UNIVERSITY OF EDUCATION, WINNEBA

COLLEGE OF TECHNOLOGY EDUCATION, KUMASI

IMPROVING POWER MAINTENANCE AND MANAGEMENT SYSTEMS IN ELECTRICAL TRANSMISSION NETWORKS IN GHANA (A CASE STUDY IN GHANA GRID COMPANY (GRIDCo), TAMALE OPERATIONAL AREA).

DZAMAKLU GODWIN

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A Thesis in the Department of ELECTRICAL/ELECTRONICS TECHNOLOGY EDUCATION, Faculty of TECHNICAL EDUCATION, submitted to School of Graduate Studies, University of Education, Winneba, in partial fulfillment of the requirement for the award of Master of Technology in (Electrical/Electronic Technology Education) degree.

OCTOBER, 2017

DECLERATION

STUDENT'S DECLERATION

I, **Dzamaklu Godwin**, declare that this Thesis, with the exception of quotations and references contained in published works which have all been identified and duly acknowledged, is entirely my own original work, and it has not been submitted, either in part or whole for another degree elsewhere.

SIGNATURE: ……………………………..……

DATE: ……………………………………………

SUPERVISOR'S DECLERATION

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of Thesis/Dissertation/Project as laid down by the University of Education, Winneba.

NAME OF SUPERVISOR: **PROF. WILLIE K. OFOSU**

SIGNATURE: …………………………………

DATE: ……………………………………….....

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I am grateful to the Almighty God for giving me the strength to complete this work successfully. I also owe a debt of gratitude to all those who in spite of their busy schedule devoted their time to guide me to complete this work. To all my lecturers at the University of Education, Winneba, Kumasi Campus, I wish to express my profound gratitude for their unconditional encouragement, guidance and support throughout the programme.

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Finally, I would like to thank the many authors and publishers whose works have guided me to better understand the subject area of the study. May God richly bless you all!

DEDICATION

This work is dedicated to my mother, father, my wife and beloved children. I am grateful for your love, patience, financial sacrifices, prayers and support.

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ABSTRACT

In Ghana, Ghana Grid Company, GRIDCo has experienced huge power losses due to poor maintenance and management practices. For this reason persistent power outage has plunged the country‟s economy into a huge set back in the last four years. Power quality problems are common in most commercial, industrial and utility networks. The specific objectives of this thesis were to study the role of automation in improving transmission systems, evaluate maintenance performance in transmission systems through benchmarking. It also assessed the performance of substation equipment in improving power quality and reliability, identified the best management practices, procedures and structures in the organization. Remedial Action Scheme (RAS) was employed and has two approaches to mitigate power quality problems. These are load conditioning (Model for composite ac–dc Transmission), which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances (Automation switching control). Simulation using MATLAB program was carried out using signals with and without fault conditions and how the waveform magnitudes for voltage, current, active P and reactive Q powers reacted. The system recovered from its disturbance as the system conditioners (rectifier and inverter) reacted swiftly to stabilize the system. It is recommended that extension of this research work should be to incorporate the views of external stakeholders like researchers, high-tech equipment dealers, financial organizations, government etc. on the barriers and drivers for improving power maintenance and management in Ghana‟s energy sector.

CHAPTER ONE

1.0 INTRODUCTION

Energy is essential for the creation of wealth and improvement of social welfare; this means that adequate and reliable supply of energy is required to ensure sustainable development (Oyedepo, 2012). However, the use and conversion of primary energy most of the time results in its reduction and emissions; they are harnessed from limited resources and also considered environmentally unsustainable. The judicious use of energy resources and technology to reduce the negative impacts of energy use are firmly embodied in two (2) concepts namely "energy efficiency" and "energy management". Energy management refers to the strategy of adjusting and optimizing energy, using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems (Chakarvarti, 2011).

1.1 Background to the Study

In today‟s competitive energy market, many power transmission networks are increasing their competitiveness by adopting new operating and maintenance philosophies. This is to reduce their Operation and Maintenance (O&M) costs within a unique context of resource, physical plant settings, and organizational goals. In this modern era, and under the pressure of rapid development in developing countries, electric utilities are confronted with a myriad of challenges that include aging infrastructure, enhanced expectation of reliability, reduced cost, and coping effectively with uncertainties and changing regulation requirements. Indeed, for systems, high voltage (HV) and medium voltage (MV) substations represent a complex and critical physical asset that requires a careful evaluation of their maintenance practices aiming at more cost-effective tasks (Yanker, 1999). The first concern of the electric power transmission company (GRIDCo) in Ghana according to (Ghana Energy Commission, 2014), is the optimization of the transmission network maintenance scheduling, to minimize system operating costs and ensure that the system is running most economically. In recent practice, power plants have started using benchmarking to identify the best practices for enhancing their maintenance management (M.A.B. Asaye, 2009). Application of automation in transmission power system can be defined as automatically monitoring, protecting and controlling switching operations through intelligent electronic devices in real time mode, to restore power after transient fault by sequential events and maintain better operating conditions back to normal operations (Gruenemyer, 1991). Due to advancement in technology, Transmission Automation System (TAS) is not just a remote control operation of substation and feeder equipment but it results into a highly reliable, self-healing power system that responds rapidly to real-time events with appropriate actions; permits the power system to operate in best optimal way, based on accurate information provided in a timely manner to the decision-making applications and devices (Ramani, 1999). Transmission Automation Systems have been defined by the Institute of Electrical and Electronic Engineers (IEEE) as systems that enable an electric utility to monitor, coordinate, and operate distribution components in a real- time mode from remote locations (Gruenemyer, 1991). Today, utilities are more concerned about improving reliability due to the implementation of effective maintenance schedules, system automation that improves power quality due to its impact on sensitive loads.

1.2 Statement of the Problem

Power quality problems are common in most commercial, industrial and utility networks in Ghana. Natural phenomena, such as lightning are the most frequent cause of power quality problems (Bollen, 2000). The proliferation of microelectronics processors in a wide range of pieces of equipment has increased the vulnerability of such equipment to power quality problems (Eichert, Mangold & Weinhold, 1999). The problem of electrical disturbances, which affects different kinds of sensitive loads, is what this thesis considered.

