UNIVERSITY OF EDUCATION, WINNEBA

COLLEGE OF TECHNOLOGY EDUCATION

ENHANCEMENT OF NETWORK MONITORING AND SECURITY ANALYSIS USING PHASOR MEASUREMENT UNITS

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BY

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AUGUST 2012

DECLARATION

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ABSTRACT

Synchronized phasor measurements are becoming an important element of wide area measurement systems used in advanced power system monitoring, protection, and control applications. Considering the current power outages in Ghana, the electric utility power system may have major blackouts or natural catastrophes. It is therefore possible to lose data from the network due to failure of communication systems during these incidents. Hence, this study explored how network monitoring and security analysis could be enhanced using phasor measurement units (PMUs). In all, 160 respondents including system operators, system engineers and system controllers participated in the study. Quantitative data analysis was performed using the Statistical Products and Service Solutions (SPSS), version 18, while thematic analysis was performed on the qualitative data obtained from the open-ended questions in the structured questionnaire and the interview data. The use of SCADA to monitor traffic in GRDICo has not been highly effective as the occurrences, disturbances and disruptions in traffic in the network are frequent. Additionally, the study concluded that, there are significant challenges that confront network monitoring and security analysis of grid in GRIDCo including real time monitoring and control, post power disturbance analysis and power systems state estimation. It is recommended that,the enhancement of network monitoring and security analysis of grid in GRIDCo using PMU could result in the unique ability to provide synchronized power system phasor measurements from widely dispersed locations in the electric power grid. Secondly, sufficient funds should be made available by government through the Ministry of Energy to help GRIDCo experience significant investment in the deployment of phasor measurement units (PMUs) and the associated infrastructure for making synchrophasor measurements and data collection.

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Last but not least, my family for their understanding, patience, encouragement and support. Thank you for all the support, comments and guidance.

DEDICATION

I dedicated this dissertation to my wife Bridget Blewusi Bansah, daughter Selorm Adenyo and my Son Selagbe Adenyo.

TABLE OF CONTENT

CONTENTS **PAGE**

LIST OF ACRONYMS

AEPSC	American Electric Power Service Corporation
BPA	Bonneville Power Administration
BPL	Broadband over Power Line
CBs	Circuit Breakers
EMS	Energy Management System
GRIDCo	Ghana Grid Company Limited
GPS	Global Positioning Satellite
IEEE	Institute of Electrical and Electronics Engineers
IED	Intelligent Electronic Devices
MRI	Magnetic Resonance Imaging
NEDCo	Northern Electricity Distribution Company
NTC	Nominal Transfer Capability
NYPA	New York Power Authority
PMUs	Phasor Measurement Units
PE	Parameter Estimation
PDC	Phasor Data Concentrator
PSERC	Power Systems Engineering Research Centre
RTC	Real-time Transfer Capability
SCADA	Supervisory Control and Data Acquisition
SE	State Estimation
SIPS	System Integrity Protection Scheme
VRA	Volta River Authority
WAMS	Wide area monitoring system
WLS	Weighted Least Square

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Society depends on reliable electricity since electricity is considered as an essential source for security, communication, water supply, heating, cooling, leisure, entertainment, education, using computers and almost every aspect of life a person can think of. In this regard, people always expect that, electricity will be available, for example, when one flicks on the switch. However, Sajal (2012) noted that, providing reliable electricity is a tough challenge with so many components and unseen conditions. According to Sajal (2010), after the electricity is generated, it requires a reliable, efficient and affordable transmission and distribution system to deliver power to customers. Thus, for the transmission and distribution system to be more affordable, reliable and sustainable, the grid has to be efficient. In the United States, for example, a number of activities were carried out to achieve efficiency (Sajal, 2010). At the same time, blackouts in the past and reliability of grid were major issues for system engineers (Nuqui et al., 2005).

Nuqui et al. (2005) observed that, Undetected Read Error (URE) operation of power systems requires close monitoring of the system operating conditions. The measurements received from numerous substations are used in control centers to provide an estimate for all metered and un-metered electrical quantities and network parameters of the power system, detect and filter out measurement and topology errors. According to Nuqui et al. (2005), until recently, the available measurements were provided by Supervisory Control and Data Acquisition (SCADA), including active and reactive power flows and injections and bus voltage magnitudes. The utilization of global positioning system (GPS), in addition to sampled data processing techniques, for computer re-laying applications, has led to the development of Phasor Measurement Units (PMUs).

Synchronized phasor measurements are becoming an important element of wide area measurement systems used in advanced power system monitoring, protection, and control applications. A Phasor Measurement Unit (PMU) is an electronic device that enables real-time computer control to protect the stability and reliability of a power grid. Using GPS-derived timing, the PMU synchronously captures voltage and current phase vectors to create SynchroPhasor data. Synchronous data from multiple PMUs are forwarded to a common point for analysis. A number of PMUs are already installed in several utilities around the world for various applications such as post-mortem analysis, adaptive protection, system protection schemes, and state estimation. PMUs become more and more attractive to power engineers because they can provide synchronized measurements of real-time phasors of voltage and currents (Nuqui et al., 2005).

The United States Energy Information Administration (2012) noted that in the United States and Canada, there are four large electric systems, called interconnection, that underpin the provision of electricity service to all consumers. Therefore, for these integrated systems to operate reliably, system operators must continuously match electricity generation to electricity demand as demand changes throughout the day. Furthermore, the operation of each component of the electric power system such as generators, transformers, and transmission circuits must be closely synchronised. Thus, a mismatch between supply and demand or a breakdown in synchronisation can put stress on the grid. If these problems are not rapidly identified and corrected, the result can be deterioration in power quality or power outages.

However, the United States Energy Information Administration (2012) indicates that, phasor measurement unit data can be used to monitor and mitigate these problems. In this regard, phasor measurement units (PMUs) are a new "smart" technology being deployed throughout the world to monitor what happens on the transmission grid. Thus PMU is a system used to improve the security of grid against false faults and load swing.

Since the introduction of computer relaying and later microprocessor relays, efforts were initiated to extract the phasors of an electric power system (Missout & Girard, 1980; Bonanomi, 1981; Phadke, Thorp & Adamiak, 1983), using the available time signals at the time. In other words, phasor measurement hold the promise of being superior to traditional supervisory control and data acquisition (SCADA) measurement in capturing system dynamic behaviours, as phasor instruments are high speed and time synchronized. Similarly, Sajal (2012) indicates that PMU is an important and promising technology which will make future grid smarter. Among the various facilitators of the smart grid are the phasor measurement units (PMU) which are rapidly populating substations in today's interconnected transmission systems. Thus, application of PMUs in power grids is required for real-time wide area monitoring of modern power systems, great grid condition visibility achievement, awareness about the system situation, stress evaluation, fast remedial action, and even analysis to support economical and reliable system operation under increased system and market operation complexity (Emami, 2011).

Phasor measurement units (PMUs) are synchronised to collect and time-stamp data 30 times per second and to continually relay this information to system operators. By evaluating data from around the system, matched by the time-stamps, system operators can produce real-time and evolving snapshots of system health. This data collection and processing capability has made PMUs useful for analyzing grid events like unexpected outages or power fluctuations, from turning into much larger problems (Smith, 2011).

According to Emami (2011), PMUs are currently the most sophisticated device used in power systems which utilises the high accuracy computation and the availability of GPS signal. Although advanced techniques in measuring and synchronizing measurements are basics for PMU operation, advances in other areas are also required to achieve the benefits of PMUs. One such area is data communication where faster and more reliable communication channels have created the chance of streaming from remote PMU site to the power system center.

Thus, a phasor measurement unit in addition to voltage and current phasors can also measure simultaneously and synchronise the associated frequency and electric power. The measurement are synchronized through Global Positioning Satellite (GPS) using one pulse per second (1 pps) as the reference. Furthermore, PMU infrastructure consists of 3 layers, namely, the measurement layer, data collection layer and application layer (Sajal, 2012). Although the benefits of PMUs are broader, Damir (2007) summarises the benefits of using PMUs as follows:

- Real-time monitoring and control;
- Power system state estimation;
- Real-time congestion management;
- Validating and tuning of models;
- Post disturbance analysis;
- Power system restoration;
- Overload monitoring and dynamic rating;
- Adaptive production; and
- Planned power-system separation.

In Ghana, energy produced from the generating stations is transmitted to VRA power sale customers through an interconnected transmission network at 69, 161 and 225kV voltage levels. The existing transmission network comprises:

1. 330Kv and 161kV closed loop grid serving the concentrated load of the southern part of Ghana
2. A long 161kV radial line from Kumasi to the relatively lightly loaded northern part of Ghana
3. A 161kV radial line from Techiman to Sawla in the north-western part of the country, which extends to Wa in the Upper West Region.
4. A single circuit 225kV 220km transmission line between Prestea substation in the Western part of Ghana and Abobo substation, located near Abidjan in Cote d'Ivoire.
5. A double circuit 161kV line connecting the Akosombo Generating Plant in Ghana to Lome substation in Togo, to supply power to both Togo and Benin (GRIDCo, 2009).

1.2 Problem Statement

The electric power grid is a complex interconnected system that may be subjected to blackouts and external disasters like hurricanes. It is necessary for electric utilities to repair and restore their power system as quickly as possible during extreme condition. Momoh (2008) argues that, the stability and security of power systems are of utmost importance to planning and operation engineers. As demand on grid resources increases, and contingency impacts on the interconnected power grids become more threatening or severe, real-time determination of power system operation and control is needed.

In addition, Electric Power Research Institute (2007) points out that, the effective operation of power systems in the present and the future depends to a large extent on how well the emerging challenges are met today. For instance, power systems continue to be stressed as they are operated in many instances at or near their full capacities. Therefore, in order to keep power systems operating securely and economically, it is necessary to further improve power and control system protection. Phasor measurement units (PMUs) are therefore ideal for monitoring and controlling dynamic power system performance, especially during high-stress operating conditions.

In Ghana, Boston et al. (2010) points out that, the conventional technology used by GRIDCo for monitoring the grid is supervisory control and data acquisition (SCADA). Thus in the transmission system, GRIDCo uses Supervisory Control and Data Acquisition (SCADA) to monitor and control switches and protective devices. ECG also runs part of its system, from the bulk supply point to the feeders feeding the distribution transformers, with SCADA. Unfortunately, there is no SCADA application from the distribution transformer to the consumer end (Nunoo & Ofei, 2010). A major challenge that is related to the use of the SCADA for grid monitoring by GRIDCo has been on cyber security of the electrical power grid. The shortcomings identified with the SCADA specifically include:

i. The system does not work well with low bandwidth communications channels in real-time control networks

ii. The need to perform real-world testing on live or test systems to isolate and mitigate vulnerabilities of integrated systems

iii. Lack of cyber security into the SCADA protocols (e.g., DNP and ICCP)

iv. High frequency of cyber-attack on the power grid

v. The system lacks a smart system that is able to either alert or block a cyber-attack

vi. Lack of common testing methods for identifying vulnerabilities

vii. Lack of reliable, inexpensive sensors and devices to ensure physical security of substations

viii. Lack of ways of performing real-world tests on systems without risking interruption of service to customers.

Generally, the SCADA is unable to effectively perform basic control and monitoring of field devices including breakers, switches, capacitors, reclosers, and transformers. Thus, since the traditional SCADA system is based on steady state power flow analysis, GRIDCo is unable to observe the dynamic characteristics of the power system as well as the limitations of "x-ray" quality visibility thereby offering limited area visibility which makes the facilitation of the capacity for distributed sensing and coordinated control action very challenging. The adaptation of PMU by GRIDCo would make measurements at short time intervals, typically 30 times per second, which is significantly faster than the conventional supervisory control and data acquisition (SCADA) technology. In other words, the above outlined problems are the specific problems this study intends to address.

1.3 Objectives of the Study

Considering the current power outages in Ghana, the electric utility power system may have major blackouts or natural catastrophes. It is therefore possible to lose data from the network due to failure of communication systems during these incidents. Against this background, this study seeks to explore how network monitoring and security analysis can be enhanced using phasor measurement units.

This is necessary to accurately measure and analyze the state of the power system based on real-time data collected from PMU located all across the network. Through this, system controllers can quickly identify power system events through visualisation of system quantities such as power flow, dynamic phase angle separation, and the rate of change of frequency from different parts of the system.

The main objective of this study is to evaluate the enhancement of network monitoring and security analysis using phasor measurement units. Specifically, the study seeks to:

i. examine the efficiency of network monitoring and security analysis of grid by GRIDCo

ii. evaluate the challenges encountered in network monitoring and security analysis of grid in GRIDCo; and

iii. examine the prospects to be associated with the use of phasor measurement units in network monitoring and security analysis of grid by GRIDCo.

1.4 Research Questions

In relation to the objectives of the study, the following research questions were formulated to guide the study:

1. How efficient is network monitoring and security analysis of grid by GRIDCo?
2. What challenges are encountered in network monitoring and security analysis of grid in GRIDCo?
3. What prospects are associated with the use of phasor measurement units in network monitoring and security analysis of grid by GRIDCo?

1.5 Significance of the Study

This study will provide insight to stakeholders such as the Electricity Company of Ghana, VRA, GRIDCo and other relevant agencies in the electricity sector on the need to use SCADA in conjunction with PMUs to monitor and improve efficiency, effectiveness and reliability of electric power transmission system in Ghana. This will help to address the gaps in using SCADA and put in place the necessary steps to acquire PMUs. In this direction, the project will inform government and policy makers on the extent to which phasor measurement units could be used for network monitoring and security analysis of grid to provide the needed resources to monitor and improve efficiency, effectiveness and reliability of electric power transmission system in Ghana.

On the academic front, the project would add to the existing literature on how to enhance network monitoring and security analysis using phasor measurement units. Thus, the outcome of this project would further advance the frontier of knowledge by identifying the relevant gaps in the literature that needs to be addressed. Regarding the potential implications for theory, this project will expand the existing power engineering literature in two main ways. First, the project will provide new empirical evidence in the field of the applications in PMUs in power systems for enhancement of power system stability. Secondly, the project will contribute to an additional study in the new context of Ghanaian energy industry regarding rotor angle stability, frequency stability, voltage security, power system oscillations, and voltage stability enhancement by using different facts controllers in an integrated power system networks.

1.6 Scope of the Study

There are various sensors distributed across different parts of the electric power grid providing measurements to the control center operator for situational awareness of the system. These sensors include voltage transformer, current transformer, relay and phasor measurement units. Specifically, this study is limited to the application of phasor measurement units in enhancing network monitoring and security analysis. Thus this study had been limited to the PMUs based on the fact that the effective utilization of PMU is very useful in mitigating blackouts and learning the real time behaviour of the power system.

Specifically, the project shows the topology employed in installing the PMUs as well as how the data in the grid was GPS time-stamped. This is essential in showing how the data is allowed to be 'synchronized' to enable enhanced grid visualization, operational awareness, stability monitoring, state estimation, and after-the-fact analysis.

1.7 Organisation of the Project

The project is structured into five chapters. Chapter One includes the background of the study, problem statement, objectives of the study, rechearch questions, significance of the study , scope of the study and finally organisation of the project. Chapter Two reviews related literature from the conceptual, empirical and theoretical perspectives. Specifically, the chapter reviews literature in relation to the historical overview of PMUs, concept and definition of PMUs, applications of PMUs in power system and challenges of PMUs. Thus the chapter reviews the literature within the conceptual, empirical and theoretical context that optimal placement of PMUs is essential in order to achieve a measurement design that is robust against bad data, loss of measurements as well as network switching.

The third chapter provides an in-depth methodology for the implementation process of PMU in GRDICo for the enhancement of network monitoring and security analysis. In other words, the chapter presents a comprehensive adoption of synchrophasors in GRIDCo wide-area monitoring system which can be installed at a large number of locations throughout the grid to make the grid more efficient. Generally, the chapter outlined the physical steps that were taken to implement the installation of the PMUs. The survey methodology for gathering relevant data from personal and management of GRIDCo is also presented in the chapter.

Chapter Four presents the results and discussion of the findings. The discussion was done in relation to the pertinent concepts discussed in the review of literature, while Chapter Five focuses on the summary, conclusions and recommendations. The major findings from the study are presented in this chapter as well as the management implications of the study, recommendations for management, and directions for further academic research. The recommendations were based on the major findings arising from the study.

CHAPTER TWO

LITERATURE REVIEW

The chapter reviews related literature from the conceptual, empirical and theoretical perspectives. Based on the objectives of the study, the following major themes are discussed in this chapter: Technologies for network monitoring and security analysis before the introduction of PMU; historical overview of phasor measurement unit; concept and definition of phasor measurement units; applications of phasor measurement units in power system; effectiveness of phasor measurement units; and challenges of phasor measurement unit.

2.1 Technologies for Network Monitoring and Security Analysis before the Introduction of PMU

In the early days of commercial electric power, transmission of electric power at the same voltage as used by lighting and mechanical loads restricted the distance between generating plant and consumers. In 1882, generation was with direct current (DC) which could not easily be increased in voltage for long-distance transmission. Due to this specialization of lines and because transmission was inefficient for low-voltage high-current circuits, generators needed to be near their loads. The rapid industrialization in the 20th century made electrical transmission lines and grids a critical infrastructure item in most industrialized nations. According to Nunoo and Mahama (2013), engineers design transmission networks to transport the energy as efficiently as feasible, while at the same time taking into account economic factors, network safety and redundancy.

2.1.1 Supervisory Control and Data Acquisition (SCADA)

Some of the earliest Supervisory Control and Data Acquisition (SCADA) systems were installed in the 1920s. At the time, some high voltage substations adjacent to power plants could be monitored and controlled from the power plant's control room. This eliminated the need for engineers to staff the substations 24/7 even if the substations were some distance from the power plant control room.

