Benin – Egbin	218	SC	Bison	2	2x350	300	0.039		0.331	
330	Benin - Omotoso	120	SC	Bison	2	2x350	300	0.039		0.331	
330	Benin – Onitsha	137	SC		2	2x350	300	0.03895	0.0049	0.3307	0.0416
330	Benin – Osogbo	251	SC	Bison	2	2x350	300	0.03861	0.0089	0.331	0.0763
330	Benin – Sapele	50	SC	Bison	2	2x350	300	0.0392	0.0018	0.3027	0.0139
330	Ihovbor – Benin	20	SC	Bison	2	2x350	300	0.039		0.331	
330	Birnin Kebbi – Kainji	310	SC	Bison	2	2x350	300	0.03899	0.0111		0.0942
330	Delta – Aladja	32	SC	Bison	2	2x350	300	0.07827	0.0023		0.019
330	Delta – Benin	107	SC	Bison	2	2x350	300	0.02341	0.0023		0.019
330	Egbin – Benin	218	SC	Bison	2	2x350	300	0.039		0.331	
330	Egbin - Erunkan	30	SC	Bison	2	2x350	300	0.039		0.331	
330	Egbin - Ikeja West	62	SC	Bison	2	2x350	300	0.039		0.331	
330	Gombe - Damaturu	160	SC	Bison	2	2x350	300	0.039		0.331	

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APPENDIX C. Transmission Line Parameter Data as collected (Continuation)

kV	Name	Length (km)	Type (DC/SC)	Conductor Name	Conductors Per Phase	Conductor Cross-Section (mm^2)	Zc (Ω)	R_1		X_1	
								(Ω/km)	pu	(Ω/km)	pu
330	Gombe – Jos	265	SC	Bison	2	2x350	300	0.03904	0.0095	0.3329	0.081
330	Gombe – Yola	240	SC	Bison	2	2x350	300	0.039		0.331	
330	Ikeja West – Akangba	18	SC	Bison	2	2x350	300		0.0022	1.0406	0.0172
330	Ikeja West – Akangba	18	SC	Bison	2	2x350	300		0.0022	1.0406	0.0172
330	Ikeja West - Egbin	62	SC	Bison	2	2x350	300	0.039		0.331	
330	Ikeja West – Omotoso	160	SC	Bison	2	2x350	300	0.039		0.331	
330	Ikeja West – Osogbo	252	SC	Bison	2	2x350	300	0.02118	0.0049	0.1798	0.0416
330	Jebba - Shiroro	244	SC	Bison	2	2x350	300	0.0299	0.0067	0.3133	0.0702
330	Jebba - Shiroro	244	SC	Bison	2	2x350	300	0.0299	0.0067	0.3133	0.0702
330	Jos – Gombe	265	SC	Bison	2	2x350	300	0.03904	0.0095	0.3329	0.081
330	Kaduna – Jos	197	SC	Bison	2	2x350	300	0.0387	0.007	0.3311	0.0599
330	Kaduna – Kano	230	SC	Bison	2	2x350	300	0.03883	0.0082	0.331	0.0699
330	Kaduna - Shiroro	96	SC	Bison	2	2x350	300	0.03857	0.0034	0.3312	0.0292
330	Kaduna - Shiroro	96	SC	Bison	2	2x350	300	0.03857	0.0034	0.3312	0.0292
330	Kainji - Birnin Kebbi	310	SC	Bison	2	2x350	300	0.03899	0.0111	0.3309	0.0942
330	Kano – Kaduna	230	SC	Bison	2	2x350	300	0.03883	0.0082	0.331	0.0699
330	Maiduguri – Damaturu	260	SC	Bison	2	2x350	300	0.039		0.331	
330	New Haven – Onitsha	96	SC	Bison	2	2x350	300		0.003	0.3312	0.0292
330	Omotosho - Benin	120	SC	Bison	2	2x350	300	0.039		0.331	
330	Omotoso - Ikeja West	160	SC	Bison	2	2x350	300	0.039		0.331	
330	Onitsha - Alaoji	138	SC	Bison	2	2x350	300	*0.3867*	*0.049*	0.3306	0.0419
330	Onitsha – Benin	137	SC	Bison	2	2x350	300	0.03895	0.0049	0.3307	0.0416

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APPENDIX C. Transmission Line Parameter Data as collected (Continuation)

kV	Name	Length (km)	Type (DC/SC)	Conductor Name	Conductors Per Phase	Conductor Cross-Section (mm²)	Zc (Ω)	R_1		X_1	
								(Ω/km)	pu	(Ω/km)	pu
330	Onitsha – Benin	137	SC	Bison	2	2x350	300	0.039		0.331	
330	Onitsha - New Haven	96	SC	Bison	2	2x350	300	0.03857	0.003	0.3312	0.0292
330	Osogb - Ihovbor	251	SC	Bison	2	2x350	300	0.03861	0.0089	0.331	0.0763
330	Osogb - Ikeja West	252	SC	Bison	2	2x350	300	0.02118	0.0049	0.1798	0.0416
330	Osogbo – Ayede	115	SC	Bison	2	2x350	300	0.03883	0.0041	0.3305	0.0349
330	Osogbo – Ganmo	87	SC	Bison	2	2x350	300	0.039		0.331	
330	Osogbo – Jebba	157	SC	Bison	2	2x350	300	0.03884	0.0056	0.3309	0.0477
330	Osogbo – Jebba	157	SC	Bison	2	2x350	300	0.03884	0.0056	0.3309	0.0477
330	Olorunsogo – Ayede	60	SC	Bison	2	2x350	300	0.039		0.331	
330	Olorunsogo - Ikeja West	30	SC	Bison	2	2x350	300	0.039		0.331	
330	Sakete - Ikeja West		SC	Bison	2	2x350	300	0.039		0.331	
330	Sapele - Aladja	63	SC	Bison	2	2x350	300	0.03976	0.0023	0.3284	0.019
330	Sapele - Benin	50	SC	Bison	2	2x350	300	0.0392	0.0018	0.3027	0.0139
330	Shiroro - Kaduna	96	SC	Bison	2	2x350	300	0.03857	0.0034	0.3312	0.0292
330	Shiroro - Kaduna	96	SC	Bison	2	2x350	300	0.03857	0.0034	0.3312	0.0292