Minor variations in power, usually unnoticed in the operation of conventional equipment, may now bring whole factories to a standstill. Many of these problems could be reduced by adjusting the mix of reactive, preventive, predictive, and proactive maintenance strategies so workers can focus on doing the right things at the right time. This research involve using benchmarking for maintenance management of transmission power systems and developing a comprehensive model which can help to improve maintenance performance in the Tamale Area of Ghana Grid Company (GRIDCo). The model will help in the search for optimum methods of maintenance management practices in order to improve the overall effectiveness of operation and maintenance in electrical power transmission systems. The energy chain consists of producing the energy and transmitting it to the costumer where the distribution feeders are the last knots of this chain. The importance of the latter part is no less than the former part in the electrical power system if not higher. Thus, many commercial experts believe that the transmission system should be taken into consideration more seriously as all the efforts to generate electrical power is with the purpose of delivering it to the customers (Mirzai & Afzalian, 2010).

Again, one of the challenging and important issues for the customer is the reliability of the provided electrical energy. At the same time electric utilities wish to reduce the revenue loss caused by outage. For this purpose, the transmission system has to be highly reliable and efficient under not only normal conditions but also emergency conditions. Much research has not gone into power transmission maintenance and management systems in Ghana, for this reason persistent power outages has plunged the country‟s economy into a huge set back in the last four years (Ghana Energy Commission, 2014).

1.3 Objectives of the Study

The purpose of this research work is to seek and establish unique consideration that needs to be applied when formulating an integrated maintenance strategy to best suit HV/MV transmission systems. Indeed, the aim of this research study is to develop an appropriate method that will aid strategies for asset management and Reliability Centered Maintenance (RCM) methodology in electric power transmission systems. The feasibility study examined five areas of concerns and the ways in which developed methodology could aid in improving power maintenance and management in transmission systems. The specific objectives of this thesis aim to:

- study the role of automation in improving transmission systems.
- evaluate maintenance performance in transmission systems through benchmarking.
- assess the performance of substation equipment (transformers, motors, cable insulation, capacitor banks, disconnect switches and circuit breakers) in improving power quality and reliability.

- identify the best management practices, procedures and structures in the organization.
- improving faults observability and location in electrical transmission systems.
- recommend best maintenance and management practices that promote energy efficiency and improvement in transmission substations and networks.

1.4 Significance of the Study

This study will provide insight to stakeholders such as GRIDCo, Electricity Company of Ghana, VRA, and other relevant agencies in the power sector on the need to improving power maintenance and management in transmission systems to improve efficiency, effectiveness and reliability of electric power transmission system in Ghana. This will help to address the gaps in maintenance and management system and put in place the necessary steps to improve it. In this direction, the project will inform government and policy makers on the extent to which power maintenance and management system could be used to provide the needed resources 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 improve power maintenance and management in transmission system. 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 improving maintenance 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 power system maintenance.

1.5 Scope of the Study

This research involve using benchmarking for maintenance management of transmission power systems and developing a comprehensive model which can help to improve maintenance performance and mitigate persistent power outages in the Tamale Area of Ghana Grid Company (GRIDCo).

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 strategies for asset management and Reliability Centered Maintenance (RCM) in electric power transmission systems in mitigating blackouts in the power system. The project shows the topology employed in installing sensitive components that is allowed to be „synchronized‟ to enable enhanced grid maintenance and management.

1.6 Organization of the Study

The study is organized into five chapters. Chapter one provides the general introduction to the study. Chapter two reviews some of the related literature works whilst chapter three shows the simulation methodology used in conducting the research. Chapter four discusses the results and evaluation of the study whereas/and chapter five deals with the conclusion and recommendations of the study.

CHAPTER TWO

2.0 LITERATURE REVIEW

The trends in the energy sector of Ghana are reviewed with particular emphasis on energy at the household level, namely, electricity. In the case of electricity there has been a steady upward trend in access rates from 28% in 1988 to 43.7% in 2000 and about 55% in 2008, making Ghana the third highest in sub-Saharan Africa, after Mauritius and South Africa (Brew-Hammond, 2007). While access to electricity has been increasing, overall household access in urban areas is nearly three times that of rural households and this is a poignant situation. Biomass in the form of wood fuel has been the main source of domestic energy for both rural and urban households. Heavy reliance on wood fuels has contributed to a consistent decline in Ghana‟s forest reserves (Botchway, 2000). Hence, in 2012 government initiated a programme to increase transmission of electricity as an alternative to wood fuel (Brew-Hammond, 2007).

2.1 Trends in Ghana's Energy Sector

The colonial administration of the Gold Coast maintained a diesel generating station and did not intend any rigorous energy programme (Botchway, 2000). Nevertheless, the idea of building a dam across the river Volta to generate electric power and turn Ghana‟s bauxite into aluminium is credited to Albert Kitson, a geologist in the government of Gold Coast in 1915 (Faber, 1990; Moxon, 1984; Hart, 1980). This idea was taken over by the first President of Ghana whose ambition was to modernize Ghana through rapid industrialization underpinned by the prime need of providing increased access to cheap electricity for the population (Nkrumah, 1961).

Following a number of proposals submitted by different consortia to realize the hydroelectric power potential of the River Volta, the government of Ghana finally initiated the Volta River Project and established the Volta River Authority (VRA) in 1961 for the generation and transmission of power (Botchway, 2000). Four hydroelectric generating units with total capacity 588 MW, including 15% overload capacity, were installed in 1965 at Akosombo. Two additional units with capacity of 324 MW, including 15% overload capacity, were commissioned in 1972 to bring the total installed capacity of hydropower to 912 MW. In 1981, a second hydro- electric plant was installed at Kpong and this added 160 MW to the installed capacity. Both plants are capable of providing long-term energy of approximately 4,800 GWh/year. On the long-term average, however, the potential energy available from the two plants is estimated to be 6,100 GWh/year (Abakah, 1993; Yankah, 1999).