In the 1930s, individual utilities started interconnecting to interchange electricity to reduce operating costs. With this came the need to control generation much more closely, so analog computers were developed to monitor and control generator output, tie-line power flows and frequency. In the late 1960s, digital computers and software were developed to replace the analog EMS systems. Software applications were developed to include the off-line analysis functions along with transmission system analysis models. Vendors modified the computer supplier's operating system to meet design and each set of application software was usually unique for each customer. Thus, when the computers needed to be upgraded or more functions were required the entire Master System had to be replaced. This trend continued into the 1980s and 1990s until open standard operating systems were developed that supported real-time applications (Nunoo & Mahama, 2013).

Many early SCADA systems used mainframe computer technology, making them hierarchical and centralized in nature. Networks did not exist at the time SCADA was developed. Thus SCADA systems were independent systems with no connectivity to other systems. Wide Area Networks (WAN) were later designed by RTU vendors to communicate with the RTU. The communication protocols used were often proprietary at that time. The first-generation SCADA system was redundant since a back-up mainframe system was connected at the bus level and was used in the event of failure of the primary mainframe system.

2.1.2 Remote Terminal Units (RTUs)

In the early application of monitoring and control systems, the interface between the power system and the control system was in a remote location. This interface was designated a Remote Terminal Unit (RTU). An RTU consisted of a cabinet or panel of terminals for the instrumentation and control wires, which connected it to the power system (Smith, 2013).

2.2 Historical Development of Phasor Measurement Units

Phasor measurement systems were developed and deployed on an experimental basis in actual power systems in North America in the 1990's. This experience led to the commercial development of phasor measurement units (PMUs) with precise time synchronisation (Zhenyu et al., 2008). Specifically, the history of PMUs goes back to 1977 when a new symmetrical based algorithm was proposed by Phadke, Helibka and Ibrahim (1997) to protect the transmission line in power systems. In this regard, calculation of the positive sequence voltages and currents in a power system was the first step in the procedure employed by the phasor measurement units. Positive sequence bus voltages of the network constitute the state vector of the power system (Phadke & Thorpe, 2008). Thus Emami (2011) indicates that, availability of global positioning satellite system (GPS) and the ability of the GPS to represent the most accurate method to synchronise the power system measurements, enabled researchers in Virginia Tech to build the first prototype model of the phasor measurement unit (PMU) in early 1980s. For example, Roel (2013) indicated that the PMUs were invented in 1988 at Virginia Tech and that the prototype PMUs built at Virginia Tech were placed at certain substations of the Bonneville Power Administration (BPA), the New York Power Authority (NYPA), and the American Electric Power Service

Corporation (AEPSC). According to Roel (2013), the first commercial PMU was introduced in 1992 and the first synchrophrasor standard was IEEE1344 in 1995. Later, the standard was updated in 2001 to become IEEE1344-2001. In addition, following the United States blackout in 2003, PMUs had a big boost. In 2005, the PMU standard was updated to C37.118-2005 while the standard was again updated in 2011 using two specifications, namely, C37.118.1 for measurement specifications and C37.118.2 for communications specifications. Figure 2.1 shows the first prototype PMU built at Virginia Tech.

Figure 2.1: First prototype PMU built at Virginia Tech

Source: Phadke and Thorpe (2008)

2.3 Applications of Phasor Measurement Units in Power System

Phasor measurement units are precise grid measurements of electrical waves to determine the health of the electricity distribution system. In furtherance, PMUs enable a superior indication of grid stress and are often used to trigger corrective actions to maintain reliability (Arbiter Systems, 2013). According to Gallucci (2011), PMUs sit in electrical substations and record electricity flows on transmissions lines up to 120 times per second and report the results to grid control centers. For instance, the United States Energy Information Administration (2012) adds that PMUs monitor the characteristics of electricity flowing through a particular location at the point where a generator connects to the bulk power system or at a substation.

Arbiter Systems (2013) further highlights the importance of PMUs for grid stability by pointing out that, PMU or synchrophasor measurements may be used to determine useful information about operation of grid. For example, power flows may be monitored in real-time, and by measuring changes in the phase shift across parts of the grid, estimates of stress and future stability can be made. Post processing of synchrophasor data, which can also be done in real time, can extract information about low-frequency system modes, and by examining whether the amplitudes of these modes are changing, advance warning of impending instability can be given. Thus, synchrophasor measurements are made practical by a widespread, economical source of accurate time (Arbiter Systems, 2013). Damir (2007) highlights and discusses the benefits of using PMUs as follows:

2.4.1 Real-time monitoring and control:

Real-time monitoring of the system provides the on-line information of the system to the power system operator. Accurate knowledge of current information of the system increase the power system efficiency under normal conditions, and helps the power system dispatcher to identify, anticipate, and modify disturbances in system abnormal conditions. Compared to current energy management system (EMS) monitoring software that uses information from state estimation and supervisory control and data acquisition (SCADA) over several second intervals, time-synchronized PMUs introduce the possibility of directly measuring the system state instead of estimating it based on system models and telemetry data. As measurements are reported 20-60 times per second, PMUs are well suited to track grid dynamics in real time. In addition, phasor measurement technology is the only known technology that can offer real time monitoring application and benefit in three specific areas:

- Angular separation analysis and alarming -enables operators to assess stress on the grid. Measurement of phase angle separation allows early identification of potential problems both locally and regionally.
- Monitoring of long-duration, low frequency, inter-area oscillations – accurate knowledge of inter-area oscillations allows operators to adopt a power transfer limit higher than the limit currently in use
- Monitoring and control of voltage stability – provides for a backup to EMS voltage stability capability.

Fan and Centeno (2007) stated that a phasor-based frequency measurement technique has very good steady-state performance, but their dynamic performance is not well documented. This literature analyzes a phasor-based frequency measurement method that considers the effect of dynamic frequency, and proposed a method to improve the dynamic performance of the phasor-based frequency measurements. Phadke and Kasztenny, 2009), presented a synchronized phasor measurements are becoming an important element of wide area measurement systems used in advanced power system monitoring, protection, and control applications.

2.4.2 Power system state estimation:

State estimation, which is a statistical analysis used to determine a "best" possible representation of the system state based on imperfect telemetered data, is widely used in transmission control centers and ISO operations today to supplement directly telemetered real time measurements in monitoring the grid; to provide a means of monitoring network conditions which are not directly telemetered; and to provide a valid best estimate of a consistent network model which can be used as a starting point for real time applications such as contingency analysis, constrained re-dispatch, volt VAR optimisation, and congestion management.

Abur and Exposito (2004) argue that to explain the role of PMUs in improvement of power system state estimation, there is the need to first review the state estimation problem formulation - the mathematical formulation that is used in current power system state estimator. State estimation solves an over determined system of nonlinear set of equation as an unconstrained weighted least square (WLS) problem.

2.4.3 Real-time Congestion Management

Phasor measurement unit facilitates the ability to maintain real-time flows across transmission lines and paths within reliable transfer capabilities through dispatch adjustments in a least-cost manner. Thus, PMUs provide additional, synchronised, highly accurate system meter data that offer significant benefit through improved calculation of path limits and path flows. The higher scan rate and precision of PMU data will enhance computation of Real-time Transfer Capability (RTC), which in many cases will exceed the NTC (Nominal Transfer Capability) for the same path. PMU technology can also improve real-time congestion management through providing a more accurate state estimator solution of the real-time flow on a line or path. For example, improvement in real time congestion management would benefit all stakeholders in the transmission grid such as utilities, ISO, regional operations. In addition, society at large also benefits through improved power flow and reliability even in times of maximum load and power transfer.

2.4.4 Validation and tuning of system models

This is also known as benchmarking. Power system parameters are not always accurate. Since each part of the power system is modelled using a different set of system parameters like network, generators and loads among others, wrong parameters will cause error in system studies. In this regard, the objective of validation of system model, and Parameter Estimation (PE) is to identify the doubtful parameters of the system and have an improved estimate of those parameters. In other words, the goal of model verification and Parameter Estimation (PE) is to identify questionable power system modeling data parameters (network, generator, load models, etc.) and calculate improved estimates for such quantities.

2.4.5 Post Disturbance Analysis

The goal of a post-mortem or post-disturbance analysis is to reconstruct the sequence of events after a power system disturbance has occurred. Thus, post disturbance analysis is the study and simulation of chronicle of events after a disturbance occurs in power system. To conduct post-disturbance analysis, an investigation should be done on data, recorded through data recorders available throughout the network. However, working with traditional data recorders is very difficult and time consuming process due to the fact that the data available through such devices are not time synchronised and it is very difficult for the engineers to align the timeline of recorded data. In recent times, however, global positioning system (GPS) technology has been used as a universal time source which allows many devices to provide time-synchronised data, and one such device is PMUs. This means that, the application of PMU to post disturbance analysis offers potential benefit in the high degree of time synchronisation. Figure 2.2 shows a block diagram of the phasor measurement unit.

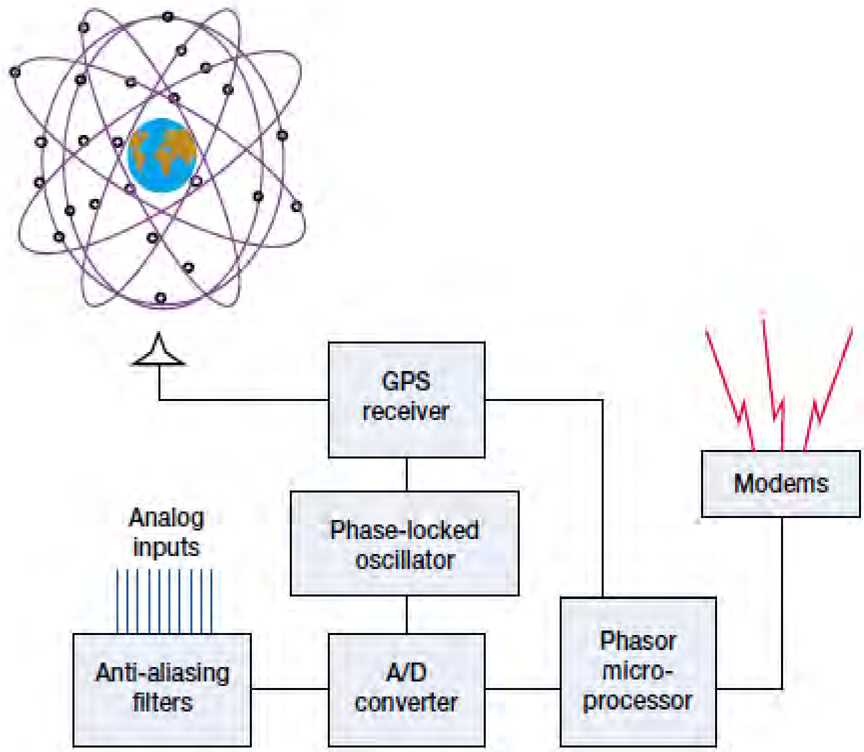

Figure 2.2: Block diagram of the Phasor Measurement Unit

Source: Abur and Exposito (2004)

2.4.6 Power System Restoration:

Standard operating procedures at most utilities define the steps to be followed for system restoration after the occurrence of an event. These procedures are generally based on some standard set of system conditions and associated operating parameters, which may or may not exist at the time the event occurred. The dynamic nature of the power system, particularly in times of outage or unusual events, creates the risk that the conditions on which the operating procedures are based may not exist at the time restoration efforts are undertaken. Nonetheless, PMU measurements can provide a valuable input into the decision processes, as the measurements are real-time quantities that give the operators current information on system status. Regarding risk mitigation in the restoration process, PMUs can also help reduce the time needed for system restoration. Therefore, the primary benefit of PMU technology in power system restoration is the ability to provide operators with real-time information about the phase angles in relevant parts of the grid. This information helps the operator with critical decisions about timing, sequences, and feasibility of prospective restoration actions. In that respect, phasor measurement technology can expedite restoration and reduce the blackout time Damir (2007).

2.4.7 Overload Monitoring and Dynamic Rating

There are many software and devices already available to power system utilities that enable them to monitor the power system equipment, however, using PMUs can make the monitoring more accurate (Rockefeller, Wagner, Linders, Hicks & Rizy, 1988). In this regard, Damir (2007) adds that the use of PMUs can offer some degree of monitoring at a high time resolution. Although PMU-based systems for overload monitoring and dynamic rating cannot match the features offered by existing equipment monitoring systems, the advantage of using PMUs is that, PMUs can be used for other purposes. In other words, the multi-tasking aspect of PMU makes them more desirable than available conventional measurement devices.

2.4.8 Adaptive Protection

Adaptive protection is a philosophy of protection design that provides for adjustments in protection functions, automatically, as system conditions change. That is to say, the protection scheme "adapts," within defined parameters, to prevailing system conditions unlike conventional protective systems that respond to faults or abnormal events in a fixed, predetermined manner. In furtherance, (Damir, 2007) argues that, though exact financial impact of adaptive protection using PMU measurement as compared to traditional protection schemes is difficult to quantify and varies from scheme to scheme, some of the benefits of adaptive protection using PMU measurement are improved reliability balance between security and dependability of a protection scheme and better utilisation of power generation, transmission and distribution equipment capabilities.

2.4.9 Planned Power System Separation

The planned separation of a power system into different segments, called islands, is the action of last resort when the power system is undergoing unstable system conditions (thermal, angle, voltage, frequency), and a separation is unavoidable. In such circumstances, it is desirable to create electrical islands and separate them from the grid on a planned basis rather than an unplanned basis, and then reconnect them with the grid later when conditions are improved or become favourable. Ideally, each island should have an approximately balanced generation and load, though in practice this may not always be the case (Damir, 2007). Therefore, direct utilisation of PMU data may improve system performance when used with current methods for planned system separation and other System Integrity Protection Scheme (SIPS), which is often called remedial action scheme. In this case, the two major methods used to accomplish system separation are System Integrity Protection Scheme (SIPS) and out of step relaying. For example, the major benefits of planned system separations using PMU measurement include minimising lost revenues and reducing generator restarting cost for utilities as well as limiting the direct impact to customers (Damir, 2007).

In addition, Boston, Heyeck and Mansoor (2010) submit that PMUs can help in the following ways:

- Situational awareness: This is a real-time understanding of the state of the system and how potential actions may affect it. Therefore, having complete and up-to-date information is essential for managing complex systems such as the grid. When monitored at critical locations, the information may help detect system stress and foretell an impending system emergency. The operator may reach a high level of awareness much quicker using this information rather than using traditional SCADA data
- Dynamic performance **:** Synchrophasors can assess how the dynamic performance of the system changes with various levels of renewable generation penetration. Many of the new generation sources are more remote from load centers than conventional generation and will result in the need to move power across longer distances. Synchrophasors provide the ability to monitor phase-angle differences and potential oscillatory modes that need to be managed to maintain system stability
- System model validation: As wind, solar photovoltaic and other emerging resources become more prevalent across the grid, accurate models will be needed to ensure reliable system planning and operation. Synchrophasors provide a key data resource for developing and validating system and component models.

2.5 Effectiveness of Phasor Measurement Units

The ability to compare time-synchronised data on the same timescale, among widely separated locations, is a relatively new achievement, based on two major improvements. Thus, the United States Energy Information Administration (2012) indicates that the two major improvements include speed and synchronisation. Speed - PMUs make measurements at short time intervals, typically 30 times per second, which is significantly faster than the conventional supervisory control and data acquisition (SCADA) technology. For example, the supervisory control and data acquisition technology makes measurements only every few seconds. That is to say, the more frequent measurements from PMUs can reveal system dynamics that would not be apparent with the older SCADA systems (United States Energy Information Administration, 2012).

Similarly, Boston, Heyeck and Mansoor (2010) points out that the conventional technology used by grid operators for monitoring the grid is supervisory control and data acquisition (SCADA). SCADA are then used by the state estimation (SE) application to determine and display the state of the power system. Thus, synchrophasors are precise grid measurements taken by PMUs at high speed, typically 30 times per second, compared to one every 4 seconds using conventional technology. For example, Figure 2.3 provides a graphical distribution of how PMUs can reveal system dynamics that would not be apparent with the older SCADA systems.

PMU data reveal dynamic behaviour as the system responds to a disturbance

Data comparison example, voltage disturbance on April 5, 2011 voltage magnitude, indexed.