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Appendix D. A Typical Load Data as Collected for a Period of 4 Months (January – April, 2017)

Appendix D1. January 2017 Load Flow Data

Name of Bus	1st Week (MW)			2nd Week (MW)			3rd Week(MW)			4th Week (MW)			Total (MW)	Arg (MW)
Lagos	804	785	644	755	800	807	336	711	452	623	441	651	7809	650.75
Kaduna	112	135	196	125	91	133	72	87	113	138	100	158	1460	121.67
Kano	151	132	110	144	154	145	179	130	102	108	87	83	1525	127.08
Yola	14	25	32	16	18	15	4	22	9	12	11	7	185	15.417
Jos	57	86	75	30	37	27	25	37	24	28	38	30	494	41.167
Gombe	68	58	90	97	66	101	19	91	22	32	30	53	727	60.583
Shiroro	33.5	20	32.8	35.7	72	51.9	12	47	5	30	27.4	49	416.3	34.692
Aiyede	140	134	145	88	90	94	58	110	90	80	100	110	1239	103.25
Osogbo	141.7	95.6	130.1	149	136.9	141.8	128.2	111.2	119	163	92	116	1524	127
Ganmo	33	33	39.5	41	50.5	33	47	29	38	15	29.5	21	409.5	34.125
Benin	164.4	111.3	127.5	141	135.1	124.9	85.3	125.7	106	139	99.7	158.5	1519.3	126.61
Effurun	9.5	42.4	47.1	68.7	59.9	67.5	66.6	55.6	26.8	45.3	32.4	32.9	554.7	46.225
Onitsha	115	118	100	142	116	133	37	73	46	54	69	98	1101	91.75
Alaoji	259.6	273.2	281.2	340	267.5	323.6		312	42.3	205	109.3	245.6	2659.5	241.77
New Haven	70	60	78	106	88	114	26	72	46	42	56	84	842	70.167
Jebba	6.7	12	17	18.7	2.3	14.2	8.1	7	15.9	9.8	16.2	9.2	137.1	11.425
Birnin Kebbi	102	118	93	119	102	131	110	126	74	88	93	99	1255	104.58
Sakate	152	156	146	80	146	79		104	35.5	100	100	112	1210.5	110.05
Katampe	218.9	261.8	260.2	173	151.5	248.7	53.9	228.7	138	176	215.9	161.8	2289.1	190.76

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Appendix D2. February 2017 Load Flow Data

Name of Bus	1st Week (MW)			2nd Week (MW)			3rd Week(MW)			4th Week (MW)			Total (MW)	Arg (MW)
Lagos	803	1007	987	910	1075	1014	1024	884	1081	988	940	598	11311	942.58
Kaduna	188	225	138	278	277	212	269	170	271	190	185	278	2681	223.42
Kano	264	278	255	208	258	243	263	196	303	143	256	292	2959	246.58
Yola	49	47	38	58	47	36	62	35	45	31	52	47	547	45.583
Jos	80	77	86	95	110	76	124	78	84	112	87	114	1123	93.583
Gombe	105	138	110	124	124	90	122	103	128	71	120	127	1362	113.5
Shiroro	84	81	66	92	72	60	92	84	56	84	101	31	903	75.25
Aiyede	194	197	190	182	164	140	160	130	180	154	174	168	2033	169.42
Osogbo	75.2	194.2	156.3	191	153.4	145.6	196.1	112.6	183	136	185.9	127.2	1856.7	154.73
Ganmo	43	53	43	29	57	39	43	51	54	35	57	32	536	44.667
Benin	139.1	145.5	123.4	184	149.2	136.6	168.3	131.1	129	154	165.5	125.7	1750.4	145.87
Effurun	77.4	71.6	68.2	54.2	53.8	63.9	99.5	84.2	83.7	43.9	67.7	60.4	828.5	69.042
Onitsha	119	140	123	184	153	112	124	128	136	105	140	103	1567	130.58
Alaoji	412	403.3	384.2	164	391.7	283.5	317.9	288.4	272	288	357.6	264.2	3827.1	318.93
New Haven	94	170	146	164	128	118	152	140	146	96	132	126	1612	134.33
Jebba	12	6.5	11.9	13.4	10	16.8	9.2	14.2	15.9	15	3.8	14.4	143.1	11.925
Birnin Kebbi	146	180	150	185	163	163	183	174	175	163	180	169	2031	169.25
Sakate	188	177	198	202	194	188	194	189	177	193	203	196	2299	191.58
Katampe	309	336.5	291.2	354	324.4	316.5	387.2	364.1	335	290	323.9	284.7	3916.4	326.37