The global oil crisis in the 1970s‟ provided the momentum for the establishment of a Ministry of Fuel and Power, which was changed to Ministry of Mines and Energy (Brew-Hammond, 2007). The objective of the Ministry was, among other things, to formulate, coordinate and supervise policies relating to the energy sector. During the national energy crisis in 1982-1983 induced by a major regional drought, the National Energy Board (NEB) was created to plan for the comprehensive development and utilization of energy resources. Particularly to promote the use of energy and cleaner forms of energy and advice government on energy issues (Akuffo, 1992). The NEB actually in 1985 and from a tottering public institution to become a dynamic national agency for energy planning and policy analysis but unfortunately there were institutional tensions and eventually dissolved in 1991 (Brew-Hammond, 1998). Encouraged by the achievements of the ERP in 1989-1990, government committed itself to increase access to electricity for all parts of the country over a 30-year period in a programme known as the National Electrification Scheme (NES). In order to extend electricity to the northern regions of Ghana, where there was no grid electricity, the legislation that established the Volta River Authority (VRA) and the Electricity Corporation of Ghana (ECG) were amended to put the VRA directly in charge of the Northern Electrification Programme (NEP). In 1987 the VRA created the Northern Electricity Department (NED) and took over the additional responsibility for extending electricity to the northern regions of Ghana (Brew- Hammond, 1996; Yankah, 1999). Through the creation of the NED and implementation of the Northern Electrification and System Reinforcement Project (NESRP) as well as the Rural Electrification Programme (REP), grid-electricity was extended to the Brong Ahafo, Northern, Upper-East and Upper-West regions (Yankah, 1999). The NESRP was followed by the Self-Help Electrification Project (SHEP) to support the efforts of rural communities to provide power for themselves. In 1990, the VRA rehabilitated and re-commissioned the Tema Diesel Generating Station which has a capacity of providing supplementary generation of 30MW thereby raising the total capacity of electrical power to about 1,102MW (Akuffo, 2009). Between 1990 and 2001, electricity consumption grew from 4457GWh to 6033GWh at an average rate of 9.42% per annum, excluding the Volta Aluminium Company, VALCO, whose aluminium smelter at Tema consumed around 40% of total electricity supply in the mid-1990s (Energy Commission, 2004). The growth of consumption, as compared with population growth of 2.67% was due to an increase in access to electricity from 28% in 1988, 32% in 1992, 43.7% in 2000 to over 50% in 2005 (Energy Commission, 2004; Ministry of

Energy, 2006; Ghana Statistical Service, 2007; Akuffo, 2009). The percentage of households with access to electricity continued to increase at the rate higher than envisaged under the Growth and Poverty Reduction Strategy (NDPC, 2007). Electricity access rate of Ghana was estimated to be 54% in 2007 (Akuffo, 2009) and 55% in 2008 (World Bank, 2008).

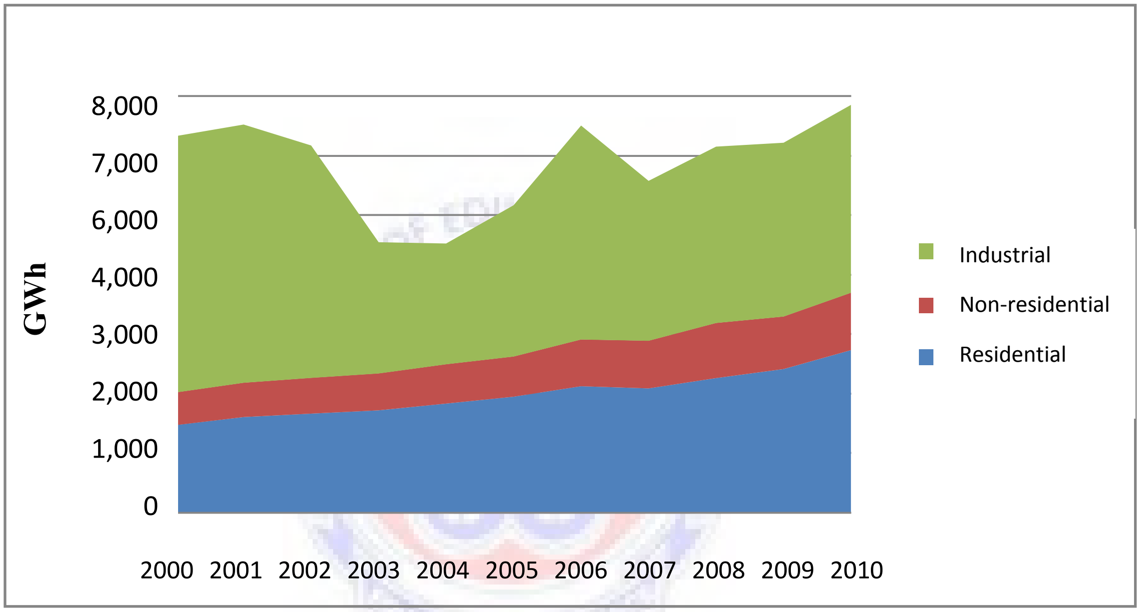

Figure 1: Trends of Electricity Consumption by Sectors

(Source: Energy Commission, 2014)

2.2 Maintenance Optimization Benchmarking

Figure 1 demonstrates the trends in electricity consumption in Ghana for residential, industrial and non-residential sectors. Access to electricity has been increasing and the levels of access in urban areas is much higher than in rural areas (Ghana Statistical Service, 2007) which reported the proportion of households in urban areas having access to electricity is nearly three times that of households in rural areas. Therefore the need for power management and maintenance is very critical.