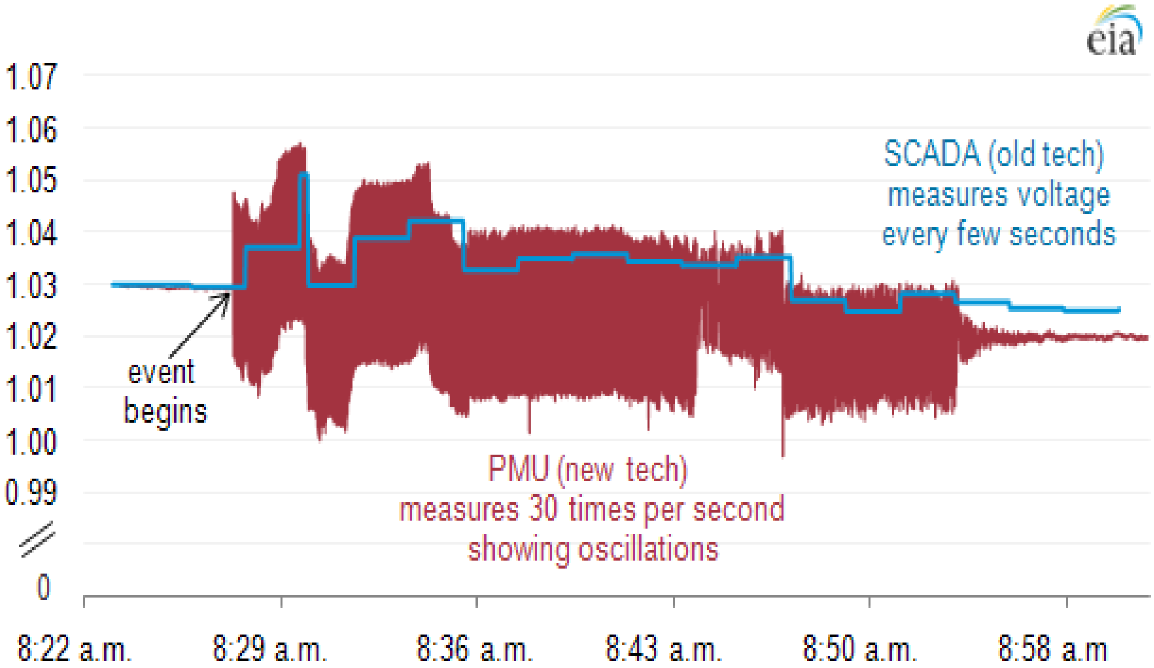

Figure 2.3: PMUs reveal system dynamics that would not be apparent with the older SCADA systems

Source: United States Energy Information Administration, 2012

***Synchronisation* -** All PMUs across an interconnection are kept in precise time synchronisation using GPS, leading to the term "synchrophasor data". This synchronisation provides the capability to easily compare system data among geographically dispersed units, creating wide-area visibility across large power systems, which was not previously possible using older technology (United States Energy Information Administration, 2012).

Furthermore, Boston et al. (2010) argues that, metaphorically, synchrophasor (that is, PMU) technology is like an MRI (Magnetic Resonance Imaging) of the power system as compared to an X-ray image provided by traditional SCADA technology. Therefore, to have instantaneous, high-resolution and more-detailed measurements, PMU data are well suited as input to activate local or centralised automated controls. Thus, using synchrophasor technology for wide-area monitoring and control will facilitate the evolution of the existing grid into a smarter transmission grid.

2.6 Tracking of External System Topology with PMU

Power systems topology is referred to as interconnections among power system components such as generators, power transformers, bus bars, transmission lines and loads among others. Thus, the interconnected infrastructure is known as power system network. The topology of the network is obtained by determining status of the switching components responsible for maintaining the connectivity status within the network. These components are called circuit breakers (CBs) and they are used to connect any power system component to the rest of the network or disconnect any power system component from the rest of the network (Kezunovic, 2005).

For example, the electric transmission network of the United States is an interconnected network where an outage in one state can cause cascading blackouts in other states or neighbouring countries. Most of the utility companies in United States have a few PMUs available in their systems whose phasor measurements are available to the internal power system dispatcher in real-time. One advantage of the PMUs in the utilities' system would be detection of external topology error using real-time internal data along with a few real-time data available through external PMUs which can in turn, help improve the internal security analysis (Emami, 2011).

Most power system utility companies have done investments on installation of PMUs on their systems. While looking for long term objectives on their system, loaded with phasor measurements, most of the utility companies in North America, for example, have a few PMUs already installed in their system; therefore, real-time external data for their neighbours are available through existing PMUs. These measurements can be used as a real time data and can be very helpful for identification of external topology changes and subsequent improvement of the internal security analysis (Emami, 2011). The proposed method is developed and presented in two parts (PSERC, May, 2012):

In the first part, the problem of external topology change is formulated using DC power flow assumptions. Once the formulated problem is solved successfully, the method can be extended to the more realistic AC power flow formulation. In the second part, the developed method is extended to the non-linear case of full AC solution. In addition to the internal system measurements, few phasor measurements installed in the external system are also assumed to exist in this part. Thus, the proposed method utilises an integer programming method to identify the changes in external system based on real-time data received from internal system along with real-time data from external phasor measurement units. The linear (D.C.) decoupled model of the power system will be used initially to formulate the external network topology tracking problem and develop its solution method (PSERC, May, 2012). Furthermore, the proposed method is required to accurately detect an external load change as an external topology change and vice versa. Different possible scenarios which the proposed method would be able to identify include the following:

A. External topology change with constant external operating conditions;

B. External operating change with constant external topology;

C. Change in neither external topology nor external operating conditions; and

D. Change in both external system operating conditions and external network topology.

The proposed method's performance is tested using the IEEE 30 bus and 118 bus test systems (PSERC, May, 2012).

According to Kezunović and Peruničić (1999), it is well know that fault location can be quite accurate if phasors of voltages and currents are available from both ends of the transmission line, and if both phasor sets are synchronized. However, what is not as widely known is that fault location can be significantly improved for two extreme cases of signals measurements, namely:

1. If the measurements at both transmission line ends (and all ends in the case of multi-terminal lines) are taken synchronously (Gopalakrishnan, Kezunović, McKenna & Hamai (2000).
2. If phasor measurements are not available at both transmission line ends, but multiple sparse phasor measurements are available at several points in the power system network (Luo, Kezunovic & Sevcik, 2004).

2.7 Challenges of Phasor Measurement Unit

Sarasij (2011), for example, outlines the challenges of phasor measurement units. In this regard, the challenges outlined by Saraji (2011) include the following:

1. Diverse requirements from all utilities such as different application requirements and difference in infrastructure.
2. Wide area monitoring system (WAMS) architecture – present architecture not suitable for large system.
3. High investment – for example, initial high investment requirement acts as a deterrent.
4. Lack of related products – thus, related products like PDC (phasor data concentrator) and application software are inadequate.
5. PMU placement such as non-linear optimization problem.

6. Visualisation of PMU data – it is difficult to visualise the voluminous data provide by PMUs.
7. Communication of PMU data – expensive communication networks are required.
8. Communication delays – for example, there is delay in generating proper control signals.
9. Low frequency oscillation monitoring – algorithms are computationally heavy, all modes may not be captured, and distorted power system waveforms
10. Bad data estimation.
11. On line voltage instability prediction – this includes high computational requirement. Lack of system models are the main challenges for this application.

In Ghana, for example, the Northern Electricity Distribution Company (NEDCo) since its establishment has been responsible for the supply of electricity to the Northern Sector of the country. In pursuance of NEDCo's role in the distribution of electricity, the Mission Statement that was adopted was to procure and supply quality electricity, reliably, efficiently, safely in a sustainable manner to meet customer demand and stakeholder expectation in Ghana and the West African sub region (Volta River Authority, 2013). Additionally, the Energy Center, Kwame Nkruma University of Science and Technology (KNUST) (2012) reports that, the Technical Operations Manager of NEDCo, Ato Mensah indicated that NEDCo's networks cover about 64 percent of the geographical area of Ghana and that, the customers of NEDCo have grown substantially since its inception in 1987. However, NEDCo has not seen adequate investments in its distribution systems. For example, poor Information Communication Technology (ICT) infrastructure, low voltages at the feeders, poor metering and high commercial and technical losses are as some of the challenges within NEDCo distribution networks.

Furthermore, Ato Mensah (KNUST 2012) pointed out that monitoring systems through sensors and Intelligent Electronic Devices (IED), computational intelligence through advanced computational methods, and measurement and control systems using smart metering and advanced digital relays were identified as some of the basic requirements for smart grid systems. In this regard, Ato Mensah mentioned that NEDCo was taking some initiatives to position itself in readiness for smart grid technology. Thus, NEDCo was in advanced stages of awarding a contract for the implementation of Enterprise Geographic Information System (EGIS) to facilitate management of network assets. In addition, NEDCo was also planning to configure and improve its network through a Supervisory Control and Data Acquisition (SCADA) project that will help manage its operations. For example, the SCADA project will involve five control centers at Sunyani, Techiman, Tamale, Bolgatanga and Wa with consolidation reporting facilities in NEDCo's Head Office (The Energy Center, KNUST, 2012).

On the other hand, BPL Global signed a 5-year modern grid contract in partnership with BPL Africa with Ghana's national utility, Volta River Authority (VRA). The agreement implements smart grid technologies and broadband over power line (BPL) communications technology on the 11kV power distribution network of VRA. In July 2008, for example, BPL Global and BPL Africa deployed a pilot project for VRA demonstrating a modern grid. As a result, VRA declared the pilot project a great success, exceeding its goals for return on investment, improved energy efficiency and service reliability. Consequently, VRA decided to deploy the smart grid and BPL solutions across VRA's power distribution network. Thus, phase 1 of the project provides services to areas such as Akosombo (population 15,000), Sunyani (population 80,000), and Tamale (population 305,000) (BPL Global Ltd, 2009).

According to BPL Global Ltd., (2009), smart grid solutions to be deployed in Ghana for VRA include BPLG's Power SG Network Monitoring and Management, Rapid Fault Location, Demand Management, Non-Technical Loss Management, Substation Automation, Transformer Monitoring and CCTV Security Systems. In furtherance, the smart grid system is designed to reduce frequency and duration of outages, improve the balance of supply and demand, and improve operational efficiency. That is to say, smart grid technology will have a significant impact by improving the efficiency and reliability of energy delivery in Ghana (BPLGlobal, Ltd, 2009).

2.8 Summary

PMUs, however, are just one aspect of the whole information and data sharing system from all parts of the grid must be improved. Less sophisticated sensors also can be helpful; they must be integrated, along with improved software, for a system that operates like a finely tuned machine. With more computers, sensors and better software, utilities can assemble a more complete picture of what's happening across the grid in real time. This allows their systems to react more quickly to changes in load and system topology and to interact more effectively with the demand by providing real-time information (e.g., price signals) to consumers, who would be able to modify their consumption. Most of this interaction on the demand side can be performed automatically using computerized energy management systems at consumer locations.

CHAPTER THREE

METHODOLOGY

Over the past ten years, direct Phasor Measurement technology has progressed from research and development to commercial availability. However, everyday use of measured synchronous phasor data has remained largely limited to research or pilot installations. This is largely due to the perception that a large roll-out would require large, concentrated investments in phasor measurement unit (PMU) hardware, communications systems and application software. This chapter focuses on the implementation process of PMU in GRDICo for the enhancement of network monitoring and security analysis. In other words, this study proposed a comprehensive adoption of synchrophasors in GRIDCo wide-area monitoring system which can be installed at a large number of locations throughout the grid to make the grid more efficient. This would ensure that supply and demand is well balanced, and that all power stations are working in perfect synchronization.

3.1 Basic Building Blocks of the System

Generally, a synchrophasor system is more than just a collection of phasor measurement units (PMUs) and phasor data concentrators (PDCs). The implementation process of this system considered the communications and security infrastructure that tied these components together as well as the application of the data. The basic building blocks of the system were:

i. GPS satellite-synchronized clocks to provide the clock synchronization at a 1 second time interval.

ii. Phasor measurement units (PMUs) to help in the detection of external topology error using real-time internal data along with a few real-time data available through external PMUs which can in turn, help improve the internal security analysis.
iii. A phasor data concentrator in each substation (SPDC) which:
    a. Allowed the use of different phasor selections and reported rates to GRIDCo applications
    b. Stored phasor data and answered PDC commands to restore offline data when communication failures occur
    c. Provided indirect access to critical devices with PMU functionality
iv. Communication equipment
v. Visualization software.
vi. Power input: Since PMUs need to operate continuously, and particularly without interruption during disturbances, the installed PMU run on station DC power.

3.2.1 Installation Topology of the System

PMU installation requires access to signals to be measured, a timing signal to synchronize the measurement, data communications to send the measurement, as well as a power supply. In considering the installation topology for the system, priorities were established by considering locations that were important for GRIDCo and its neighbours (control area boundaries, generation sites, etc.), and coordinating installations with existing plans for maintenance and construction. Using this strategy, engineers of GRIDCo will be able to methodically add to the installed base of phasor measurement devices in subsequent periods.

The installation was done by specialized crews with participation from: the Information Services Department, Plant Engineering, Protection Maintenance, Communication Engineering, Commissioning, and Transmission Services of GRIDCo. The following steps were followed for the installation of PMU in GRIDCo:

i. Swilled bolt equipment rack to the floor of the substation following established seismic mounting requirements.

ii. The PMU along with a modem and other support equipment were mounted on the equipment rack

iii. Setting up a global positioning satellite (GPS).This involved the installation of the Global Positioning Satellite (GPS) antenna on the roof of the substations. Thus the GPS receiver provides a precise and universal time base. The availability of a very accurate clock through the Global Positioning System made it possible to synchronize phasor measurement units over a large area, and therefore detected early warning signals of larger grid problems. Specifically, by utilizing the GPS, the PMU provided a timestamp for each measurement to ensure that measurements taken from the different PMUs installed at the different locations were accurately compared.

   Most of the signals came from the south (in the Northern hemisphere) from the horizon to about 15 degrees north of vertical. Small obstructions more than 15 degree away from the antenna should not cause a problem, but a large flat obstruction within a few hundred meters could act as a reflector and cause multi-path problems.

iv. Sychronisation.This was achieved using same-time sampling of voltage and current waveforms through timing signals from the global positioning satellite (GPS). This synchronisation provided the capability to easily compare system data among the geographically dispersed units (sub-stations), creating wide-area visibility across large power systems.

v. Communications Devices/Communications Format Transitions

The PMU will need communication access and that cabling is required between the PMU and the communication interface. Since substations are sometimes notorious for high interfering signals, particularly during a nearby fault, the best policy was the use of fiber optic cable (FO) for all signals that travel outside of a single rack (grounding unit). In moving data from the substations to GRIDCo centralized control center at Tema, the PMU data transitioned across different communications interfaces.

vi. Installed "shunts" in all current transforms (CT) secondary circuits that were to be measured.

vii. Visualisation of PMU data.This step in involved configuring the PMUs, PDCs, applications, and visualization software are shown in Figure 3.1

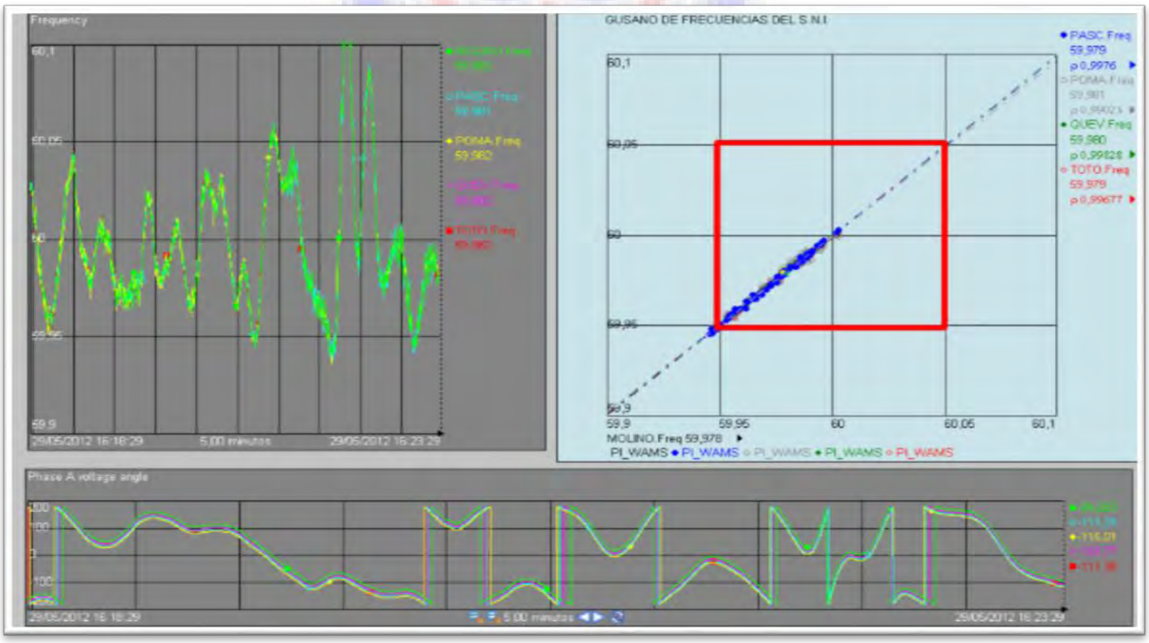

Figure 3.1: Configuring the PMUs, PDCs, applications, and visualization software

Source: Researcher Construct, 2014

All the nodes which are observed with the PMUs are represented on display, and are associated with voltage, frequency and power measurements in real time. The operator workplace consists of active elements, meaning that clicking on an element in Figure 3.2 opens a faceplate that displays the measured signals. In the same way access to advanced applications (phase angle monitoring, power oscillation monitoring) is realized. Figure 3.2 further shows the visualization for the installation of four PMU across the four substations.