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Appendix D3. March 2017 Load Flow Data

Name of Bus	1st Week (MW)			2nd Week (MW)			3rd Week(MW)			4th Week (MW)			Total (MW)	Arg (MW)
Lagos	343	942	762	886	670	874	716	973	725	694	624	851	9060	755
Kaduna	194	235	175	220	173	262	274	266	244	236	179	250	2708	225.7
Kano	257	250	260	280	303	306	290	303	300	274	239	256	3318	276.5
Yola	24	49	61	57	46	67	58	64	58	65	63	51	663	55.25
Jos	71	100	97	64	80	92	65	97	72	128	98	79	1043	86.92
Gombe	91	150	113	103	105	130	97	115	66	90	147	131	1338	111.5
Shiroro	80	105	62	82	73	89	27	58	49	108	98	100	931.2	77.6
Aiyede	130	16	60	139	50	166	120	174	144	62	90	136	1287	107.3
Osogbo	148.5	129	96.6	192	103.9	225	138	175	156	143	91.4	139	1738.2	144.9
Ganmo	71	49.5	39.5	57	28.3	59	2.4	51.5	29.4	24	28	34	473.6	39.47
Benin	120.4	157	116	161	85.4	117	115	118	98.8	174	186	178	1626.8	135.6
Effurun	62.3	102	39.9	84.4	29.7	83.1	41.1	46	60	83	74.9	29.8	736.4	61.37
Onitsha	76	145	130	111	51	133	76	162	72	133	124	94	1307	108.9
Alaoji	287.8	397	240	331	134.5	335	239	279	79.5	401	348	350	3422.2	285.2
New Haven	98	176	104	182	104	144	112	140	76	140	140	108	1524	127
Jebba	9.9	2.8	5.8	20.5	12.1	8.1	12.6	12.8	11.5	13	13.9	6.2	129.6	10.8
Birnin Kebbi	170	163	171	181	162	187	170	169	164	184	195	191	2107	175.6
Sakate	185	220	155	220	155	208	185	209	172	214	215	201	2339	194.9
Katampe	376	337	322	325	295.9	335	185	375	265	358	360	345	3877.7	323.1

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Appendix D4. April 2017 Load Flow Data

Name of Bus	1st Week (MW)			2nd Week (MW)			3rd Week(MW)			4th Week (MW)			Total (MW)	Arg (MW)
Lagos	821	847	848	805	738	709	794	925	623	675	664	876	9325	777.1
Kaduna	258	259	219	207	221	232	232	236	170	189	235	280	2738	228.2
Kano		280	256	232	220	235	160	266	234	187**S**	226	264	2560	232.7
Yola	46	58	34	44	42	42	36	36	40	43		67	488	44.36
Jos	132	80	114	66	64	49	73	65	45	65	63	106	922	76.83
Gombe	133	131	102	100	100	86	77	94	85	85		128	1121	101.9
Shiroro	79.4	85	82	68.8	57	60.2	89.3	66.1	58	90	49.6	62	846.9	70.58
Aiyede	148	90	110	130	140	120	80	140	80	140	90	146	1414	117.8
Osogbo	81.6	134	93.2	82.5	87.3	148	154	144	151	186	129	105	1493.6	124.5
Ganmo	26.5	26	52.5	36	64.3	37.5	31	38.5	47.5	69	43.1	48	519.4	43.28
Benin	141.1	131	140	182	165.7	179	126	153	130	179	144	74	1744	145.3
Effurun	30.4	39.1	17.1	89.8	57.9	57	69.6	51.9	72.4	49	52.2	88.3	674.8	56.23
Onitsha	111	132	32	32	43	83	103	69	75	97	104	116	997	83.08
Alaoji	230.6	277	282	302	265.4	341	167	216	243	218	300	270	3111	259.3
New Haven	88	114	88	100	78	92	68	72	72	100	84	92	1048	87.33
Jebba	7.7	11.5	4.8	14.5	13	10.9	11.8	6.1	11.2	17	14.4	5.4	128.6	10.72
Birnin Kebbi	175	131	169		140	171	140	154	157	148	150	176	1711	155.5
Sakate	200	211	184	204	222	236	216	217	230	193	228	243	2584	215.3
Katampe	287.4	317	269	392	320.3	293	302	323	322	301	202	189	3519.3	293.3

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Appendix D5. Summary of Load Flow Data from January to April, 2017

Name of Bus	Jan	Feb	Mar	Apr	Total (MW)	Arg (MW)	Arg (MVA)
Lagos	650.75	942.583	755	777.08	3125.42	781.35	976.69
Kaduna	121.67	223.417	225.667	228.17	798.917	199.73	249.66
Kano	127.08	246.583	276.5	232.73	882.894	220.72	275.9
Yola	15.417	45.5833	55.25	44.364	160.614	40.153	50.192
Jos	41.167	93.5833	86.9167	76.833	298.5	74.625	93.281
Gombe	60.583	113.5	111.5	101.91	387.492	96.873	121.09
Shiroro	34.692	75.25	77.6	70.575	258.117	64.529	80.661
Aiyede	103.25	169.417	107.25	117.83	497.75	124.44	155.55
Osogbo	127	154.725	144.85	124.47	551.042	137.76	172.2
Ganmo	34.125	44.6667	39.4667	43.283	161.542	40.385	50.482
Benin	126.61	145.867	135.567	145.33	553.375	138.34	172.93
Effurun	46.225	69.0417	61.3667	56.233	232.867	58.217	72.771
Onitsha	91.75	130.583	108.917	83.083	414.333	103.58	129.48
Alaoji	241.77	318.925	285.183	259.25	1105.13	276.28	345.35
New Haven	70.167	134.333	127	87.333	418.833	104.71	130.89
Jebba	11.425	11.925	10.8	10.717	44.8667	11.217	14.021
Birnin Kebbi	104.58	169.25	175.583	155.55	604.962	151.24	189.05
Sakate	110.05	191.583	194.917	215.33	711.879	177.97	222.46
Katampe	190.76	326.367	323.142	293.28	1133.54	283.39	354.23