Maintenance optimization and reliability can be tracked back to the 1950s‟ when preventive maintenance plans became a popular and a growing concept up to the 1960‟s when operation research methods was applied to preventive maintenance plans for the first time (Moubray, 1991). In the 1970s‟, condition monitoring improved the effect of the maintenance with the introduction of cheaper and more available computers in the 1980s‟, making maintenance optimization more widespread (Moubray, 1991). Maintenance optimization according to (Moubray, 1991) is here defined as a method aimed at finding the optimal balance between preventive and corrective maintenance with respect to objectives. The objectives are assumed to be revenue, asset and satisfied customers. Satisfied customers are important, if not, they will potentially buy their energy from other companies and/or cause increased regulation (Elfosk, 1999).The definition of maintenance optimization is in accordance with the definition of asset management. A good maintenance optimization supports asset management (Moubray, 1991). There are numerous definitions of benchmarking, but it essentially involves learning, sharing information, and adopting best practices to bring about step changes in performance. More recently, Harrington and James, (1996) described benchmarking as “a systematic way to identify, understand, and creatively evolve superior products, services, designs, equipment, processes, and practices to improve your organization‟s real performance" (Harrington, 1996). From a reliability viewpoint the reason for maintenance is quite clear, that is to increase the reliability by means of improving apparatus. Another aspect of maintenance is to reduce risk, usually by inspection and identifying substandard and/or hazardous equipment.

In the 1990s" Reliability Centered Maintenance (RCM, which was originally created in the 1960s" for the aircraft industry), became a method for maintenance planning of electric power networks (Elfosk, 1999). A description and overview of the current situation of general maintenance optimization is found in (Dekker, 1997) research with general model for quantitative maintenance optimization compared to the qualitative approach of RCM. A common problem discussed in the publications above is the gap between research efforts and practitioners of maintenance, where the research is focused on advanced mathematical models to connect the two. Maintenance optimization and reliability of electric power networks, is not a very common topic in literature, however there exist a number of publications according to (Li and Brown, 2004) in methodologies to establish failure rates for maintenance interval optimization. A method for prioritization of maintenance activities in transmission networks is presented for the best approach in performance per monetary unit using measured index that is a weighted combination of traditional power reliability indices (Li, et al., 2004). In Gustavesen (2000), generic algorithms are used for power system reliability optimization, using multistate systems to capture the fact that power systems in general have different task performance levels when intensified. The above mentioned literature discussed all answers problems of maintenance in general, but current research is focusing on components (mostly single sets of components) which are optimized for electrical power maintenance. One of the major contributions of this thesis is to connect component reliability performance to the overall objectives in order to establish the right level of maintenance for every major component.

2.3 Maintenance Optimization Objective

In Hilber, (2003) methods found in maintenance optimization usually performed with one of the objectives can be seen in Table 1. The first two objectives are related to each other in that they utilize constraints regarding the other method‟s objective (duality), whereas the last incorporates the two previous into one objective.

Table 1: Objective for maintenance optimization benchmarking

Objective	Description
Reliability	Maximize reliability under given constraints (e.g. cost constraints).
Minimal cost	Minimize cost given constraints (on reliability and/or maintenance requirements).
Minimal total cost	Minimize total cost (of interruptions and maintenance)

The time horizon, for the maintenance optimization, can be divided into three major concepts. The first is performed for one time period as the time horizon. The second concept involves multiple time periods and often uses the net present value, costs of all actions and it effects are recalculated to the present value. The third concept suggests a plan for a relatively long time but is built to adapt to changes due to events in the maintained system as shown in Table 2.

Table 2: Time Horizon for Maintenance Optimization

Time	Description
One time period	Optimize for an average or next time period (e.g. 1 year).
Multiple time periods	Optimize for a distant time period (for power systems typically 30 years). Often involves lifecycle cost planning
Adaptive	Methods that based on data revealed during the maintenance process adjust the maintenance

Factors for maintenance optimization will never be complete if accurate data are not available to capture the organizations activities and objective (Brew-Hammond, 2007).

2.4 Maintenance of Power Transmission Systems

Maintenance is crucial for distribution system operators both when acquiring new assets (apparatus) and when trying to utilize already existing assets. The cost of maintenance and consequences of failures can be significantly higher than the cost of the equipment. It is important to study maintenance and its effects in all stages of the lifetime of transmission system. The failures can be grouped into two categories (Hilber, 2003):

1. Reoccurring failures (to some extent possible to predict).
2. Random failures.

2.4.1 Four Basic Maintenance Strategies

Corrective Maintenance: Corrective maintenance is performed after fault recognition and is intended to put the component in good state (Faouthia, 2004) until the component fails. Corrective maintenance might be considered as a last resort. Corrective maintenance has its place in a sound maintenance strategy at least in the planning stage (Li et al., 2004).

Preventive Maintenance: The concept of preventive maintenance is to reduce failure probabilities by maintenance before failure or significant degradation would occur (Hilber, 2003). This often translates into trying to avoid costs of corrective maintenance and other costs that belong to unexpected failures.

Predictive Maintenance: Predictive intelligence increases maintenance productivity by detecting and diagnosing potential equipment problems before they grow – reducing the frequency, severity, and cost of repairs while enabling your team to avoid unnecessary and unproductive tasks. Its information integration and easy-to-use control and optimization capabilities also increase productivity by enabling operators to expand their span of control and run the process at the most economical operating points (Berlanger et al., 2002).

Proactive Maintenance: This analyzes why performance is degrading and then corrects the source of the problems. The goal is not just to avoid a "hard failure," but to restore or even improve equipment performance (Bever, 2000). The best-practices plan of the future will actually be to spend more on this maintenance in investment to regain in increased electrical plant efficiency. Above maintenance strategies are therefore needed to improve power system maintenance in transmission networks in Tamale Operational Area of GRIDCo.

2.5 Maintenance Strategies Benchmark in Electric Power Systems

Regulation has led the transmission system operators to center their attention towards profit optimization. That is a shift from an engineering era, focusing on reliability and "good technical solutions", to a more business and profit orientated regime. This is illustrated with a study performed by Cigré (2000) in the 1990s‟ on circuit breakers, as shown in Fig 2. It seems like periodical maintenance is losing ground to condition based maintenance and RCM approaches. This is further illustrated with the distribution of maintenance activities around the year 2004 for Ghana‟s power companies with: 5% corrective maintenance, 90% periodical maintenance, and 5% condition based maintenance, (Energy Commission, 2004).