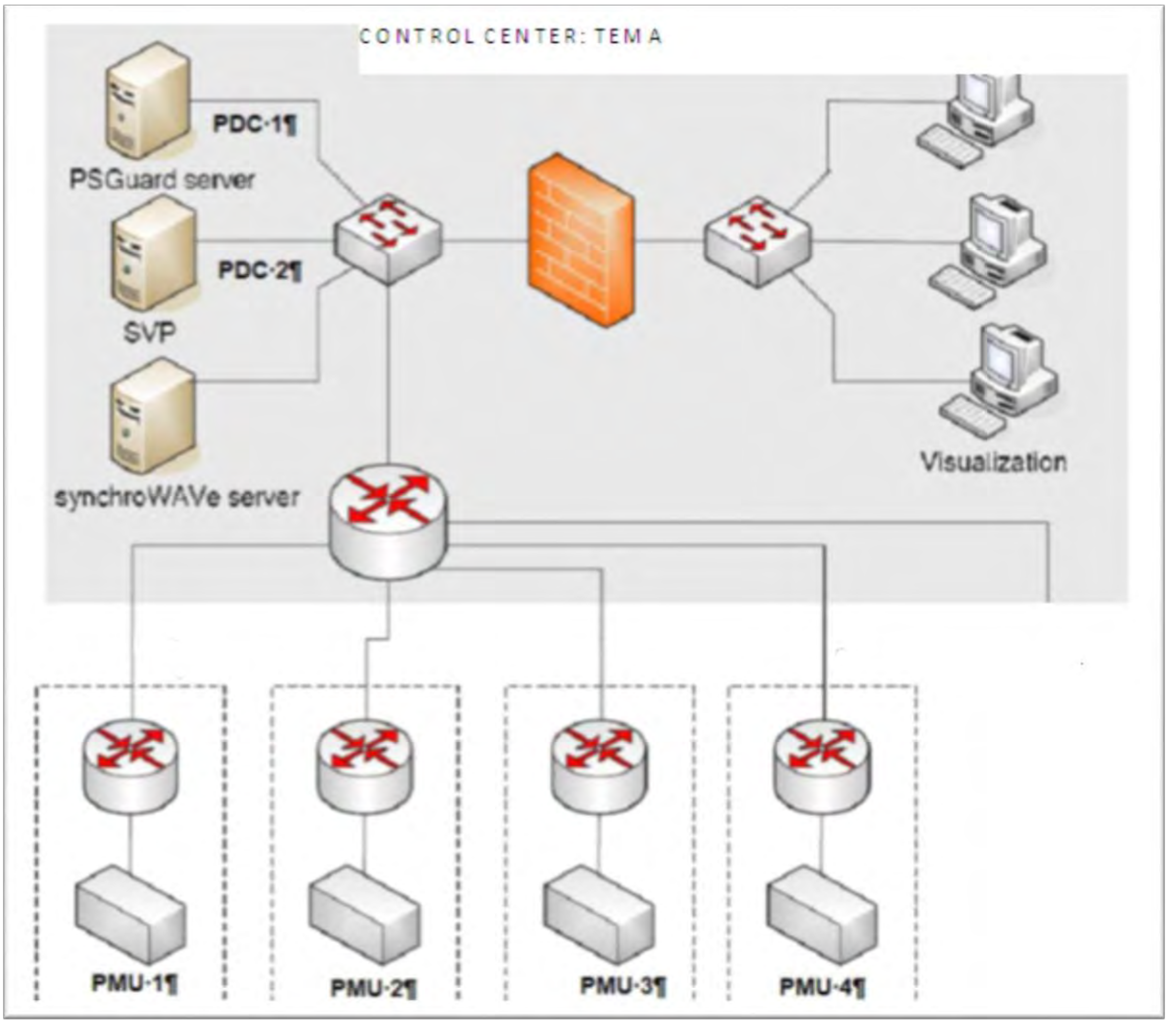

Figure 3.2 Visualization for the installation of four PMU across the four substations

Source: Researcher Construct, 2014

3.2.2 Setting up the PMUs

Besides making the physical connections to the potential transformers (PTs) and current transformers (CTs), PMU settings are created, verified, and loaded into each device.

The setting up process made sure that the PMU and its corresponding clock were working properly. Also, the independent system operators (ISO) Coordinated Universal Time (UTC) make sure that the date and time were correct. The settings between the substation PMUs and the connecting PDC matched since a common error is entering information for the PDC input that does not match the PMU. Figure 3.3 shows the stacking of the PDC.

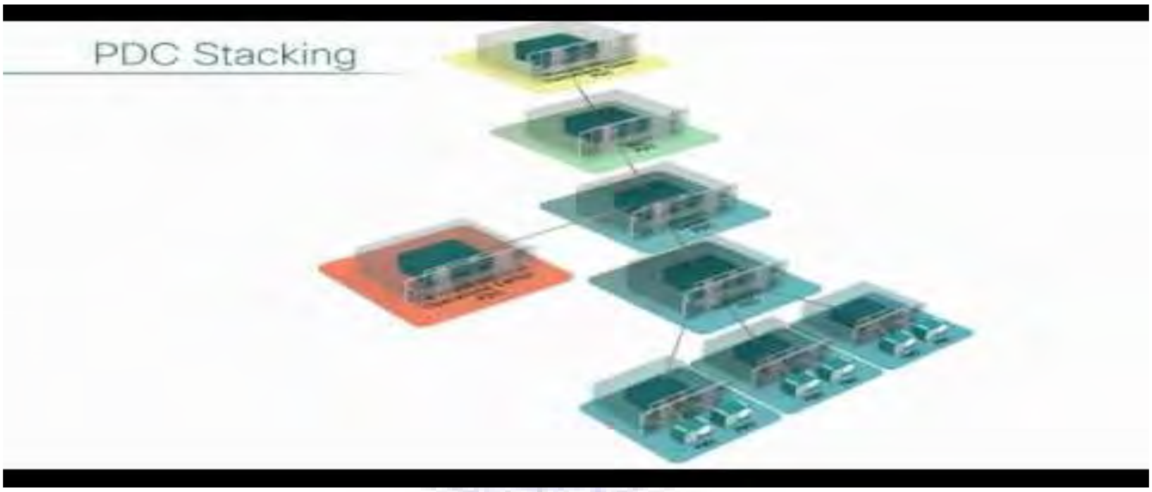

Figure 3.3 Stacking of the PDC

Source: Researcher Construct, 2014

The antenna for the setting of the GPS was mounted with a clear view to the south and as far north as possible. Checks were made around the mounting location for structures such as a flat metal roof that is oriented so that it could reflect a satellite signal to the antenna since satellites will traverse most points in the sky. The synchrophasor message rate was defined and set from 1 to 60 messages per second. This message rate matched the expected rate at the PDC

As per the IEEE C37.118 protocol, each PMU was given a station name, which was used by the downstream receiving device in order to distinguish the data source as a unique PMU. This setting ensured that it matched the station name entered into the PDC, since otherwise there would have been errors. Extra characters as well spaces were also watched out for during the setting up. Figure 3.4 represents the network architecture of the system implementation. In this case, the SEL-5073 at the control center (Tema) was configured with redundant inputs. In the case of a faulty primary PDC, or when there is a loss of communication on one data path, synchrophasor data are still collected and archived on the SEL-5073 without missing. Enabling the secondary data stream to the regional ISO is merely a matter of enabling the dedicated ISO output of the secondary PDC. This configuration required that the regional ISO at Tema create a dedicated input for the secondary PDC that is enabled. This method was useful for eliminating the need for a coordinated manual failover.

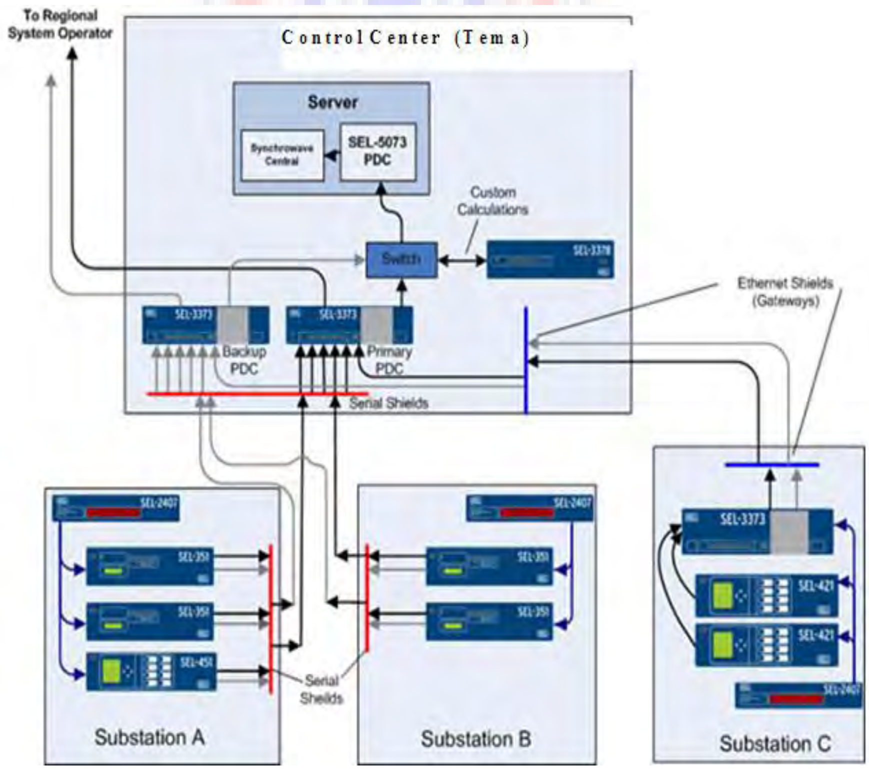

Figure 3.4: Network architecture of the system implementation

Source: Researcher Construct, 2014

Power System Observability: After mounting the PMU, the observability of the power system was checked. The typology observability of the system used the decoupled measurement model and graph theory where decision was based on logical operations. Only information about the network connectivity, measurement types and their locations was required. Generally, if a full rank spanning tree can be constructed with the current measurement set, then it gives the indication that the system will be observable as shown in Figure 3.5.

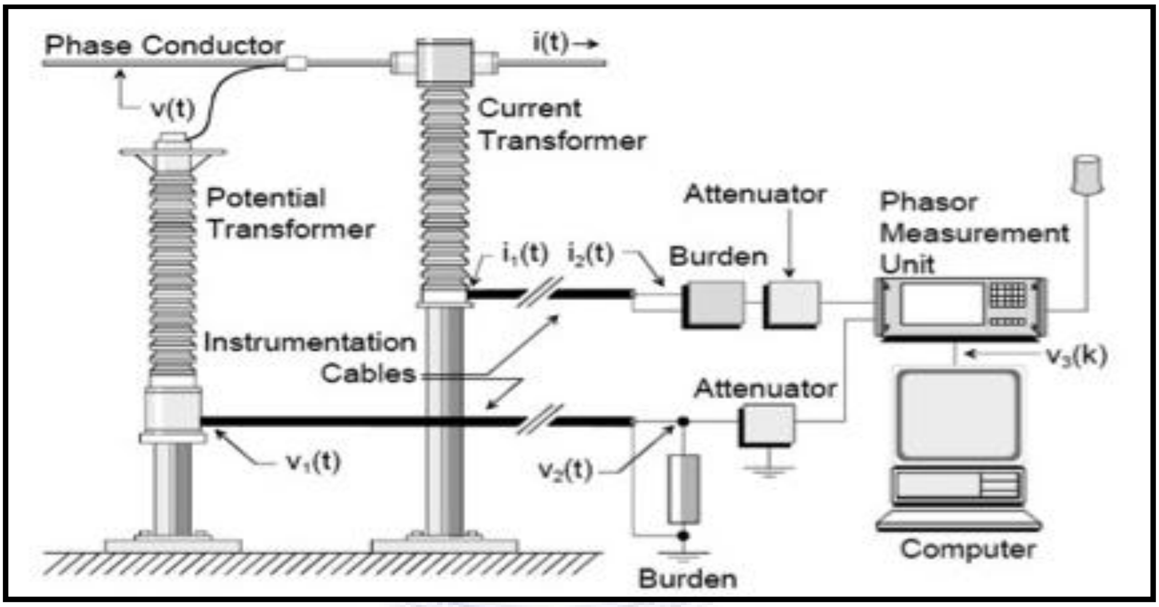

Figure 3.5: Power system observability monitoring the "heart beat" of power flowing through the electric grid

Source: Researcher Construct, 2014

If the system is observable, the placement stops, else the placement would have continued. Figure 3.7 shows the flowchart for the setting up of the PMUs. The flowchart was constructed as part of the project to aid in the implementation. Figures 3.6 further shows some images during the PMU setting up process

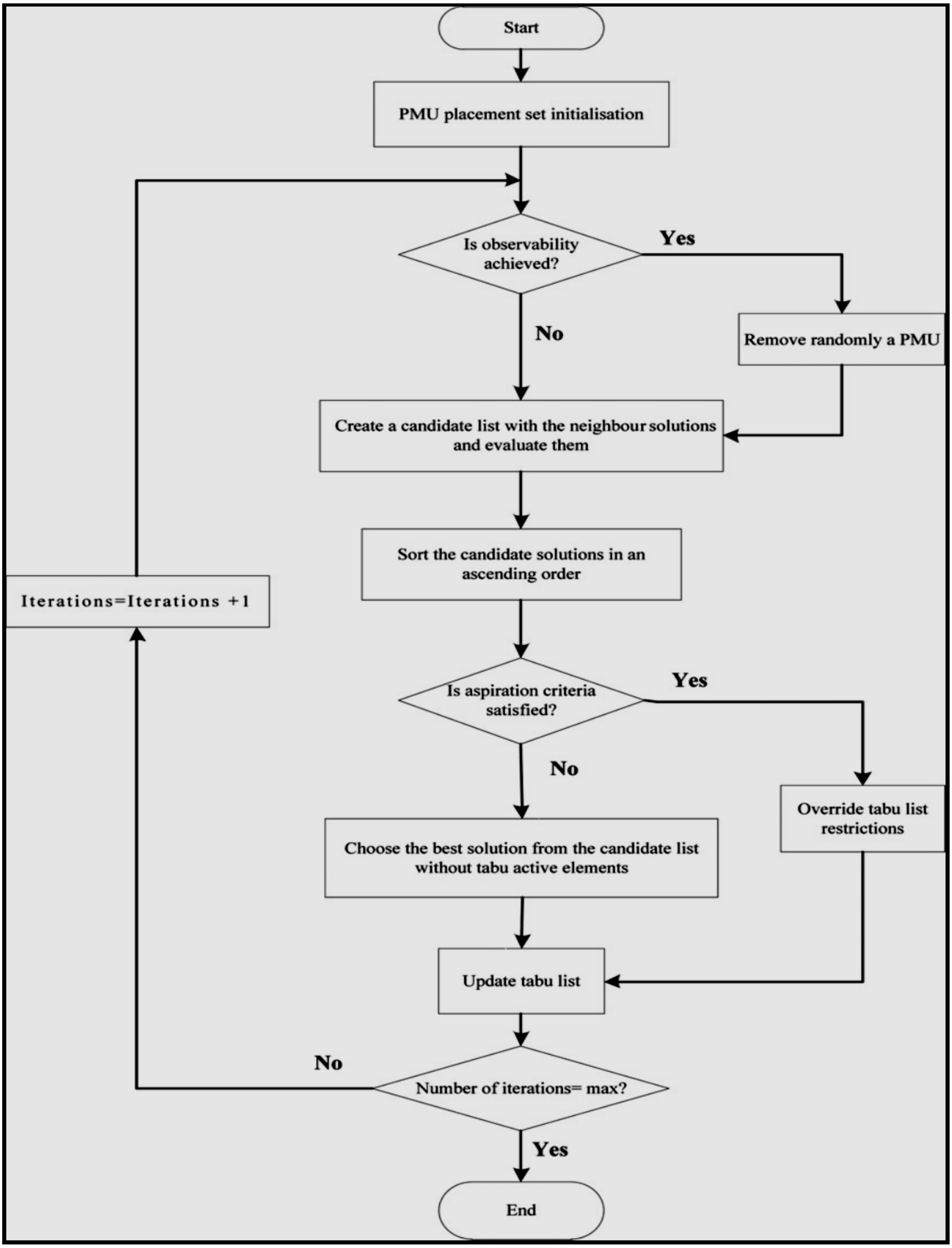

Figure 3.6: Flowchart for the setting up of the PMU

Source: Researcher Construct, 2014

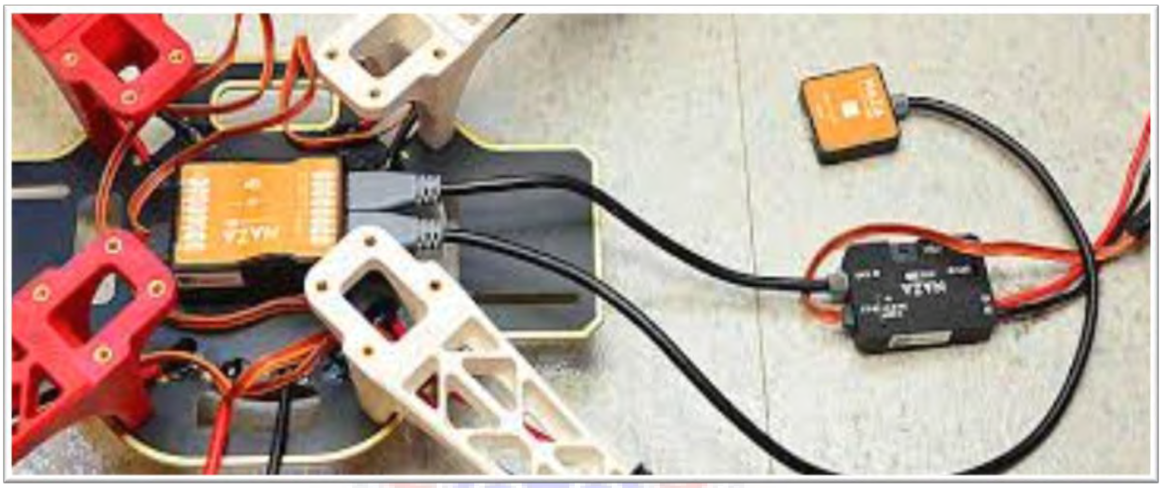

Figure 3.7: Images during the PMU setting up process

Source: Researcher Construct, 2014

3.2.3 Operational Topology of the System

The PMUs sent data to local PDCs, which in turn sent data to centralized PDCs located in GRIDCo control centers (Akosombo, Tasto, Kintapo and Goasu). The regional control center at Tema will send data on to the independent system operators (ISOs) to provide measurement information for the entire regional interconnection. With the system architecture shown in Figure 3.8, the PMUs data will travel over many communications links, through many communications devices, and through many PDCs before arriving at the final destination.