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Appendix E. Data for Generating Stations from January to April, 2017

Appendix E1. January 2017 Generating Stations Data

Generating Station	1st Week (MW)			2nd Week (MW)			3rd Week (MW)			4th Week (MW)			Total (MW)	Arg (MW)
Kainji	61	210	406	290	406	285	295	289	294	408	404	407	3755	312.92
Jebba	365	439	437	353	438	356	252	348	280	285	192	287	4032	336
Shiroro	300	300	300	300	300	300	300	300	300	300	300	300	3600	300
Egbin	N/G	360	360	328	359	361	336	384	317	N/G	N/G	106	2911	323.44
Sapele	64	65	64	65	65	67	42	40	40	67	65	65	709	59.083
Delta	240	240	240	180	240	N/G	140	140	140	140	140	160	2000	181.82
Afam IV-V	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Geregu	60	100	100	94	94	120	273	302	259	245	202	200	2049	170.75
Omotosho	67	113	109	99.5	112	104	33.8	109	109	109	101	111	1177.6	98.133
Olorunsogo Gas	N/G	28.4	30	32.7	32.5	63.4	126.3	129	132	102	118	126	920.1	83.645
Geregu NIPP	70	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	70	70
Sapele NIPP	109.6	N/G	N/G	N/G	N/G	N/G	113.6	115	115	N/G	N/G	N/G	453.7	113.43
Alaoji NIPP	N/G	N/G	116	63.8	117	111	N/G	100	N/G	N/G	N/G	112	620.3	103.38
Olorunsogo NIPP	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	154	78.6	N/G	232.5	116.25
Omotosho II NIPP	108.3	95.9	106	101	102	110	99.4	111	109	112	103	105	1262.6	105.22
Ihovbor	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	88	89.3	93.1	89	359.4	89.85
Okpai	N/G	143	148	142	150	419	209	211	213	210	205	210	2260	205.45
Afam VI	573	559	578	562	581	410	413	421	424	N/G	N/G	170	4691	469.1
Ibom	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Omoku	85.2	5.4	71	27.3	75.3	N/G	58.1	55.5	56	55	53.3	56	597.7	54.336
A.E.S.	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Trans Amadi	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Rivers IPP	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
ASCO	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Odukpani NIPP	114.3	114	117	113	119	114	113.9	117	102	115	109	117	1365.1	113.76
Gbarain	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Paras Energy	No Reading													

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Appendix E2. February 2017 Generating Stations Data

Generating Station	1st Week (MW)			2nd Week (MW)			3rd Week (MW)			4th Week (MW)			Total (MW)	Arg (MW)
Kainji	316	315	315	315	317	249	412	422	417	407	405	404	4294	357.83
Jebba	276	370	286	370	360	375	371	368	288	325	369	282	4040	336.67
Shiroro	300	300	100	300	300	300	300	300	210	200	300	300	3210	291.82
Egbin	310	328	320	320	341	325	355	327	324	545	362	350	4207	350.58
Sapele	N/G	N/G	38	45	46	40	47	N/G	68	67	67	67	485	53.889
Delta	450	450	330	460	460	540	540	480	490	450	500	390	5540	461.67
Afam IV-V	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Geregu	161	252	200	175	240	N/G	254	224	249	168	225	N/G	2148	214.8
Omotosho	142.3	202	242	193	222	207	171.4	172	173	167	168	140	2198.9	183.24
Olorunsogo Gas	227.6	212	209	141	145	N/G	117.6	98.1	115	94.5	97.7	98	1554.9	141.35
Geregu NIPP	67	68	85	111	144	197	140	81	93	65	136	N/G	1186.9	107.9
Sapele NIPP	106.6	111	110	110	110	106	108.2	104	111	106	108	108	1299.9	108.33
Alaoji NIPP	111.2	115	114	115	115	N/G	N/G	N/G	N/G	N/G	N/G	N/G	570.7	114.14
Olorunsogo NIPP	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Omotosho II NIPP	174.4	188	107	159	N/G	197	202.9	136	193	154	203	186	1901.5	172.86
Ihovbor	N/G	221	224	218	110	220	215.6	209	222	199	213	214	2264.2	205.84
Okpai	427	453	403	394	397	259	428	218	433	208	210	368	4198	349.83
Afam VI	403	561	524	563	6033	413	537	186	621	274	613	568	11296	941.33
Ibom	83.7	102	106	91.6	91.5	101	102.9	83.2	92	83.3	82.1	82	1102.2	91.85
Omoku	47.6	48	50	49.1	49.4	51.3	49.1	50.6	48	49.8	48.7	49	590.9	49.242
A.E.S.	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Trans Amadi	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Rivers IPP	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
ASCO	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Odukpani NIPP	112.4	118	118	334	357	229	229.5	221	237	225	229	222	2630.9	219.24
Gbarain	107.3	112	113	113	112	107	109.4	N/G	112	107	108	105	1205.8	109.62
Paras Energy	65.1	65.1	65	65.1	65.1	65.5	65.1	63	66	35.2	65.8	65	750.7	62.558