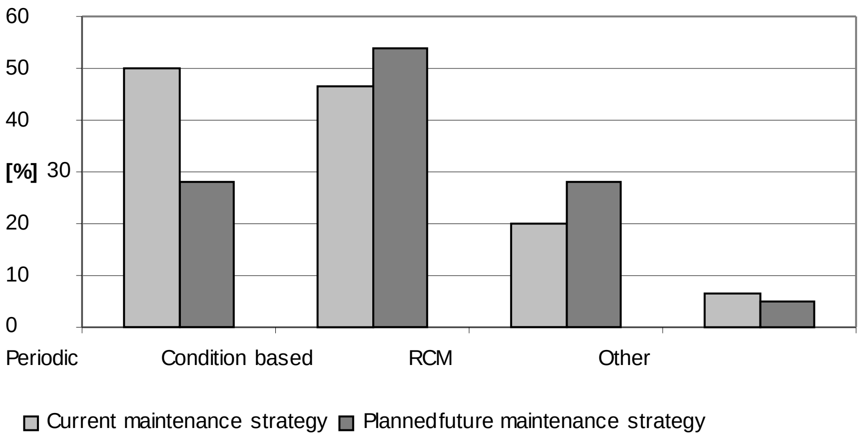

Figure 2: Current and planned maintenance strategies for circuit breakers

Source: Energy Commission (2004)

2.5.1 Preventive Maintenance

A preventive strategy assumes equipment is relatively reliable until, after some period of time, it enters a "wear-out" zone where failures increase. To postpone this wear-out, equipment is serviced on a calendar or run-time basis whether it needs it or not. On average, this "fix it just in case" approach is about 30% less expensive than reactive maintenance (PlantWeb.com, 2010).

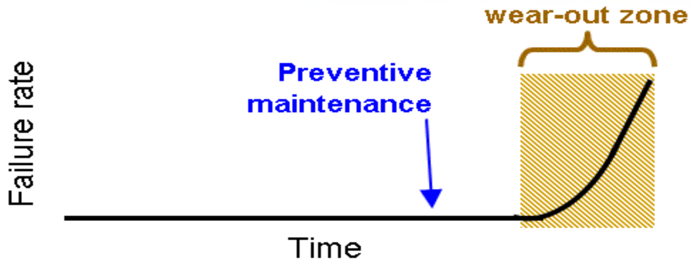

Figure 3: Preventive Maintenance strategy

However, determining when the wear-out zone might begin has traditionally been an inexact science, relying on estimates and averages rather than actual equipment condition. Because of this uncertainty, preventive maintenance schedules are usually very conservative (Berlanger et al., 2002). As a result, maintenance often takes place too soon, when there"s nothing wrong and service can actually create new problems. In fact, about 30% of preventive maintenance effort is wasted, and another 30% is actually harmful (Berlanger et al., 2002). Decision models for timing of inspection, repair and replacement based on asset failure data are described in Fig. 3 by Jardine (2007). Collecting accurate failure data for optimizing frequencies for a wide range of assets is regarded as problematic. In the absence of data for such decision support, the setting of frequencies by "personal judgement" is widely recommended and practiced. A straw survey of industry supported by published maintenance frequencies (Moubrey, 1999) shows a distinct preference for certain intervals when specifying Preventive Maintenance frequencies. These are: monthly, quarterly (3 monthly), semi-annually (6 monthly) and annually. Depicted in figure 4 is the best practice of maintenance strategies; 10% corrective, 30% preventive, 50% predictive and 10% proactive. Current research, however, wish to improve corrective maintenance to over 40% (Kahn, 2006).

2.5.2 Impact of Preventive Maintenance Frequency on Reliability

It is assumed that as Preventive Maintenance frequency increases (i.e. the interval between Preventive Maintenance activities is reduced) the cost of performing the Preventive maintenance activity increases. It is also often assumed that the probability of failure reduces with increased Preventive Maintenance frequency. The relationship between Preventive Maintenance frequency and the probability of failure prevention (assumes that the Preventive Maintenance activity is successful and the penalty costs are avoided) as shown in Fig. 4 according to Bever (2002).

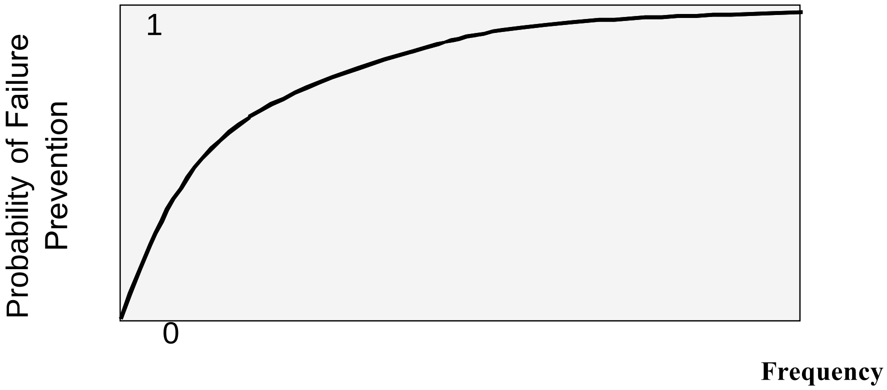

Figure 4: Probability of Failure Prevention

Figure 4 shows a diminishing return in relation to probability and frequency of electrical power Preventive Maintenance. If the correct inspection frequency for a bearing is 6 weeks then there is very little to be gained by carrying out the inspection 4 weekly or 2 weekly (Hardwick et al., 2002).

2.6 Transmission Substation

A transmission substation is a combination of switching, controlling, and voltage step-up equipment arranged to reduce transmission voltage to sub-transmission voltage for distribution of electrical energy to distribution substations. Transmission substations frequently have two or more large transformers. They function as bulk power distribution centers, and their importance in the system often justifies bus and switching arrangements that are much more elaborate than distribution substations. Combination of switching and controlling equipment arranged to provide circuit protection and system switching flexibility. Flexible switching arrangements in a transmission network can aid in maintaining reliable service under certain abnormal or maintenance conditions (Sadat, 1999). Figure 5 is a single-line diagram for a basic transmission substation. Depending on system requirements, initial substation construction may be limited to one power transformer and one sub-transmission circuit.