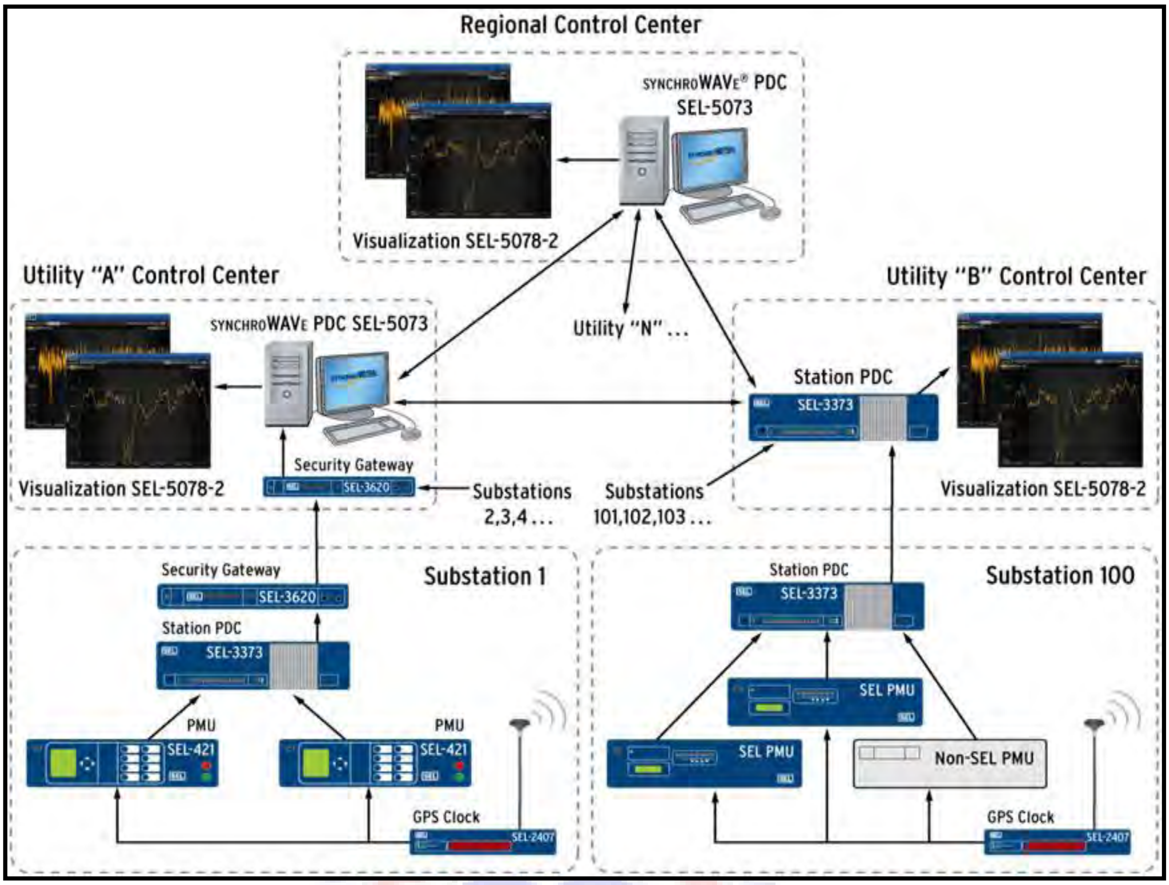

Figure 3.8: PMU to PDC Communications

Source: Researcher Construct, 2014

Depending on the location of the PMU, the communications link between the PMU and PDC can be a wired connection, a serial or Ethernet cable, or a wireless link (such as serial or Ethernet radio). Although Ethernet is the preferred communication interface for Phasor Measurement Units fitted at locations that are already connected to the command center via Transmission Control Protocol (TCP)/ Internet Protocol (IP), the vast majority of transmission lines and distribution transformers in Ghana are not connected to the Internet. In this regard, for this study, for most of the remote areas, the PMU data is sent via microwave or even satellite radios, which can add significant latency (>500 ms).

In moving data from the substations to GRIDCo centralized control center at Tema, the PMU data was transitioned across different communications interfaces. Additionally, the data would be encrypted and go through security gateways or firewalls that help securely transport data to the desired locations as shown in Figure 3.9.

Figure 3.9: Syncrowave displaying the average network latency of PMU on the upper half of the scree and average interpacket latency on the lower half of the screen.

Source: Researcher Construct, 2014

3.2.4 Configuration of the PMUs

Generally, the PMUs were configured as illustrated earlier. After the configuration of the PMUs, the following prospects seemed to be achieved:

i. The provision of dynamic information on the grid, which helps system operators and engineers in GRIDCo to initiate corrective actions to enhance the power system reliability.
ii. Data is now being streamed into the Control Center from far-flung points in the grid, where it is evaluated to give grid operators a clearer precise picture of what is happening in the system, online
iii. System operators in GRIDCo are now able to see what is happening beyond their own control area – an advance over traditional monitoring and protection method (SCADA)
iv. With the configuration of the PMUs, system operators in GRIDCo are now provided with real time information about voltage phase angle deviation, improve voltage control, improve system stability, security and reliability
v. There is also an improvement over the detection of oscillation, assessment of power system damping, increase power transfer at defined security, and early warning. This has reduced the frequency of power system collapse in GRIDCo
vi. Improvement in the calculation for real time path flow and optimal dispatch
vii. Provision of actual limits of the system instead of the conservative ones from offline calculations
viii. Improvement in backup protection
ix. Reduction in chance of recurrence of system outage
x. Reduction in time needed for a system restoration

Generally, after the configuration of the PMUs, there is advancement in early warning technology for GRIDCo power grid that helps system operators of GRIDCo to ensure grid reliability by detecting and counteracting the first signs of grid instability.

3.2.5 Installation Tests, Maintenance and Evaluation

Some quality assurance testing was done to be sure that the units work in the planned system and are reasonably in calibration. The testing involved putting the signals into the PMU and checking that the output meets specifications for a few magnitude and phase angle checks as follows:

i. For off-line applications, reliable data acquisition and archiving are the most important requirement, while there is no hard time limit to meet.
ii. For off-line applications, current placement plan calls for 434 voltage positive sequence phasors and 434 current positive sequence phasors measurement
iii. For real-time applications, it is important to meet the overall speed requirement, preliminarily set at 2 second latency, reliable data acquisition and archiving are also important
iv. For overall system, the scalability of the system must be considered

The performance of the installed PMUs needs to be evaluated as well as maintained, so that their impact on applications can be characterized and understood so as to provide guidelines to the users. For the maintenance of the system, a small group of system engineers of GRIDCo must meets regularly to maintain the implementation plan and also coordinate the installation between departments a to help promote the PMU program within the company.

i. Training classes for system operators
ii. Use positive sequence voltage phase angles
iii. Analysis of zero and negative sequence angles
iv. Add phase portrait displays
v. Add voltage stability displays QV charts and PV charts

vi. Automatic notifications of oscillations

vii. Plots of mode shapes

In order not to yield to different or inaccurate readings, it is recommended that PMUs should be sourced from one vendor since multiple vendors could introduce multi-vendor source of conflicts, standards, protocols, or performance characteristics.

3.3 Survey Methodology

3.3.1 Research Design

To meaningfully conclude and answer the formulated research questions and objectives, this study employed both qualitative and quantitative strategies (Mixed-methodology). In-depth interviews with management of the GRIDCo in charge of network monitoring and security analysis of grid were the qualitative methods employed in this study, whereas the quantitative design was employed using structured questionnaires for staff comprising (System Controllers, Power Engineers, Power system engineers and System operators) of GRIDCo.

The crucial aspect in justifying a mixed methodology research design is that both single methodology approaches (qualitative only and quantitative only) have strengths and weaknesses. Employing both qualitative and quantitative approaches in this study increased the comprehensiveness of the overall findings by showing how the qualitative data provides explanations for statistical data as well as increased the methodological rigour as findings in both phases could be checked for consistency.

It was against these backgrounds that this study employed the mixed design to evaluate the enhancement of network monitoring and security analysis using phasor measurement unit in GRIDCo. Using a mixed method approach greatly enhanced the understanding of pharsor measurement units and their implications for network monitoring and security analysis as well as the challenges management of GRIDCo encounter in using phasor measurement unit for network monitoring and security analysis of grid. This combination of approaches was necessary because of the wide range of data needed to develop effective communication in the effective implementation of pharsor measurement units.

3.3.2 Study Population

The target population for this study involves employees of GRIDCo Specifically, the units of analysis include System Controllers, Power Engineers and System Operators of GRIDCo However, house men and causal system controllers, power engineers, power system engineers and system operators of GRIDCo were not included in this study. This was because they were not considered permanent engineers of GRDICo and might not be able to effectively evaluate pharsor measurements units' enhancement of network monitoring and security analysis in providing a reliable energy.

Also, management of GRIDC in charge of network monitoring and security analysis participated in the study. Statistics from the human resource of GRDICO shows that there are 240 system controllers, power engineers, power system engineers and system operators employees.

3.3.3 Sample and Sampling Techniques

To effectively sample the study population, the study employed both the stratified and purposive sampling methods. The purposive sampling method was used to sample managers in charge of network monitoring and security analysis. In this method, the researcher sampled with a purpose in mind. The purposive sampling method was considered as the most appropriate for sampling managers since they are directly involved in network monitoring and security analysis of grid.

On the other hand, the stratified sampling method was used to sample system controllers, power engineers, power system engineers and system operators of GRIDCo. The different target population made the study population to vary, hence the need to sample each subpopulation independently. Thus the study divided the staff of the engineering department into homogenous subgroups (system controllers, power engineers, power system engineers and system operators) before sampling. Specifically, the study employed the stratified random sampling because:

- The method allowed for greater precision since the populations had been chosen so that staff performing the same engineering function were as similar as possible in respect of the characteristic of interest;
- The method reduced the sampling error
- The method guaranteed a prescribed number of observations from each department.

The sample size of every statistical study to a very large extent has an influence on the level of precision obtain from such studies. Many researchers have argued that the larger the sample size for a particular study, the more accurate the result obtained.

The sample size for the study is determined using the Slovin Formula (Umar, 2000), $n = \frac{N}{1 + Ne^2}$,using population size of 240 and significant level of 0.05, then the sampling size is 150

3.3.4 Data collection

Both quantitative and qualitative data were obtained in this study. Quantitative data were obtained from staff through structured questionnaire while qualitative data were obtained from management through unstructured interviews.

The quality of a research may be influenced by the types and sources of evidence used. Various sources and types of evidence abound and could be used for a study as indicated by Yin (2003). This study shall employ both primary and secondary data (multiple source of evidence). The primary sources of data were obtained directly from the study's unit of analysis through the use of interviews and structured questionnaires. Secondary data on the other hand were obtained through library research of books, journals, and the internet using search engines like Google and Mozila.

Since the study made use of both the qualitative and quantitative research methods to improve the validity and reliability of the result, different instruments were used for gathering data relevant to answering the research objectives. Structured questionnaires were used to obtain quantitative data while in-depth interviews were used for gathering qualitative data.

Management of GRIDCo in charge of network monitoring and security analysis participated in the study through the use of an interview guide. The interview sought to ask questions in relation to the study's topic. The interviewees were selected based on their experiences and roles play in rolling out an effective network monitoring system for reliable energy distribution.

According to Tannor (2011), ultimately, designing the perfect survey questionnaire, interview guides and protocols is impossible. However, effective surveys can still be created. To determine the reliability of a survey instrument, it is necessary for it to be pre-tested before actually using it. Both the questionnaire and the interview guide were subject to pre-testing with five engineers and one management. Pretesting of the survey instruments helped identify potential challenges to be encountered during the main study which improved the questions in terms of wording, repetition and key issues to be investigated.

To adequately answer the research objectives of the study, the questionnaire was structured into five parts. The first relates to the socio-demographic characteristics of the respondents including age, gender, educational background, number of years of working with GRIDCo. The other sections are designed in line with the objectives of the study. Regarding the type of questions, the questionnaire contained both opened and close-ended questions. To make data analysis as easy as possible, majority of the questions were coded. In other words, most of the questions were closed-ended.

The questionnaire was self-administered. Thus, respondents responded to the questionnaire without the help of the researcher since they are literates who could read and write hence understand the contents of the questionnaire. However, permission was sought from the head of GRIDCo to seek the consent of staff and management to participate in the study. Also, not to interfere with the daily activities of staff, the Head distributed the questionnaires to staff on behalf of the researcher across the engineering units of which completed questionnaires were returned to the office of the Head after a two week period. This gave the respondents enough time to study the items on the questionnaire to adequately respond to them.

The interviews were tape-recorded with the permission of all the respondents and supported with notes taken by the researcher. Each interview lasted averagely between 20-30 minutes. This eliminated the boredom often associated with long interviews.

3.3.5 Method of Data Analysis

Before analysing the data from the field, all completed questionnaires and interview guides were adequately checked for completeness. Thus data cleaning and processing were done to identify errors in data recording prior to the data analysis. The quantitative data gathered was coded and entered using the Statistical Product and Service Solutions (SPSS) , version 18. Quantitative analysis involved the generation of descriptive statistics. Descriptive statistics such as frequencies and percentages in the form of tables and figures were used to present the results. Qualitative analysis also involved the categorisation of data from interviews and field notes into common themes.

CHAPTER FOUR

RESULTS AND DISCUSSION

The results of the data analysed and the discussion of the findings are presented in this chapter. The discussion involves the possible implications of the findings. In discussing the findings, attempts were made to relate the findings of the study to the pertinent concepts and theories discussed in the review of related literature in Chapter Two.

The study explored the enhancement of network monitoring and security analysis using phasor measurement units. The results are presented in four parts where each part focused on one of the objectives of the study. The first part of the chapter presents the demographic characteristics of the respondents. The second section analysed and discussed network monitoring and security analysis of grid in GRIDCo while the results on the challenges encountered in network monitoring and security analysis in GRIDCo was the focus of the third section. The last section of the chapter analysed and discussed the prospects associated with the use of phasor measurement units (PMUs) in network monitoring and security analysis of grid in GRIDCo.

4.1 Demographic Characteristics of the Respondents

This section presents the analysis and discussions of respondents' demographic characteristics. In all, there were 160 respondents who were made up of 80 System Operators, 40 System Engineers and 30 Controllers as well as 10 management of GRIDCo in charge of network monitoring and security analysis. The following six demographic variables were analysed: gender, age, educational background, number of years of working with GRIDCo, department under which the respondents work and the specific role of the respondents' in relation to network monitoring and security analysis.

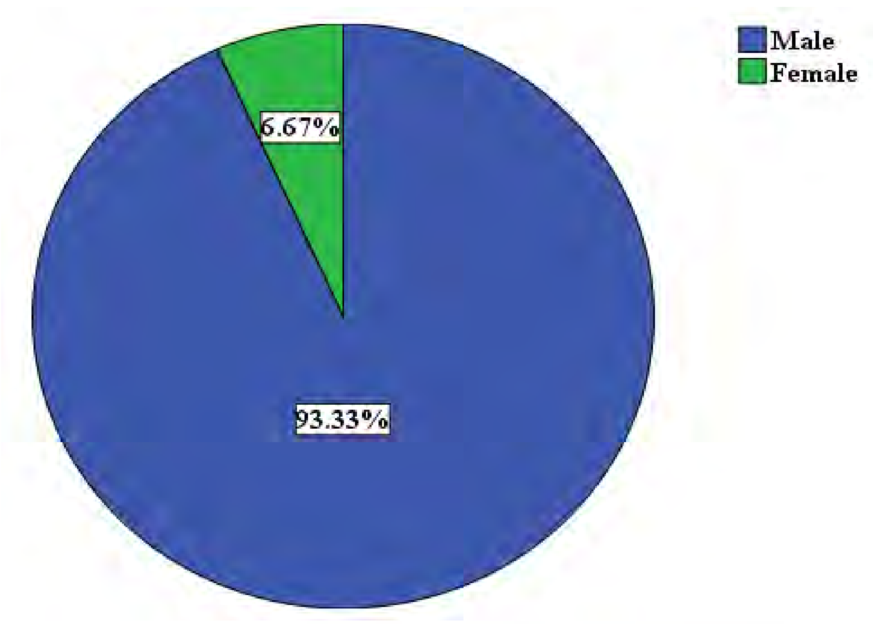

Figure 4.1 Gender Distribution of the respondents

Figure 4.1 show that more than 90 percent (93.3%) of the respondents were males. Thus the males who responded to the study were 86.6 percent higher than the proportion of the females who also responded to the study. Generally, it can be deduced that the male respondents significantly outnumbered the females giving the indication that females have not been attracted to the engineering profession.

The ages of the respondents were also analysed. Descriptive statistical analysis presented an average age of 35 years with minimum and maximum ages of 24 years and 50 years respectively. A standard deviation of 8.048 was also obtained giving the indication that the ages of the respondents were uncluttered around the mean age. Table 4.1 further shows detailed result of the ages of the respondents based on the minimum and maximum ages obtained.

Table 4.1: Age of Respondents

Age	Frequency	Percentage
24-28	58	38.5
29-33	11	7.6
34-38	35	23.1
39-43	23	15.4
44-50	23	15.4
Total	150	100.0

It is noted in Table 4.1 that the most prevalent age group among the respondents was 24-28 years (38.5%) followed by 34-38 years (32.1%). Further assessment of the results in Table 4.1 shows that more than half of the respondents (53.9%) were aged above 33 years. Generally, it can be deduced from the ages that they respondents were young and could be economically viable and productive in enhancing the energy sector of the country.