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Appendix E3. March 2017 Generating Stations Data

Generating Station	1st Week (MW)			2nd Week (MW)			3rd Week (MW)			4th Week (MW)			Total (MW)	Arg (MW)
Kainji	395	393	126	399	148	398	264	398	147	393	380	391	3832	319.33
Jebba	363	356	355	341	340	339	340	367	358	357	328	338	4182	348.5
Shiroro	279	276	201	280	196	270	198	271	270	271	198	267	2977	248.08
Egbin	60	431	402	564	537	559	434	535	444	380	370	388	5104	425.33
Sapele	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Delta	325	325	240	260	260	345	250	345	300	320	320	320	3610	300.83
Afam IV-V	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Geregu	180	257	N/G	292	N/G	138	N/G	250	40	300	N/G	260	1717	214.63
Omotosho	86.2	221	224	215	153	213	211	222	220	216	168	182	2330.6	194.22
Olorunsogo Gas	N/G	60.4	140	136	137	145	173	186	177	173	163	168	1657.1	150.65
Geregu NIPP	N/G	83	N/G	142	N/G	135	N/G	117	N/G	119	2	115	713	101.86
Sapele NIPP	212	222	188	223	180	197	105	212	222	220	204	222	2405.5	200.46
Alaoji NIPP	109	113	115	114	83.8	106	112	117	116	115	105	113	1319.6	109.97
Olorunsogo NIPP	N/G	105	110	111	84.3	100	N/G	N/G	N/G	N/G	N/G	N/G	510.2	102.04
Omotosho II NIPP	77.5	153	175	183	105	307	327	288	226	202	103	80	2226.1	185.51
Ihovbor	103	111	112	109	84.7	109	106	114	112	110	103	111	1284.7	107.06
Okpai	414	421	375	317	317	366	278	328	279	361	342	343	4141	345.08
Afam VI	108	108	108	108	108	108	108	108	108	140	137	210	1459	121.58
Ibom	108	102	83	110	72.5	102	107	82.2	68	108	82.6	107	1131.1	94.258
Omoku	58.9	58.6	60	52.2	19.2	40	50.6	43	60	69.9	69.2	72	653.7	54.475
A.E.S.	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Trans Amadi	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Rivers IPP	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
ASCO	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Odukpani NIPP	204	224	225	227	201	216	226	80.5	190	216	211	232	2453	204.42
Gbarain	106	112	105	112	91.7	111	96.7	115	N/G	N/G	N/G	112	961.5	106.83
Paras Energy	60	60	68	67.5	56	56	62	63.2	64	66.3	68.5	64	755	62.917

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Appendix E4. April 2017 Generating Stations Data

Generating Station	1st Week (MW)			2nd Week (MW)			3rd Week (MW)			4th Week (MW)			Total (MW)	Arg (MW)
Kainji	285	392	389	392	390	389	284	389	349	390	283	389	4321	360.08
Jebba	349	347	349	361	264	351	347	357	356	340	262	340	4023	335.25
Shiroro	194	266	270	269	270	269	269	270	N/G	267	268	265	2877	261.55
Egbin	349	343	338	330	341	341	329	343	322	353	354	350	4093	341.08
Sapele	N/G	45	46	50	51	55	54	55	53	54	52	50	565	51.364
Delta	250	250	250	250	250	250	189	250	250	250	260	260	2959	246.58
Afam IV-V	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Geregu	160	297	120	241	180	229	200	200	130	190	130	240	2317	193.08
Omotosho	139.7	148	81	145	140	146	139	148	144	141	140	143	1654.7	137.89
Olorunsogo Gas	139.6	145	141	144	159	171	162	181	141	135	136	133	1786.7	148.89
Geregu NIPP	78	91	76	114	65	109	20	90	79	129	70	130	1051	87.583
Sapele NIPP	110.4	215	217	217	139	140	119	147	171	198	173	175	2021.3	168.44
Alaoji NIPP	111.2	115	113	114	117	113	48.3	113	N/G	N/G	N/G	N/G	843.8	105.48
Olorunsogo NIPP	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Omotosho II NIPP	112.5	118	114	115	105	109	103	106	110	110	95	110	1307.3	108.94
Ihovbor	108.5	111	110	110	108	111	101	110	111	105	107	109	1299.9	108.33
Okpai	419	428	312	360	362	360	344	363	363	354	222	359	4246	353.83
Afam VI	142	143	143	144	144	144	139	143	143	140	143	142	1710	142.5
Ibom	92.7	108	108	109	108	108	76.5	91.4	46	101	102	103	1154	96.167
Omoku	59.1	61.6	62	60.2	58.1	60.5	1.1	60.1	60	87	83.3	85	738.5	61.542
A.E.S.	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Trans Amadi	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Rivers IPP	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
ASCO	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G	N/G		
Odukpani Nipp	220	191	223	224	111	335	314	344	196	220	235	335	2947.5	245.63
Gbarain	107.7	114	111	111	110	111	N/G	110	112	111	112	110	1219.6	110.87
Paras Energy	64	67.8	68	64.4	61.6	61.6	61.6	63	63	63	63	60	760.9	63.408