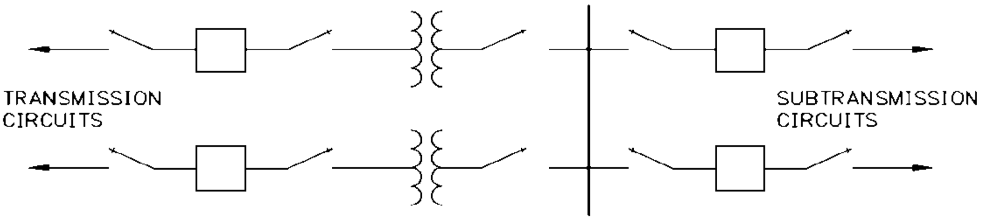

Figure 5: Basic Transmission systems

Source: Sadat (1999)

Power circuit breakers are included in the two transmission circuits to help prevent complete substation shutdown for line faults (Glover, 2002). The circuit breakers have disconnected switches on both source and load sides to permit isolation during maintenance or other periods requiring complete de-energization. These switches are normally of the three-pole, single-throw, group-operated type, mounted on separate stands (Glover, 2002).

Figure 6: GRIDCo Transmission Station in Tamale

2.7 Major Components of the Transmission Systems

The major components identified in the power system which need effective maintenance to enhance quality and reliable power delivery are as listed below:

Lightning Arrestors: Lightning arresters or surge diverters are protective devices, which conduct the high voltage surges on the power system to the ground. They are located at the entrance of the transmission line into the substation and as near as possible to the transformer terminals. The high voltage surges are very dangerous to the costly instruments used in the transmission system. In any substation, the main importance is of protection which is firstly done by these lightening arrestors (Saadat, 1999).

Transformers:

Transformers come in a range of sizes from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge units weighing hundreds of tons used to interconnect portions of national power grids. All operate with the same basic principles, although the range of designs is wide. Transformers are essential for high voltage power transmission, which makes long distance transmission economically practical. In case of a 220KV or more kilovolt stations, auto transformers are used. While in the case of lower kilovolt lines, such as less than 132kV lines, double winding transformers are used (Saadat, 1999).

Capacitor Banks:

Capacitor banks are used across bus-bars so that voltage levels can be maintained in long outgoing power lines. Capacitor Control is usually done to achieve the following goals: Reduce losses due to reactive load current; reduce KVA demand, decrease customer energy consumption, improve voltage profile and increase revenue. Indirectly, capacitor control also results in longer equipment lifetime because of reduced equipment stress. Experience shows that switched feeder capacitors produce some of the fastest returns on equipment investment. Sources of Energy Loss (Glover, 2002).

Insulator and Disconnect Switches:

The insulator and disconnect switches plays an important role in transmission systems. There are several types of them including the ball and socket type disc insulator and pantograph shown in Figure 7 and 8 with the purpose of providing insulation and disconnection in the system.

Figure 7: Ball and Socket type disc insulator

Figure 8: Disconnect Switch

Isolator with Earth Switches:

Isolators are the no load switches used to isolate the equipment. (Either line equipment, power transformer equipment or power transformer). The line isolators are used to isolate the high voltage from flowing through the line into the bus. Air break isolators or disconnecting switches are not intended to break on load and are also used to isolate equipment for maintenance. These are available mainly in two types vertical break type and horizontal break type. The later type requires larger width. However the space requirement can be reduced in the horizontal break isolators by having double break with a center rotating pillar.

Circuit Breakers:

Over the years, different variations of circuit breakers have been invented for different applications. The vacuum circuit breaker has become the technology of choice for high voltage applications from the day it was born, with a challenge from SF_6 gas in the 1980‟s and1990‟s. Both technologies are currently available but the vacuum circuit breaker remains dominant in the field of high voltage applications (Anderson, 1999).

Figure 9: Vacuum Chamber Breaker

Figure 10: Vacuum Circuit Breaker

When the live contacts are opened in a vacuum circuit breaker, the spiral electrodes vaporize to form a metal vapor which provides a medium for arc formation. The arc is eliminated as the metal vapor deposits on the electrodes and walls of the chamber.

Electrical Motor:

Permanent magnet synchronous motor (PMSM) has high efficiency, high energy density, large starting torque and other characteristics. With the performance increasing of NdFeB permanent magnet materials and the development of vector control theory, high-performance processors and high-power high-switching speed of the power electronics element makes the performance of permanent magnet synchronous motor control continuously improved. Since vector control of PMSM drives provides the decoupling control between flux and torque components, it is possible to obtain good performance characteristics similar to that of a DC motor. Therefore this technique is widely used in most of reported work on PM synchronous motor control; PMSM is now widely used for industrial control (Anderson, 1999).

2.8 Transmission Line Equations

From Vijay, et al., (2011), the equations below relate to the model for composite ac-dc transmission line. These equations neglect the resistive drops because of dc currents, giving a set of algebraic expressions for ac voltage, ac current, and also for active and reactive powers in terms of A, B, C, D parameters of the line. These may be written as:

$Es = AER + BIR$ (1)

$Is = CER + DIR$ (2)

$Ps + jQs = -Es^*ER^*/B^* + D^*E^2/B^*$ (3)

$PR + jQR = Es^*ER/B^* - A^*E^2/B^*$ (4)

If we neglect the resistive drops in the zigzag transformers and the tie lines, the dc current Id, dc power Pdr and Pdi of each rectifier and inverter may be expressed as:

$Id = [Vdro \cos\alpha - Vdio \cos\gamma] / [Rcr + Req - Rci]$ (5)

$Pdr = Vdr^*Id$ (6)

$Pdi = Vdi^*Id$ (7)

Reactive powers needed by the converters are:

$Qdr = Pdr^*\tan\theta r$ (8)

$Qdi = Pdi^*\tan\theta i$ (9)

$\cos\theta r = [\cos\alpha + \cos(\alpha + \mu r)]/2$ (10)

$\cos\theta i = [\cos\gamma + \cos(\gamma + \mu i)]/2$ (11)