The educational background of the respondent was also analysed with the results presented in Table 4.2 below.

Table 4.2: Education of respondents

Response	Frequency	Percentage
Secondary/Technical in electrical engineering	10	6.7
HND in electrical engineering	50	33.3
First degree in electrical engineering	80	53.3
Second degree in electrical engineering	10	6.7
Total	150	100.0

More than half (53.3%) of the respondents had a First Degree in Electrical Engineering followed by HND in Electrical Engineering (33.3%) while the respondents with Secondary/Technical and Second Degree in Electrical Engineering respectively were the least (6.7%). Generally, 60 percent of the respondents had a University Degree. Although generally, it can be deduced that a significant proportion of the respondents had tertiary educational backgrounds, the educational background of the respondents need further up-grading considering the technicalities involved in undertaking networking monitoring and security analysis using pharsor measurement unit as noted by Emami (2011).

Further analysis was carried out on the educational background of the respondents across gender with the results depicted in Table 4.3.

Table 4.3: **Education across gender**

	Education								
	Secondary		HND		First degree		Second degree		Total
Male	10	7.1	50	35.8	50.0	10	7.1	140	100.0
Female	0	0.0	0	0.0	100.0	0	0.0	10	100.0
Total	10	6.7	50	80	53.3	10	6.7	150	100.0

Half (50.0%) of the male respondents had a first degree as against all (100.0%) the female respondents who also had a first degree. However, none of the females had second degree. Generally, all the females who responded to the study had a university degree while more than half (57.1 %) of the males also had a university degree. This implies that although there were few females in the electrical engineering profession, the few who are in the profession have some higher education.

The number of years for which the respondents have worked with GRIDCo was also studied. Descriptive statistical analysis shows that averagely, the respondents have worked with GRIDCo for seven years with minimum and maximum years of one year and 21 years respectively. Table 4.4 further shows the detail results on the period for which the respondents have worked with GRIDCo.

Table 4.4: Years of working with GRIDCo

Response	Frequency	Percentage
1-7	70	46.7
8-14	60	40.0
15-21	20	13.3
Total	150	100.0

The most prevalent period for which the respondents have worked with GRIDCo is 1-7 years (46.7%) followed by 8-14 years (40.0%). Although a marginal proportion of the respondents were aged 15-21 years, generally, it can be concluded that the respondents have had longer years of working with the Company. This long period of working with the Company is expected to exhibit in the level of experience the respondents attached to their work in relation to network monitoring and security analysis as well as being well informed about the challenges they encounter in undertaking network monitoring and security analysis.

The department under which the respondents currently work was also analysed with the results shown in Table 4.5.

Table 4.5: Department under which the respondents work

Response	Frequency	Percentage
Northern network services	50	33.3
Protection and control	30	20.0
Electrical maintenance	20	13.2
Communication	10	6.7
Line maintenance	10	6.7
Operation and maintenance	10	6.7
Operation and safety	10	6.7
System operation	10	6.7
Total	150	100.0

The Northern network services department had the highest proportion of participants (33.3%) which was followed by the Protection and Control Department (20.0%).

4.2 The Efficiency Network Monitoring and Security

This section of the chapter analysed the effectiveness and efficiency of the network monitoring and security of grid in GRIDCo. As part of exploring network monitoring and security analysis of grid in GRIDCo, the study examined the role respondents' play in GRIDCo in relation to network monitoring and security analysis. The following major roles emerged:

- Monitoring and protection of station equipment
- Maintenance of transmission lines
- Monitoring the power flow on the national grid

- Monitoring and replacing of faulty substation equipment
- General electrical maintenance which includes transformers, breakers etc.

In this regard, the respondents were asked to describe the effectiveness and efficiency of networking monitoring and security analysis of grid in GRIDCo. The following descriptions were significant among the respondents:

i. Network monitoring has been enhanced with the upgrade of the SCADA facilities
ii. It is somehow consistent and effective in terms of monitoring of the system
iii. Network monitoring is somewhat better at the national control centres than that of the local areas because, the local areas do not have the necessary monitoring structures.
iv. Generally, network monitoring has not been so effective

The respondents also described the efficiency of traffic monitoring by GRIDCo using SCADA. The results are presented in Table 4.6.

Table 4.6: Description of traffic monitoring by GRIDCo using SCADA

Response	Frequency	Percentage
Very efficient	40	26.7
Somehow efficient	90	60.0
Inefficient	20	13.3
Total	150	100.0

Majority (60.0%) of the respondents rated the efficiency of traffic monitoring by GRIDCo using SCADA as “Somehow effective” while the least proportion of the respondents (13.3%) rated it as “Ineffective”. Generally, it can be deduced from Table 4. 6 that the use of SCADA to monitor traffic by GRDICo has not been very efficient. This the respondents explained by attributing to the following factors:

- The overall network is not fully controlled by SCADA
- Not all equipment used at the various substations are SCADA. In this regard, one of the respondents stated:

Not all substations and power equipment have SCADA coverage

- SCADA is not totally reliable. One of the respondents stated:

SCADA is not so consistent in terms of monitoring the system

Furthermore, the respondents described the occurrence, disturbances and disruptions in traffic in the network.

Table 4.7: Occurrence, disturbances and disruption in traffic in the network

Response	Frequency	Percentage
High frequent	10	6.7
Somehow frequent	130	86.6
Infrequent	10	6.7
Total	**150**	**100.0**

More than 80 percent (86.6%) of the respondents described the occurrence, disturbances and disruptions in traffic in the network as somehow frequent. The results give an indication that the occurrence, disturbances and disruptions in traffic in the network is a common experience the Company encounters in network monitoring and security analysis of grid. This one of the management explained that, it is the main reason for which the Company must complement the current SCADA technology with other advanced technology such as PMU to reduce the occurrences, disturbances and disruption in traffic in the network.

4.3 Challenges Encountered in Network Monitoring and Security

Sajal (2012) noted that providing reliable electricity is a tough challenge with so many components and unseen conditions. This section of the study analysed the problems encountered in the network monitoring and security analysis of the network. The study investigated whether or not there are challenges encountered in network monitoring and security analysis of grid in GRIDCo. The results are presented in Table 4.8.

Table 4.8: Existence of challenges encountered in network monitoring and security analysis

Response	Frequency	Percentage
Yes	90	
60.0		
Not sure	50	
33.3		
No	10	6.7
Total	**150**	**100.0**

Majority (60.0%) of the respondents admitted that challenges are encountered in network monitoring and security analysis of grid in GRIDCo. Generally, from Table 4.8, it can be deduced that there are numerous challenges encountered by GRIDCo in network monitoring and security analysis. The major challenges that the respondents mentioned included:

- The absence of proper structure in the network at GRIDCo
- Inconsistency in the internal communication system
- Power lines are lost. One of the respondents stated

4.3.1 Power outage at the Generation Stations and on Transmission lines

- Unavailability of centralized disturbance recorders for timely analysis of faults in the network
- Analysis of data manually takes time which slows the work done.
- There is difficulty in locating a particular fault at a time
- Frequent outages and system collapses
- Difficulties in monitoring the load on the transformers

The study further disaggregated the challenges encountered by separately analysing the views of the respondents in relation to the challenges encountered in network monitoring of grid by GRIDCo. Figure 4.2 further illustrates the findings.

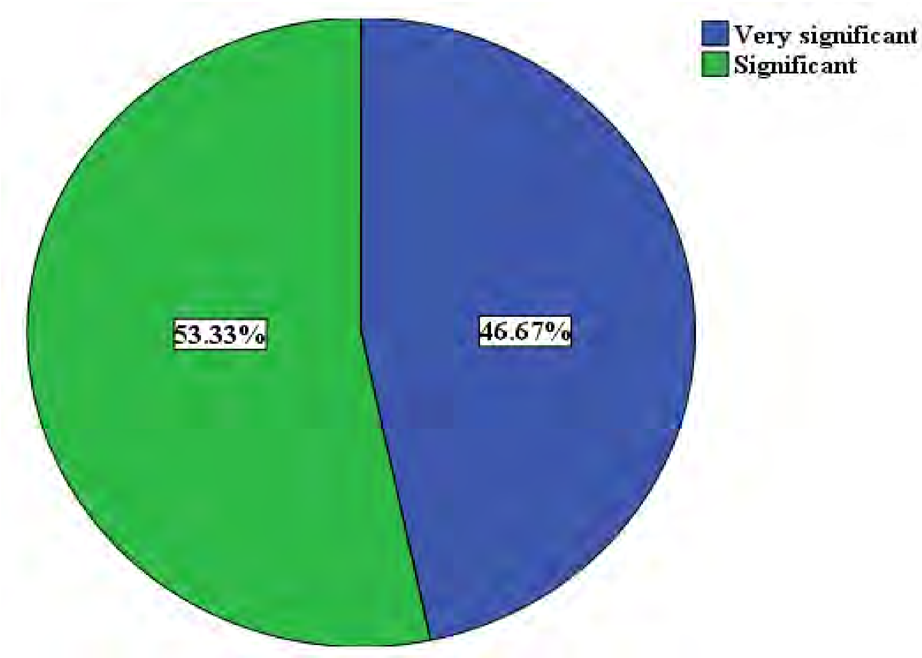

Figure 4.2: Challenge of network monitoring of grid by GRIDCo

In Figure 4.2, it is noted that a little over half (53.3%) of the respondents rated the challenges encountered in network monitoring of grid by GRIDCo as "Significant" whereas 46.7 percent rated it as "Very Significant". None of the respondents rated the challenges encountered in this regard as "Insignificant'. This gives the indication that there are numerous challenges encountered in network monitoring of grid by GRIDCo .

In this regard, the study investigates the significant challenges that are encountered in network monitoring of grid by GRIDCo. The following major challenges were identified by the respondents.

- Frequent equipment breakdown as the SCADA equipment freezes often. One of the respondents stated:

  > *When the SCADA equipment breaks down, networking monitoring becomes very difficult which causes inconvenience in the transmission system*

- Lack of effective communication in real time

- Wiring of equipment to SCADA has not been completed. One of the respondents stated:

  Substation equipment wiring to SCADA is yet to be completed

- Defect of equipment due to environmental conditions
- Lack of modern equipment which will facilitate network monitoring
- Obsolete analogue meters

The study also analysed the views of the respondents in relation to the challenges encountered in the security analysis of grid by GRIDCo. Figure 4.3 illustrates the findings.

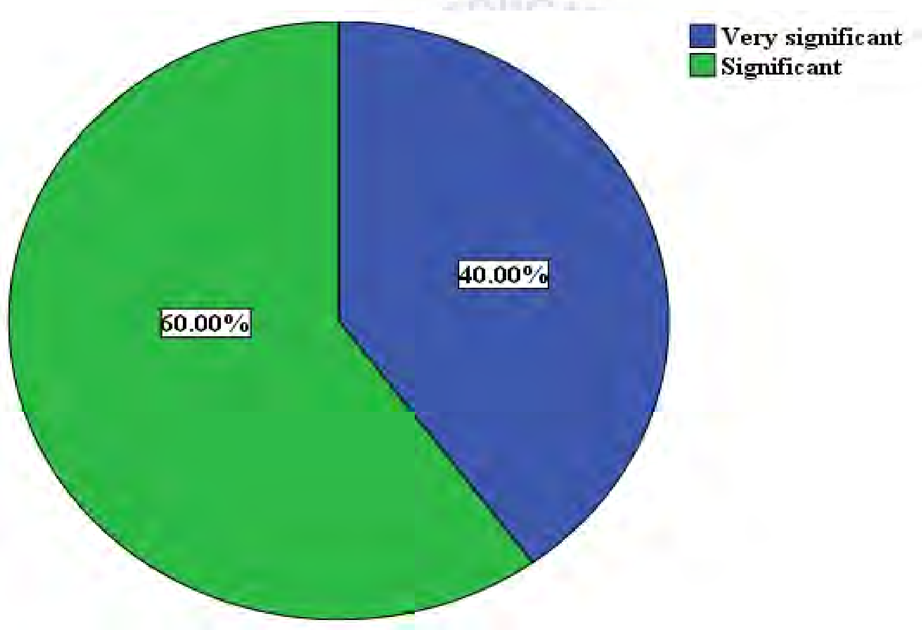

Figure 4.3: Challenge of security analysis of grid by GRIDCo

Majority (60.0%) of the respondents rated the challenges encountered in security analysis of grid by GRIDCo as "Significant" whereas 40 percent rated it as "Very Significant". The study can therefore deduce that there are significant challenges encountered by GRIDCo in security analysis of grid. Comparison of the results in Figure 4.3 to that of Figure 4.3 suggests that there are more significant challenges encountered by

GRIDCo in security analysis of GRIDCo as compared to network monitoring although, generally, there are significant challenges for both network monitoring and security analysis of grid by GRIDCo.

The following major challenges were identified by the respondents as confronting security analysis of grid by GRIDCo.

- Inadequate training of personnel on power analysis. One of the respondents stated: *The security personnel are not trained often on how to monitor the system and also on how to carry out the readings*
- *Lack of* the required equipment to record disturbances in the system
- Lack of effective communication between security personnel

The study further explored the views of the respondents on eight challenges that are significantly encountered in network monitoring and security analysis of grid in GRIDCo as identified from the literature. The results are presented in Table 4. 9.

Table 4.9: Significant challenges encountered in network monitoring and security analysis of grid in GRIDCo

Response	Frequency	Percentage
Real time monitoring and control	100	66.7
Post power disturbance analysis	100	66.7
Power system state estimation	90	60.0
Overload monitoring and dynamic rating	70	46.7
Adaptive protection	70	46.7
Power system restoration	60	40.0
Validation and tuning of system models	40	26.7
Planned power system separation	30	20.0

The three most significant challenges encountered in network monitoring and security analysis of grid by GRIDCo as shown in Table 4.9 are real time monitoring and control, post power disturbance analysis and power systems state estimation. In responding to the issue of real time monitoring and control, the management of the System Control Department indicated:

From a system reliability standpoint, the problem of real-time measurements do not allow early identification of potential problems both locally and regionally

Conducting post power disturbance analysis noted as a major challenge in network monitoring and security analysis could be explained by Abur and Exposito (2004) assertion that working with traditional data recorders is very difficult and time consuming process due to the fact that the data available through such devices are not time synchronised and it is very difficult for the engineers to align the timeline of recorded data.

One of the respondents explained that the traditional SCADA is not sufficiently able to evaluate data from around the system, matched by the time-stamps, to can produce real-time and evolving snapshots of system health. These challenges have affected the reliability of power supply. According to one of the management who responded to the interviews:

For the transmission and distribution system to be more affordable, reliable and sustainable, the grid has to be smarter

This is consistent with Sajal (2010) assertion that after the electricity is generated, it requires a reliable, efficient and affordable transmission system to deliver power from utility to customer.

The study further noted from the management that real time monitoring and control as the major challenge encountered in network monitoring and security analysis of grid could be explained by the fact that the current traditional systems for network monitoring and security analysis including the SCADA could not satisfactory monitored the grid system. Relating this to Nuqui et al. (2005) view that URE operation of power systems requires close monitoring of the system operating conditions, it implies that there is the need to adopt a system such as the PMU which are becoming an important element of wide area measurement systems used in advanced power system monitoring, protection, and control applications.

The least significant challenges encountered in network monitoring and security analysis as shown in Table 4.9 were validation and tuning of system models and, planned power system separation. Figure 4.4 further presents a graphical representation of the results in Table 4.9.

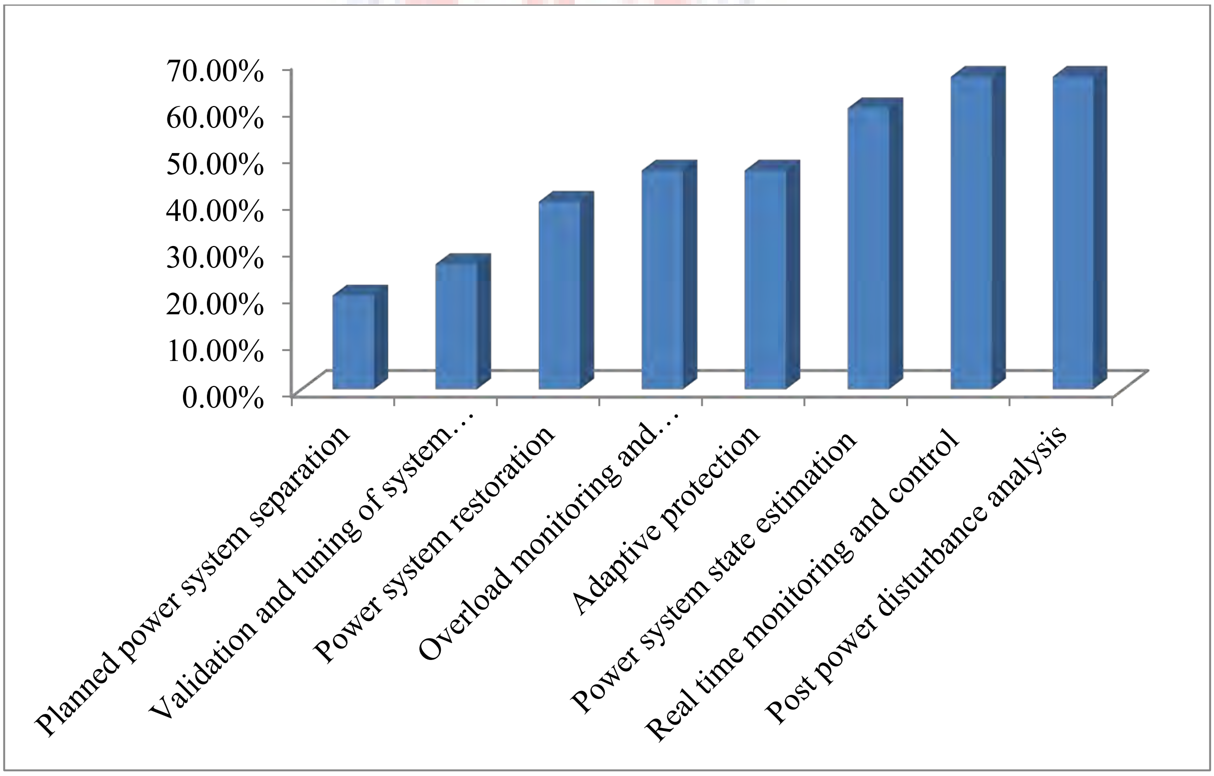

Figure 4.4: Significant challenges encountered in network monitoring and security analysis of grid in GRIDCo

In Figure 4.4, overload monitoring and dynamic rating not been a major challenge confronting GRIDCo in network monitoring and security analysis in the absence of the use of PMU could be explained by Rockefeller, Wagner, Linders, Hicks and Rizy (1988) view that there are many software and devices already available to power system utilities that enable them to monitor the power system equipment, however, using PMUs can make the monitoring more accurate.