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Appendix F. Script For Matlab Plot

```
y1=[0.0746,0.0562,0.1522,0.1522,0.1522,0.7515,0.0424,0.0424,0.0424,0.0827,0.605]
y2=[0.1251,0.035,0.1151,0.1164,0.1164,0.6169,0.0375,0.0375,0.0375,0.1214,0.737]
xx1=[1,2,3,4,5,6,7,8,9,10,11]
 hold on
plot(xx1,y1,'r')
plot(xx1,y2,'b')
hold off
xlabel('Matrix Index');
ylabel('Normalised');
title('Line 9 IKEJA WEST - OSOGBO')
grid on
y13=[0.0445,0.4297,0.0445,0.0445,0.0445,0.0445,0.695,0.0445,0.0445,0.0445,0.429]
y23=[0.0366,0.128,0.0347,0.0933,0.1222,0.0945,0.6211,0.0365,0.0366,0.0366,0.128]
xx3=[1,2,3,4,5,6,7,8,9,10,11]
hold on
plot(xx3,y13,'r')
plot(xx3,y23,'b')
hold off
xlabel('Matrix Index');
ylabel('Normalised');
title('Line 3 AIYEDE - OLORUNSOGO')
grid on
y15=[0.0558,0.0399,0.1079,0.7579,0.1079,0.5689,0.0301,0.0301,0.0301,0.0587,0.2603]
y25=[0.0367,0.0394,0.1659,0.854,0.1659,0.1741,0.0326,0.0326,0.0326,0.3671,0.210]
xx5=[1,2,3,4,5,6,7,8,9,10,11]
hold on
plot(xx5,y15,'r')
plot(xx5,y25,'b')
hold off
xlabel('Matrix Index');
ylabel('Normalised');
title('Line 4 SAKETE - IKEJA WEST')
grid on
```

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Appendix G. Load Flow Result when the System was Stable

From Bus	To Bus	Line	P Flow (MW)	Q Flow (MVar)	P Loss (MW)	Q Loss (MVar)
Ikeja W. TS	Egbin Bus	1	-21.38575512	-61.6889582	0.232292547	1.68927168
Ajah TS	Egbin Bus	2	-1.29337E-07	0.100006155	4.95032E-07	-0.09999871
Ikeja W. TS	Akangba TS	3	5.21416E-08	-0.09480167	5.21416E-08	-0.094801672
Ikeja W. TS	Sakete TS	4	21.85388473	22.09116469	0.052804731	0.312330687
Omotosho NIPP / Sec	Ikeja W. TS	5	71.44236746	23.32227776	0.300375509	2.214276731
Ikeja W. TS	Olorunsogo Sec	6	-25.75158564	-39.0093316	0.119019769	0.818934359
Aiyede TS	Olorunsogo Sec	7	-31.3925109	-18.4653041	0.694049192	0.497617124
Osogbo TS	Aiyede TS	8	-15.85716567	-3.03059035	0.011455233	0.004153713
Ikeja W. TS	Osogbo TS	9	5.776257462	18.78979753	0.02006519	0.076356444
Ajah TS	Lekki TS	10	1.29337E-07	-0.10000616	1.29337E-07	-0.100006155
Ajah TS	Alagbon TS	11	1.29337E-07	-0.10000616	1.29337E-07	-0.100006155
Ajah TS	Egbin Bus	12	-1.29337E-07	0.100006155	4.95032E-07	-0.09999871
Osogbo TS	Ganmo TS	13	4.651657937	4.696231432	0.002449937	-0.074128568
Okearo TS	Egbin Bus	14	-2.805499495	-7.8884222	0.003609361	-0.071911724
Okearo TS	Egbin Bus	15	-2.805499495	-7.8884222	0.003609361	-0.071911724
Ikeja W. TS	Okearo TS	16	-2.777387294	-7.78868905	0.028112201	0.099733143
Ikeja W. TS	Okearo TS	17	-2.777387294	-7.78868905	0.028112201	0.099733143
Ikeja W. TS	Akangba TS	18	5.21416E-08	-0.09480167	5.21416E-08	-0.094801672
Omotosho NIPP Phase Pri	Omotosho NIPP / Sec	19	71.5805643	26.08621448	0.138196836	2.763936718
Egbin GS Pri	Egbin Bus	20	0	0	0	0
Olorunsogo GS Pri	Olorunsogo Sec	21	58.00723764	59.79262985	0.050072138	1.001442754

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Appendix G. Load Flow Result when the System was Stable (Continuation)