μ_i is the commutation angles of inverter and μ_r is the commutation angle of rectifier and the overall active and reactive powers at both the ends are:

$$Pst = Ps + Pdr \text{ and } Prt = PR + Pdi \tag{12}$$

$$Qst = Qs + Qdr \text{ and } Qrt = QR + Qdi \tag{13}$$

Transmission loss for each line is:

$$PL = (PS + Pdr) – (PR + Pdi) \tag{14}$$

Ia is the rms ac current through the conductor at any part of the line, the rms current per conductor of the line becomes:

$$I = [I^2a + (Id/3)^2]^{1/2} \tag{14.1}$$

Power loss for each line = $PL \approx 3I^2R$. (14.2)

The total current I in any of the conductors is offset from zero. Now by setting the net current through the conductor similar to its thermal limit (I^{th}):

$$I^{th} = [Ia^2 + (Id/3)^2]^{1/2} \tag{15}$$

Let Vp be per phase rms voltage of the initial ac line. Also Let us consider Va be the per phase voltage of the ac part of simultaneous ac-dc tie line with constant dc voltage Vd composed on it. As the insulators are unchanged, the peak voltage in the two cases must be equal.

If the rated conductor current with respect to its allowable temperature increase is I^{th} and $Ia = X * I^{th}$; X (too less than unity) hence the dc current becomes:

$$Id = 3 x (sqrt (1-x^2)) I^{th} \tag{16}$$

The total current I in all the conductors are asymmetrical but the two original zero-crossings in each one cycle in current wave are possessed for (Id/3Ia) <1.414.

The instantaneous value of voltage of each conductor that is phase to ground voltage can be written as the dc voltage Vd with a composition of sinusoidally varying ac voltages that has rms value Eph and the peak value being:

$$\text{Emax} = V + 1.414\ \text{Eph} \qquad (17)$$

Electric field of the composite AC-DC line also consists of the field produced by the dc line feeding power and also the ac line creating a superimposed effect of electric fields. It can be easily seen that the sudden changes in electric field polarity occurs and it changes its sign twice in a single cycle if (Vd/Eph) < 1.414. Therefore, we are free from incurring higher creepage distance for insulator discs used in HVDC lines.

Each conductor has to be insulated for the maximum Emax but the fact is line to line voltage has no component of dc voltages and ELL (max) = 2.45 Eph. Therefore, we come to the conclusion that conductor to conductor separated distance is found out only by ac voltage of the line in lieu of the total superimposed one.

Assuming Vd/Eph = k

$$\text{Pdc/Pac} = (\text{Vd} * \text{Id}) / (3 * \text{Eph} * \text{Ia} * \cos\theta) = (k * \text{sqrt}(1-x^2))/(x * \cos\theta\ ) \qquad (18)$$

Total power:

$$\text{Pt} = \text{Pdc} + \text{Pac} = (1 + [k * \text{sqrt}\ (1-x^2)]/(x * \cos\theta)) * \text{Pac} \qquad (19)$$

The above equations and expressions will be relevant to this thesis in the study of the simulation of composite ac-dc transmission line, to determine the outcome of under no fault and fault response conditions analysis.

2.9 Fault Location Methods on Power Transmission Lines

Fault location methods use different measurements and techniques to indicate possible fault locations, thus helping the maintenance engineers to rectify faults early on long lines and restore transmission lines on time.

In order to meet demand, electric power systems have grown rapidly by largely increasing the power lines as well as employing new energy sources and transmission system generation. The problem arises when these lines experience faults in their operation which happens with high probability due to the large length of lines (Kalam, 2014).

In most cases, the major effects of electrical faults appear in the form of mechanical damage, which must be repaired before returning the line to service (Saadat, 1999). For this reason the presence of a fault location method can accelerate the restoration procedure when the location of the fault is either known or can be estimated with reasonable accuracy.

Temporary faults caused by trees penetration or insulators degradations known as high resistance faults are difficult to detect as they do not result in breaker operations and mainly cause minor damage that is not easily visible in inspection. Hence, fault locator that is able to estimate both sustained and transient faults is necessary (Mohan et al., 2002).

The research that has been done so far mostly focuses on finding the locations of distribution line faults. The reason is mainly that, the time required to physically check the lines in transmission system is much more than in the distribution line according to Mohan et al., (2002). However, nowadays the location of faults on transmission systems has taken more attention because of recent deregulation in utility industry to supply reliable and quality power at minimum cost to customers (Mohan et al., 2002). In spite of major technological advances and widespread use of Intelligent Electronic Devices (IEDs) for measurement and monitoring, accurate fault location in transmission system lines is still a challenge and considerable interesting to electric power utility engineers and researchers for over twenty years (Kannan, 2012). Fault location accuracy in transmission lines varies vastly because of nonhomogeneous nature of the network as opposed to distribution system lines.

2.9.1 Classification of Fault Location Methods on Power Transmission Lines

Below are the classification of some of the Fault location methods in use to detect possible fault locations on long transmission lines.

2.9.1.1 Impedance Method

When a fault occurs in the system by assuming that the line is uniform and based on measured voltage and current at the measurement point the impedance of fault loop can be calculated. Since the calculated impedance is proportional to the line length, distance between measured point of device and fault location can be reached. This principle is used in relays such as distance relays. Double-end impedance method is utilized to increase the accuracy of fault location. The basis of the analysis in this method is impedance can cover the effect of line parameters (Yuan, 2011).

2.9.1.2 Travelling Wave Method

Travelling wave method is defined as a fault location method in which the phenomenon of traveling wave is employed. Reflected traveling wave difference, between healthy phase and faulted phase of traveling wave can be used for fault location. In literature there are different approaches based on this method to calculate the distance; namely, A, B, C, D, E and F. Among these methods only C-Traveling method is utilized in transmission system networks with multi-terminal, usually called single-ended injection traveling wave method. This method is based on sending pulse to healthy and faulted phases and records the reflected waveforms (Yuan, 2011). By comparing waveforms of healthy and faulted phase and wave characteristic at fault point the fault area can be estimated.