4.4 The Prospect Associated with the use of PMU

4.4.1 The Use of Phasor Measurement Units in Network Monitoring and Security and Security Analysis of Grid by GRIDCo

According to the United States Energy Information Administration (2012), phasor measurement units (PMUs) are a new "smart" technology being deployed throughout the world to monitor what happens on the transmission grid. This section of the chapter examined the prospects associated with the use of phasor measurement units. This is to help enhance networking monitoring and security analysis of gird in GRIDCo by using PMUs.

The study explored the views of the respondents on the extent to which network monitoring and security analysis of grid could be enhanced using PMU with the results shown in Figure 4.5.

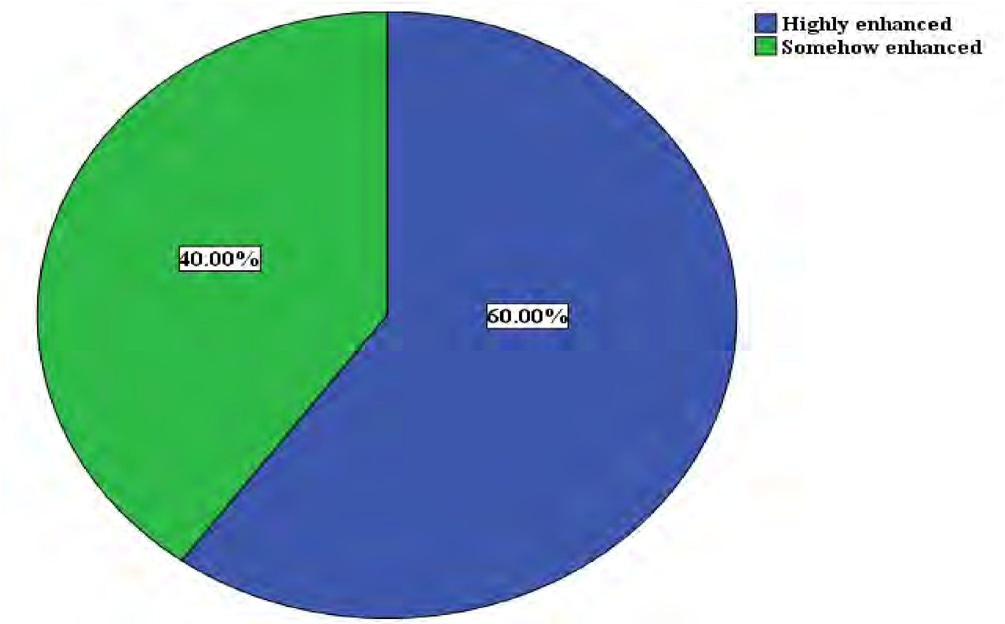

Figure 4.5: Prospects associated with the use of phasor measurement units

None of the respondents was of the view that the use of phasor measurement units in network monitoring and security analysis could neither be less enhanced nor not enhanced. However, the majority (60.0%) of the respondents indicated that network monitoring and security analysis of grid by GRIDCo could be highly enhanced using phasor measurement units. From Figure 4.5, it can be deduced that there could be numerous prospects to be associated with the use of PMUs for network monitoring and security analysis of grid, and that PMU could be an important and promising technology which will make future grid smarter as indicated by Sajal (2012).

The prospects to be associated with the use of the phasor measurement unit as expressed by the respondents included:

- It would increase power quality as it gives precise analysis
- Demand response mechanisms to manage the grid effectively
- Improvement of power factor correction
- Effective monitoring and analysis of network
- Accurate and consistent measurement when monitoring the network

Specific ways in which network monitoring and security analysis could be enhanced using phasor measurement as enumerated by the respondents included:

- It can minimize the occurrence of load shedding
- It can automate the correction of sources of systems degradation
- It can help in early restoration of power supply to the system
- It can further enhance real time control or problems
- It can enhance voltage and current stability
- It can enhance timely fault location

The study also analysed the extent to which the challenges in identified in Table 4.9 could be overcome by using pharsor measurement units. Specifically, the study analysed to what extent real-time monitoring and control could be enhanced through the use of PMU. Table 4.10 shows the results.

Table 4.10: Enhancement of real time monitoring and control using PMU

Response	Frequency	Percentage
Most enhanced	130	86.6
Enhanced	10	6.7
Less enhanced	10	6.7
Total	**150**	**100.0**

A significant proportion of the respondents (86.6%) in Table 4.10 were of the view that real time monitoring and control could be most enhanced using pharsor networking monitoring and security analysis of grid in GRIDCo. This meant that PMU could enable real-time computer control to protect the stability and reliability of a power grid. This suggests that PMUs are become more and more attractive to power engineers because they can provide synchronized measurements of real-time phasors of voltage and currents as indicated by Nuqui et al. (2005). According to the head of the System Control Department who participated in the interviews:

> *PMU for network work monitoring and security analysis could provide more adequate and very efficient on-line data of the system to the Power System Department of GRIDCo than the current SCADA*

This result is similar to Emami (2011) who indicated that the application of PMUs in power grids is required for real-time wide area monitoring as it would provide the on-line information of the system to the power system operator.

The study further explored to what extent power system state estimation could be enhanced using pharsor measurement units for network monitoring and security analysis of grid in GRIDCo. Figure 4.6 illustrates the results.

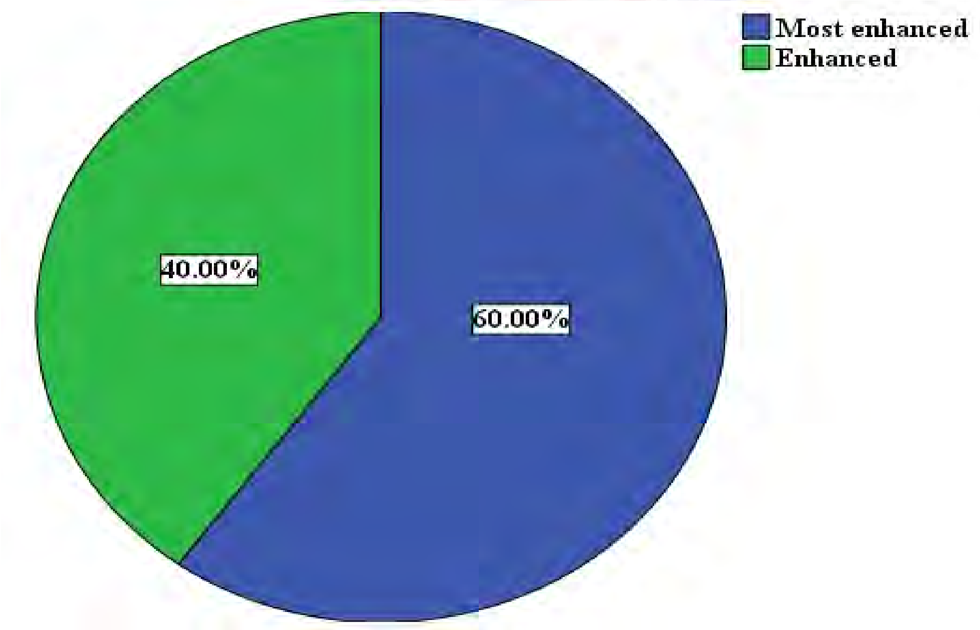

Figure 4.6: Power system state estimation

Source: Fieldwork, 2013

About 60 percent of the respondents were of the view that power system state estimation could be most enhanced using phasor measurement unit for network monitoring and security analysis of grid in GRIDCo. None of the respondents rated the extent of enhancement as neither "less enhanced" nor "not enhanced". Generally, the results in Figure 4.6 shows that the second most significant challenge that confronting GRIDCo in network monitoring and security analysis could be most enhanced using pharsor measurement units.

Damir (2007) disclosed that improvement in real time congestion management using PMU would benefit all stakeholders in the transmission grid such as utilities, ISO, regional operations. In this regard, the study also analysed to what extent real time congestion management could be enhanced using PMU.

Table 4.11: Enhancement of real time congestion management using PMU

Response	Frequency	Percentage
Most enhanced	100	66.7
Enhanced	26	16.7
Less enhanced	12	8.3
Not enhanced	12	8.3
Total	**150**	**100.0**

More than 60 percent (66.7%) of the respondents were of the view that real time congestion management would be most enhanced using phasor measurement units. This implies that by enhancing real-time congestion management, networking monitoring and security analysis could be enhanced by facilitating the ability to maintain real-time flows across transmission lines and paths within reliable transfer capabilities through dispatch adjustments in a least-cost manner as noted by Abur and Exposito (2004).

The head of Communications department responded by indicating that PMU could be more superior to the traditional SCADA measurement in capturing system dynamic behaviours since phasor instruments are high speed and time synchronized. Specifically, according to the manager of the Communication department:

PMU could enhance the provision of a more accurate state estimator solution of the real time flow on a line or paths

This Damir (2007) explained could help society through improved power flow and reliability even in times of maximum load and power transfer. The enhancement of validation and tuning of system models using PMU was also examined with the results shown in Table 4.12.

Table 4.12: Enhancement of validation and tuning of system models using PMU

Response	Frequency	Percentage
Most enhanced	58	38.4
Enhanced	68	46.2
Indifferent	12	7.7
Less enhanced	12	7.7
Total	**150**	**100.0**

Less than half of the respondents were of the view that validation and tuning system models would be respectively most enhanced (38.4%) and enhanced (46.2%) in using pharsor measurement unit. The less enhancement of validation and tuning of system models by PMU in the views of the respondents could be explained by the fact that the current traditional method including the SCADA and the Energy Management System seemed to be efficient in this regard. This could also explain why validation and tuning of system models was rated the second least challenge confronting GRIDCo in the monitoring and security analysis of grid.

However, it can be deduced that the use of PMU for network monitoring and security analysis could enhance the validation and tuning of systems models. This result could be linked to Damir (2007) assertion that validation of system model would identify the doubtful parameters of the system and have an improved estimate of those parameters as the power system parameters are not always accurate.

The goal of a post-mortem or post-disturbance analysis according to Damir (2007) is to reconstruct the sequence of events after a power system disturbance has occurred. As part of exploring the prospects associated with the use of PMU for network monitoring and security analysis, the study also investigated whether or not post disturbance analysis could be enhanced using PMU for grid.

Table 4.13: Enhancement of post power disturbance analysis using PMU

Response	Frequency	Percentage
Most enhanced	68	45.5
Enhanced	68	45.5
Indifferent	14	9.0
Total	**150**	**100.0**

Respondents views were evenly distributed in this regard where an equal proportion of the respondents (45.5%) were of the view that post power distribution analysis could be respectively most enhanced and enhanced using PMU. This gives an indication that the use of PMUs would improve post disturbance analysis as it would reconstruct the sequence of events after a power system disturbance has occurred. This means that, the application of PMU to post disturbance analysis offers potential benefit in the high degree of time synchronization.

Enhancement of power system restoration through PMU was also investigated for network monitoring and security analysis.

Table 4.14: Enhancement of power system restoration using PMU

Response	Frequency	Percentage
Most enhanced	92	61.5
Enhanced	46	30.8
Indifferent	12	7.7
Total	**150**	**100.0**

A little over half of the respondents (61.5%) were of the view that power system restoration would be most enhanced using PMU. Generally, it can be deduced from Table 4.14 that power system restoration would be most enhanced using PMU for network monitoring and security analysis. This gives the indication that the application of PMU for network monitoring and security analysis could provide operators with real-time information about the phase angles in relevant parts of the grid. According to the management who responded to the study through the interviews, the enhancement of power system restoration could help system operators and engineers with the decision of timing, sequences, and feasibility of prospective restoration actions. The head of Protection and Control department further stated:

Phrsor measurement technology can expedite restoration and reduce the blackout time

The benefit of enhancement in the overload monitoring and dynamic rating was analysed and the results are presented in Table 4.15.

Table 4.15: Enhancement of overload monitoring and dynamic rating using PMU

Response	Frequency	Percentage
Most enhanced	90	60.0
Enhanced	40	26.7
Indifferent	20	13.3
Total	**150**	**100.0**

Majority (60.0%) of the respondents were of the view that the use of phasor measurement in networking monitoring and security analysis of grid would most enhance overload monitoring and dynamic rating. This gives an indication that enhancement in overload monitoring and dynamic rating is a benefit that comes with the use of phasor measurement unit supporting Damir (2007) assertion that the use of PMUs can offer some degree of monitoring at a high time resolution.

The benefit to be accrued from PMU for adaptive protection was anlysed and the results are presented in Table 4.16.

Table 4.16: Enhancement of Adaptive protection using PMU

Response	Frequency	Percentage
Most enhanced	87	58.3
Enhanced	25	16.7
Indifferent	38	25.0
Total	**150**	**100.0**

More than half (58.3%) of the respondents were of the view that adaptive protection would be most enhanced with the use of phasor measurement unit in networking monitoring and security analysis of grid. The interviews with the management indicated that through the implementation of PMU, adaptive protection could be enhanced by:

i. Reliability balance between security and dependability of a protection scheme
ii. Better utilisation of power generation, transmission and distribution equipment capabilities.

The last stage of this section focus on how planned power system separation could be enhanced using PMU. Figure 4.7 illustrates the results.

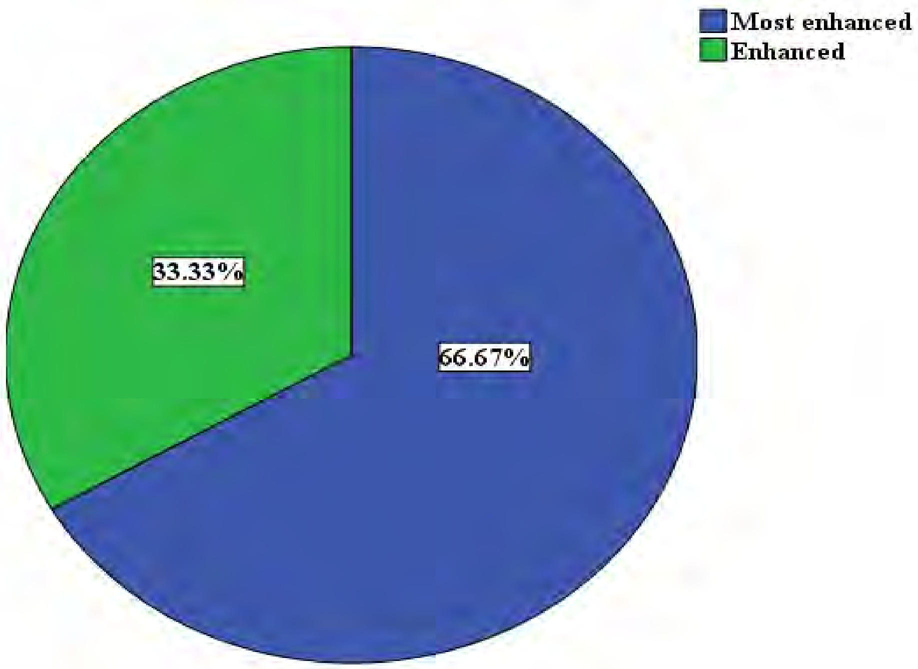

Figure 4.7: Planned power system separation could be enhanced using PMU

Majority (66.7%) of the respondents admitted that planned power separation would be most enhanced with the use of phasor measurement unit. Thus all the respondents were positive on the enhancement of planned power system separation with the use of phasor measurement unit. This meant that with PMU for network monitoring and security analysis, lost revenues could be minimised while generator restarting cost for GRIDCo could be reduced.

Figure 4.8 further shows the aggregation of the areas of network monitoring and security analysis which could be most enhanced.