From Bus	To Bus	Line	P Flow (MW)	Q Flow (MVar)	P Loss (MW)	Q Loss (MVar)
Line Flows						
Egbin Bus	Ikeja West TS	1	21.61804766	63.37822986	0.232292547	1.68927168
Egbin Bus	Ajah TS	2	6.24369E-07	-0.20000486	4.95032E-07	-0.09999871
Akangba TS	Ikeja West TS	3	3.78106E-15	6.91822E-13	5.21416E-08	-0.094801672
Sakete TS	Ikeja West TS	4	-21.80108	-21.778834	0.052804731	0.312330687
Ikeja West TS	Omotosho NIPP / Sec	5	-71.14199195	-21.108001	0.300375509	2.214276731
Olorunsogo Sec	Ikeja West TS	6	25.87060541	39.82826592	0.119019769	0.818934359
Olorunsogo Sec	Aiyede TS	7	32.08656009	18.96292118	0.694049192	0.497617124
Aiyede TS	Osogbo TS	8	15.8686209	3.034744059	0.011455233	0.004153713
Osogbo TS	Ikeja West TS	9	-5.756192271	-18.7134411	0.02006519	0.076356444
Lekki TS	Ajah TS	10	0	0	1.29337E-07	-0.100006155
Alagbon TS	Ajah TS	11	0	0	1.29337E-07	-0.100006155
Egbin Bus	Ajah TS	12	6.24369E-07	-0.20000486	4.95032E-07	-0.09999871
Ganmo TS	Osogbo TS	13	-4.649208	-4.77036	0.002449937	-0.074128568
Egbin Bus	Okearo TS	14	2.809108856	7.816510473	0.003609361	-0.071911724
Egbin Bus	Okearo TS	15	2.809108856	7.816510473	0.003609361	-0.071911724
Okearo TS	Ikeja West TS	16	2.805499495	7.888422197	0.028112201	0.099733143
Okearo TS	Ikeja West TS	17	2.805499495	7.888422197	0.028112201	0.099733143
Akangba TS	Ikeja West TS	18	3.78106E-15	6.91822E-13	5.21416E-08	-0.094801672
Omotosho NIPP / Sec	Omotosho NIPP Phase Pri	19	-71.44236746	-23.3222778	0.138196836	2.763936718
Egbin Bus	Egbin G.S Pri	20	0	0	0	0
Olorunsogo Sec	Olorunsogo G.S Pri	21	-57.9571655	-58.7911871	0.050072138	1.001442754

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Appendix G. Load Flow Result when the System was Stable (Continuation)

From Bus	To Bus	Line	P Flow (MW)	Q Flow (MVar)	P Loss (MW)	Q Loss (MVar)
Global Summary Report						
Total Generation						
Real Power (MW)			156.8240686			
Reactive Power (Mvar)			164.4900854			
Total Generation						
Real Power (MW)			155.139843			
Reactive Power (Mvar)			155.719864			
Total Generation						
Real Power (MW)			1.68422556			
Reactive Power (Mvar)			8.770221396			

DOI: https://doi.org/10.37121/jase.v2i3.68

Appendix H. Voltage and Power Profiles for a Stable System

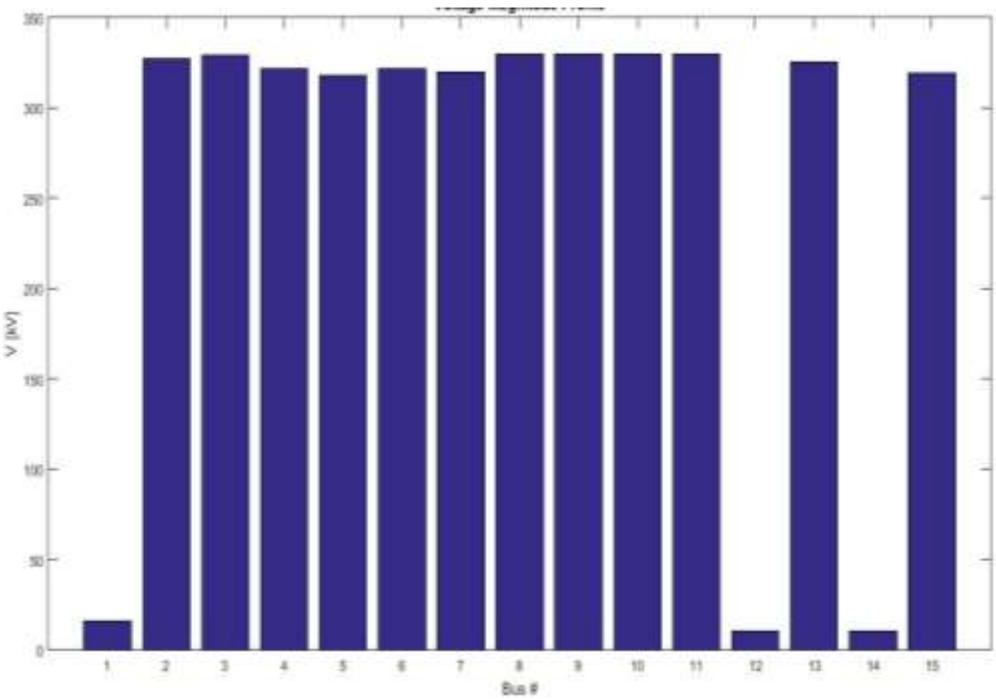

Figure H1. Voltage Magnitude Profile for a stable system

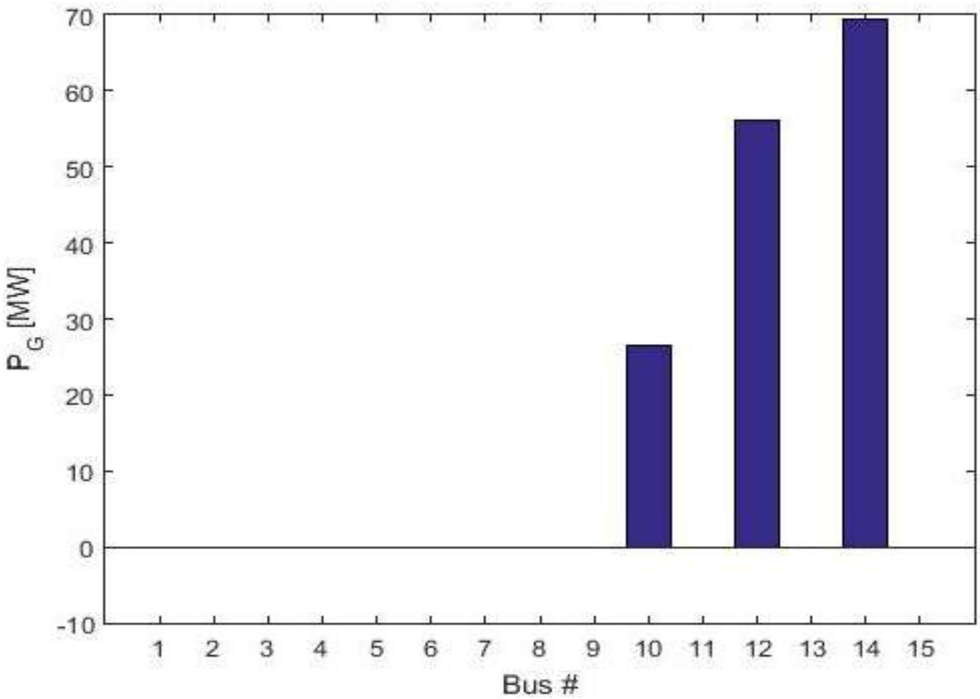

Figure H2. Real Power Profile for a Stable System

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Appendix I. Network Considered For Optimal Placement of PMU

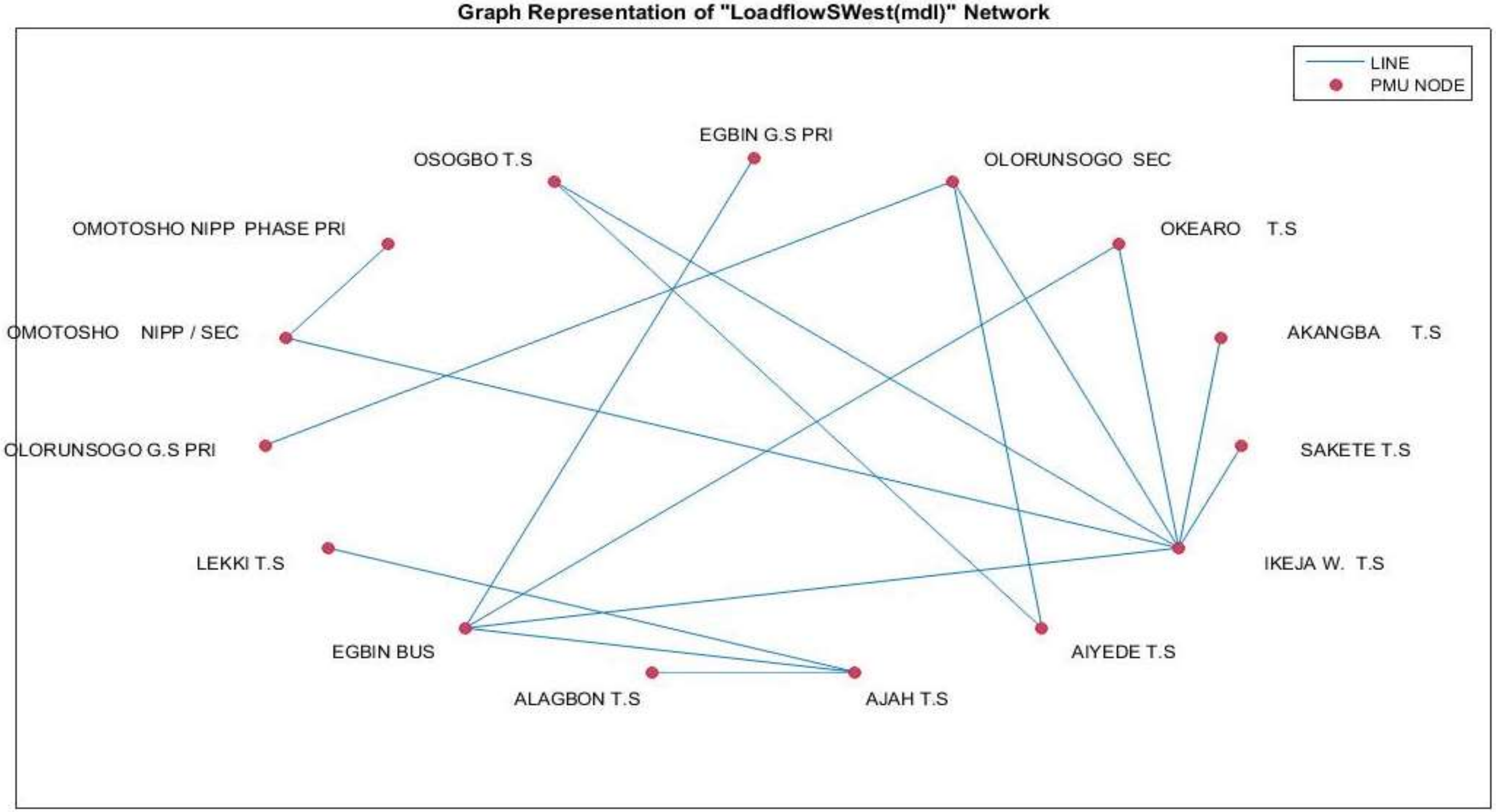

Figure I. Graphical Representation of the Network Considered for Optimal Placement of PMU