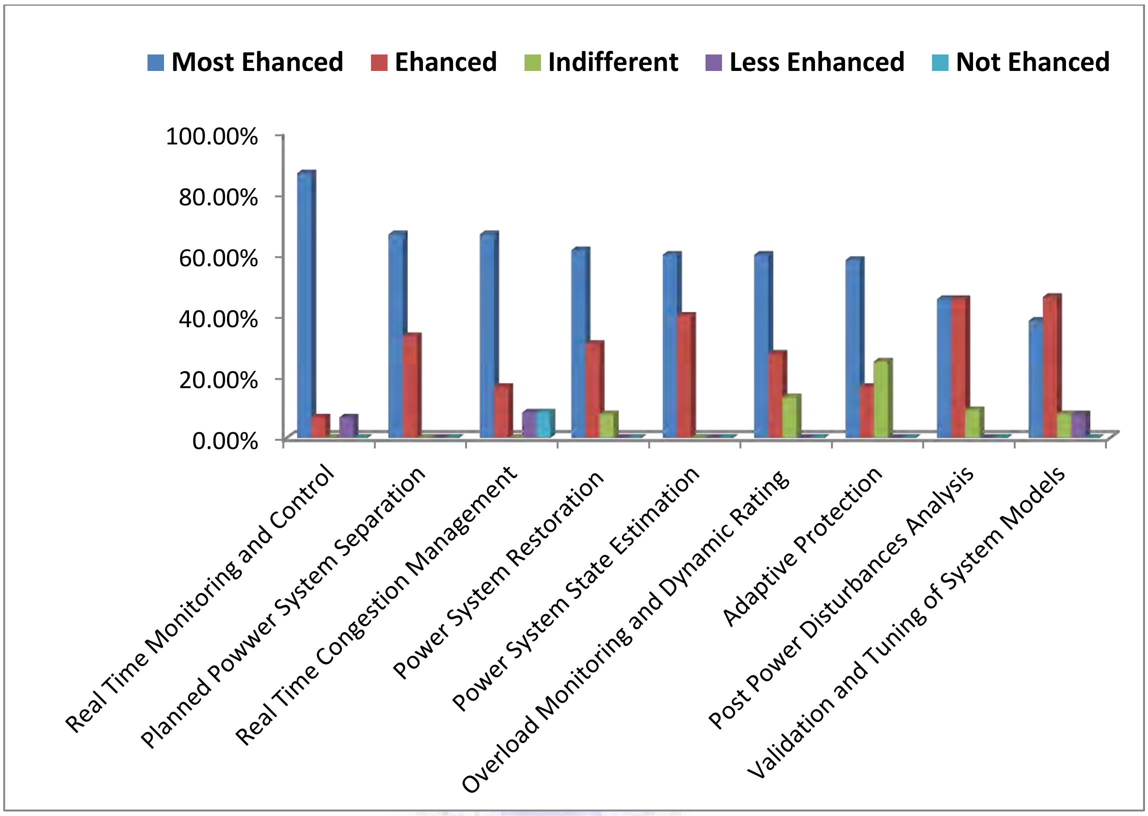

Figure 4.8: Enhancing network monitoring and security analysis of grid in GRIDCo

It is noted in Figure 48 that the major benefit to be obtained from the implementation of PMU as noted by the respondents was the enhancement of real-time monitoring and control. Other major areas of enhancement included planned power system separation, real-time congestion management, power system restoration, power system state estimation and overload monitoring and dynamic rating. On the other hand, validation and tuning of systems models was noted as the least area of network monitoring and security analysis that could be most enhanced using PMU. However, the views of management show that PMU could be used in network monitoring and security analysis for enhancement of power system stability such as rotor angle stability, frequency stability, voltage security, power system oscillations, and voltage stability.

The study also identified the following major challenges which could confront the successful implementation of PMU to enhance network monitoring and security analysis of grid in GRIDCo:

i. Less skill of personnel in advanced techniques in measuring and synchronizing measurements
ii. Integration of PMU in the traditional SCADA could take some time
iii. Expensive nature of PMU could make investment in the area difficult

These meant that although advanced techniques in measuring and synchronizing measurements are basics for PMU operation as noted by Emami (2011), advances in other areas such as training of personnel is critical to achieve the benefits of PMUs. These results are also consistent with Sarasij (2011) view that PMU implementation involves high investment.

4.5 Using SCADA in conjunction with PMU

In summarising this chapter, it is concluded that there is the need for the PMUs to be used in conjunction with the traditional SCADA which GRDICo is currently using. This is based on the assertion that traditional security approach based on SCADA data is becoming increasingly unreliable for real time operations, and that new technologies which rely on accurate, high resolution, real-time monitoring of actual systems conditions using pharsor measurement is needed to support SCADA data in real-time operations.

Table 4.17 shows the comparison developed from the use of SCADA in conjunction with PMU for effective grid security.

Table 4.17: Using SCADA in conjunction with PMU

Attribute	**SCADA**	**PMU**
Resolution	1 sample every 2-4 seconds (steady state observability)	10-16 samples per second (Dynamic/Transient observability)
Quantity measured	Magnitude only	Magnitude and phase angle
Time synchronisation	No	Yes
Output channels	100+Analog & Digital	= 10 phasors 16 + Digital 16+ Analog
Focus	Local monitoring and control	Wide area monitoring and control

Source: Author's construct, 2014

Table 4.17 implies that generally, the use of SCADA in conjunction with PMU for grid security analysis in GRIDCo is essential to ensure that while SCADA measurements has the capability to provide only steady state view of grid / system, the PMU technology would provide wide area dynamic real time visualization, monitoring safety, security of the grid in effective manner with advancement in communication in IT technology.

In other words, there is the need for an efficient numerical method for observability analysis of systems including both conventional (SCADA) measurements and synchronized phasor (PMU) measurements. Thus this chapter concluded that there is the need for the use of Supervisory Control and Data Acquisition (SCADA) and synchronized measurements for complete observability of the grid system in GRIDCo.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This chapter presents a summary of the major findings from the study as well as the conclusions, recommendations, and directions for further research. Thus, the chapter focuses on the implications of the findings from the study for policy making and further research.

5.1 Summary

The study explored the enhancement of network monitoring and security analysis using phasor measurement units. The findings of the study are presented under three headings namely: network monitoring and security analysis of grid in GRIDCo, challenges encountered in network monitoring and security analysis and prospects associated with the use of phasor measurement units in network monitoring and security analysis of grid in GRIDCo. In all, there were 160 respondents made up of 80 System Operators, 40 System Engineers and 30 Controllers as well as 10 management of GRIDCo in charge of network monitoring. Questionnaires were used in the collection of data while data analysis was performed using the Statistical Product and Service Solutions (SPSS), version 18 and Microsoft Excel.

The first objective focused on network monitoring and security analysis of grid in GRIDCo. The following major findings emerged:

i. Network monitoring has been somehow enhanced with the upgrade of SCADA facilities

ii. Traffic monitoring by GRIDCo using SCADA has been somehow effective.

iii. There are frequent occurrences, disturbances and disruptions in traffic in the network

iv. Generally, network monitoring and security analysis of grid in GRIDCo has been inefficient

The challenges encountered in network monitoring and security analysis in GRDICo were studied in the second objective. The following major findings emerged:

i. Significant challenges are encountered in network monitoring and security analysis of grid in GRIDCo including the absence of proper structure in the network at GRIDCo, inconsistency in the internal communication system and the unavailability of centralized disturbance recorders for timely analysis of faults in the network

ii. Generally, there were more significant challenges encountered in network monitoring as compared to security analysis of grid in GRDICo

iii. The three most significant challenges encountered in network monitoring and security analysis of grid by GRIDCo were real time monitoring and control, post power disturbance analysis and power systems state estimation

iv. The least significant challenges encountered in network monitoring and security analysis were validation and tuning of system models and, planned power system separation.

In relation to the third section which focused on prospects associated with the use of phasor measurement units in network monitoring and security analysis of grid in GRIDCo, the following major findings emerged:

i. Network monitoring and security analysis would be highly enhanced through the use of phasor measurement units

ii. The major benefit to be obtained from the implementation of PMU was the enhancement of real-time monitoring and control

iii. Other major areas of enhancement included planned power system separation, real-time congestion management, power system restoration, power system state estimation and overload monitoring and dynamic rating

iv. Less skill of personnel in advanced techniques in measuring and synchronizing measurements, integration of PMU in the traditional SCADA and the expensive nature of PMU were noted as significant challenges that could hinder the successful implementation of PMU for network monitoring and security analysis of grid in GRIDCo.

5.2 Conclusions

Although network monitoring has been somehow enhanced with the upgrade of SCADA facilities, this study concluded that the use of SCADA to monitor traffic in GRDICo has not been highly effective as the occurrences, disturbances and disruptions in traffic in the network are frequent. Additionally, the study concluded that there are significant challenges that confront network monitoring and security analysis of grid in GRIDCo including real time monitoring and control, post power disturbance analysis and power systems state estimation.

The study finally concludes that the use of phasor measurement units in network monitoring and security analysis has very high prospects. Thus the enhancement of network monitoring and security analysis of grid in GRIDCo using PMU could result in the unique ability to provide synchronized power system phasor measurements from widely dispersed locations in the electric power grid. Specifically, this study concluded that with PMUs, there would be improvement in real time monitoring and control of networking monitoring and security analysis of grid in GRIDCo. Improvement in power system state estimation, real time congestion management, validation and tuning of system models and post disturbance analysis would be greatly improved.

5.3 Recommendations

Based on the key findings that emerged from the study, the following recommendations are made for policy making:

Investment in pharsor measurement units:

The present generation phasor measurement unit relies upon venerable existing current and voltage transducer technology that are very expensive. Thus PMUs have proven to be very expensive and bulky. This prompts for sufficient funds to be made available by GRIDCo in collaboration with the government and other stakeholders for the acquisition of PMUs. In other words, sufficient funds should be made available by government through the Ministry of Energy to help GRIDCo experience significant investment in the deployment of phasor measurement units (PMUs) and the associated infrastructure for making synchrophasor measurements and data collection.

Using SCADA in conjunction with PMU:

Since the actual status of coexist of supervisory control and data acquisition system (SCADA) and phasor measurement unit (PMU), precision of traditional power system state estimation without PMU phasor is low. In this regard, a new algorithm based on PMU/SCADA mixed measurements is proposed. Thus GRIDCo can integrate synchrophasors into existing SCADA management systems by taking constraints of zero-injection nodes and PMU measurements into estimation equation, and the optimal estimation under double constraints can be derived by optimization theory of Lagrange multipliers method. This integration could improve the accuracy and coherency of SCADA systems and allows system-wide application of synchrophasor data.

The government through the Ministry of Energy should create the needed incentives to attract investors in the energy sector for the acquisition of PMUs. This can be achieved by creating a system of tariffs and subsidies that ensures sustainable cost recovery while minimizing price distortions.

As with all new technologies, extensive end user training would be needed to successfully transit phasor technology into full use as a real-time operational tool. Operations personnel need to see how phasor data and applications can improve their ability to reliably operate the system, hence the need to train Systems Operators, System Engineers and Controls in the use of the PMU. This study further recommends that any training for this purpose should cover areas such as:

i. Understanding phasors,
ii. Synchronization mechanisms including standards for distributing accurate timing information,
iii. Performance requirements for phasor data concentrators (PDCs)
iv. Data aggregation and alignment,
v. Phasor data communication and archival,

Future research

For the purpose of further research, this study recommended that based on the key findings that emerged from the study; a further research should be conducted to investigate real-time hybrid state estimation incorporating SCADA and pharsor measurement units.

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APPENDICES

APPENDIX A

ENHANCEMENT OF NETWORK MONITORING AND SECURITY ANALYSIS USING PHASOR MEASUREMENT UNITS

INTERVIEW GUIDE FOR MANAGEMENT

Introduction

This guide has been designed purely for academic purpose to evaluate the enhancement of network monitoring and security analysis using phasor measurement units in GRIDCo with specific focus on the types of technology used for network monitoring and security analysis of grid by GRIDCO, the challenges encountered in network monitoring and security analysis of grid in GRIDCO and the prospects to be associated with the use of phasor measurement units in network monitoring and security analysis of grid by GRIDCO.

You have been selected as one of the most trusted system controller, power system engineer and system operator of GRIDCO to respond to the study to your best of ability and that information provided to complete this study would be treated with the strictest confidentiality.

Section A: Background information

1. What position do you occupy in GRIDCo?...
2. How long have you worked with GRIDCo?...
3. What specific role do you play in GRIDCo in relation to network monitoring and security analysis using phasor measurement units?..

Section B: Network monitoring and security analysis of grid in GRIDCo

4. Generally, how would you describe the effectiveness and efficiency of networking monitoring and security analysis of grid in GRIDCo?

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Section C: Types of technology used for network monitoring and security analysis of grid by GRIDCO

5. Currently, what type (s) of technologies are being used for:

   i. Network monitoring of grid in GRIDCo?

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   ii. Security monitoring of grid in GRIDo?

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   iii. How efficient are the technologies being used for network monitoring and security analysis of grid in GRIDCo?

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Section E: Challenges encountered in network monitoring and security analysis of grid

6. Are there any significant challenges confronting GRIDCo in:

   i. Network monitoring of grid in GRIDCo?

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   ii. Security analysis of grid in GRIDCo?

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Section D: Prospects associated with the use of phasor measurement units in network monitoring and security analysis of grid by GRIDCO?

7. What prospects would be associated with

   i. Network working monitoring of grid in GRIDCo using phasor measurement unit

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   ii. Security analysis of grid in GRIDCo using phasor measurement units

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8. How can the challenges encountered in network monitoring of grid in GRIDCo be overcome using phasor measurement unit?

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9. How can the challenges encountered in the security analysis of grid in GRIDCo be overcome using phasor measurement unit?

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APPENDIX B

ENHANCEMENT OF NETWORK MONITORING AND SECURITY ANALYSIS USING PHASOR MEASUREMENT UNITS QUESTIONNAIRE FOR SYSTEM CONTROLLERS, SYSTEM ENGINEERS AND SYSTEM OPERATORS

Introduction

This guide has been designed purely for academic purpose to evaluate the enhancement of network monitoring and security analysis of grid using phasor measurement units in GRIDCo with specific focus on the types of technology used for network monitoring and security analysis of grid by GRIDCo, the challenges encountered in network monitoring and security analysis of grid in GRIDCo and the prospects to be associated with the use of phasor measurement units in network monitoring and security analysis of grid by GRIDCo.

You have been selected as one of the most trusted system controller, power system engineer and system operator of GRIDCo to respond to the study to your best of ability and that information provided to complete this study would be treated with the strictest confidentiality.

Please tick where appropriate

SECTION A: Socio-economic background

1. Gender
   a. Male ☐
   b. Female ☐

2. Age ……………………………………………………………………………………..

3. Educational background
   a. Secondary/Technical in electrical engineering ☐
   b. HND in electrical engineering ☐
   c. First Degree in elecrical enginerring ☐
   d. Second degere(Masters) in electrical engineering ☐
   e. Specify if others……………………………………………………

4. How long have you been working with GRIDCo?……………………….................

5. Under which department do you currently work?...

6. What specific role do you play in GRIDCo in relation to network monitoring and security analysis of grid?

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Section B: Network monitoring and security analysis of grid in GRIDCo

7. Generally, how would you describe the effectiveness and efficiency of networking monitoring and security analysis of grid in GRIDCo?

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8. How would you describe traffic monitoring by GRIDCo using SCADA?
   a. Very efficient ☐
   b. Somehow efficient ☐
   c. Inefficient ☐

9. Kindly give reasons to your choice of answer in question 9

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10. How would you describe the occurrence, disturbances and disruption in traffic in the network?

a. High frequent ☐
b. Somehow frequent ☐
c. Infrequent ☐

Section C: Challenges encountered in network monitoring and security analysis

11. Are there are any challenges encountered in network monitoring and security analysis of grid by GRIDCo

a. Yes ☐ b Not sure ☐ c. No ☐

12. Kindly indicate your reasons for your choice of answer in question 12

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13. How would you describe the challenges encountered if any in

i. Network monitoring of grid by GRIDCo

a. Very significant ☐ b. Significant ☐ c. Insignificant ☐

ii. Security analysis of grid by GRIDCo

a. Very significant ☐ b. Significant ☐ c. Insignificant ☐

14. Indicate the significant challenges if any encountered in

i. Network work monitoring of grid in GRIDCo

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ii. Security analysis of grid in GRIDCo

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15. Which of these are significant challenges encountered in network monitoring and security analysis of grid in GRIDCo?. You may tick more than one.

i. Validation and tuning of system models ☐
ii. Real-time monitoring and control ☐
iii. Power system state estimation ☐
iv. Post power Disturbance Analysis ☐
v. Power System Restoration ☐
vi. Overload Monitoring and Dynamic Rating ☐
vii. Adaptive Protection ☐
viii. Planned Power System Separation ☐

Section E: Prospects associated with the use of phasor measurement units in network monitoring and security analysis of grid by GRIDCO

16. To what extent would network monitoring and security analysis of grid be enhanced in GRIDCo using phasor measurement unit?

a. Highly enhanced ☐
b. Somehow enhanced ☐
c. Less enhanced ☐
d. Not enhanced ☐

17. How would you describe the prospects to be associated with the use of phasor measurement units for network monitoring and security analysis of grid in GRICo using phasor measurement units?

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19. In what specific ways can network monitoring and security analysis of grid in GRIDCo be enhanced using phasor measurement units?

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20. Below are a set of benefits which can be obtained to enhance networking monitoring and security analysis of grid in GRIDCo. Which of these benefits would be most enhanced using phasor measurement units? You may tick more than one where 1=Most Enhanced (ME), 2= Enhanced (E), 3= Indifferent (I), 4= Less Enhanced (LE), 5= Not Enhanced (NS).

Variables	Satisfaction Level				
	Most Enhanced	Enhanced	Indifferent	Less Enhanced	Not Enhanced
Real-time monitoring and control					
Power system state estimation					
Real-time congestion management					
Validation and tuning of system models					
Post disturbance analysis					
Empowerment in taking decisions					
Power system restoration					
Overload monitoring and dynamic rating					
Adaptive protection					
Planned power system separation					

THANK YOU FOR YOUR TIME AND COOPERATION