2.9.1.3 Signal Injection Method

Injection method is the short term of “injecting signal tracing method.”

In this method particular frequency of current is injected through bus to ground circuit. When a fault occurs, the injected signal flows into the earth along the faulted line and grounded point. Then, a signal detector is employed to detect the faulted line while injected signal flows through it. Finally, the location of the fault can be obtained by signal tracking along the line using portable detector (Dekker 1997).

2.9.1.4 Zero Sequence Component Based Method

In this method, by considering the appropriate reference direction where the direction of line head end to load terminal is the positive direction, the phase of zero-sequence current in the faulted line (before fault point) lags behind zero-sequence voltage around 90° while the phase of zero-sequence current in healthy line (healthy branch, after fault point) leads zero-sequence voltage around 90°. If the phase angle of zero-sequence voltage is considered as the reference phase angle, then zero-sequence current phase in faulted line is opposite to it in healthy line. Moreover, the maximum amplitude of zero-sequence current along the fault path happens in the fault point. This method has been proposed for single-phase to ground fault and the recorded current waveform is analyzed after determination of the fault region by inquiring the current transformers (CTs) installed nearby the sectionalized switches (Kannan, 2012).

2.9.1.5 Composite Location Method

Complexity of recent TS networks has increased the necessity of using an approach which is able to locate the fault precisely (Brahma, 2011). Therefore, research on a comprehensive location method is one of power engineers concerns recently. The basic idea of this method is employing two different methods in principle for fault location which can effectively compensate the shortage of using any each method alone, and benefiting from advantages of both to improve the accuracy of fault location (Brahma, 2011).

2.9.1.6 Impedance Based Fault Location Method

Impedance based fault location method is more suitable and widely used than the other methods since it relies on minimum data and does not require costly hardware. Also, it uses simple algorithm and no communication is required (Yuan, 2011).

2.10 Electrical Degradation

The most dangerous defects in polymeric insulation are caused by electrical degradation. Partial discharges, electrical trees and water trees are the most important mechanisms. Electrical degradation will affect the insulation locally and randomly. Electrical degradation does not affect whole cable length, as thermal degradation does. The defect leading to final breakdown will usually be a local phenomenon. Low electric field intensity and long development time are common for electrical degradation mechanisms in medium voltage cables (Faradonbeh, 2011).

2.11 Lightning Effects on Power Transmission Lines

Lightning may cause failure of whole substation equipment that affects quality and reliability of power delivery to customers. Lightning flashovers cause damage to substation equipment as in (McGeehan, 2007) because of its unpredictable and probabilistic nature (Hileman, 1999). Lightning protection scheme for substations is essential for the minimization of lightning strokes to equipment and buses (IEEE, 1996). There are three different lightning protection schemes with the help of which lightning protection can be achieved: by using shield wires, earth masts, and shielding wires and earth masts both (IEEE, 1996).

Lightning over voltages are categorized as Fast Transients, which cover a frequency range from 100 kHz up to 100 MHz (IEEE, 1999). They are caused by lightning strokes to the transmission line, either into the phase wire (direct stroke) or to the shield wire, which causes a flashover along the insulator chain (back-flash). As a result, a high overvoltage wave is generated, which propagates along the network leading to acceleration of the insulation ageing processes and in most severe conditions even failures of machines and apparatuses. This is the reason why computer models for lightning studies are more complex in comparison to those used during load flow or slow-front surges studies. For networks with nominal voltage rated at U_N = 420 kV, the BIL is standardized to 1425 kV (McGeehan, 2007; IEEE, 1996).

2.12 Transmission Automation System (TAS)

Automation is “the application of machines to tasks once performed by human beings, or increasingly, to tasks that would otherwise be impossible”, Encyclopaedia Britannica (Gruenemeyer, 1991). According to the IEEE, a Transmission Automation System (TAS) is “a system that enables an electric utility to remotely monitor, coordinate and operate distribution components, in a real-time mode from remote locations (Kojovic, 2008)". In situations where there are large networks, the network (primary distribution) itself is subdivided into more segments, namely, one for large consumers (no transformation provided) and for the rest at a lower HV voltages (secondary distribution) (Figure 5).

Power system automation happens in segments of the power system which can serve different functions (www.ABB.com). One segment is bulk transmission of power which traditionally was handled by the power producer, but increasingly (in de-regulated environments), is handled by an independent transmission system operator (TSO). Bulk transmission is usually associated with outdoor switchyards and high voltage operating voltage levels (in excess of 132 kV). Bulk transmission substations play a critical role in energy trading and power exchanges. The complex interconnections between equipment, such as transformers, lines and bus- bars etc. are such that manual operation is not a practical proposition in the GRIDCo electrical power transmission network (Fig. 6). Automation has existed at the distribution level for many years, but has been restricted to situations involving either large numbers of customers or critical loads. For power transmission, automating rural supplies was not cost-effective due to the dispersed nature of the lines and loads (Choi, 2008). It is generally applied to that element of the transmission/distribution system which operates at voltages above 22 kV.

2.12.1 Primary Automation Technique

Different functions of Primary Automation Technique are listed below.

1. Transformer Load Balancing: Transformer load balance monitoring provides remote access to near real-time information concerning the overall operation of the TS.

This information can be used on a daily basis to verify the effects of other down line events such as capacitor switching, residential load control, and recloser operations. It is also useful on a periodic basis to fine tune the efficiency of the Utility's power distribution configuration (Brahma, 2011).

2. Voltage Regulation: This feature of TAS offers utility personnel the ability to reduce line voltage during peak demand times by remotely taking control of the Load Tap Changer. It also facilitates the remotely boosting of line voltages above the local LTC settings in case of emergency situations such as back-feeding.
3. Fault Isolation and Sectionalizing: Remote monitoring of the recloser operation to the melting of a fuse link, utilities can detect the fault very fast and can take quick action to clear that fault. Even during the outage of the power supplies TAS devices on that line can report the data remotely. By correlating the last voltage or current measured before an outage from several points along the, an indication of the nature of the fault as well as its approximate location can be obtained.
4. Remote Interconnect Switching: TAS can be deployed to drive remotely interconnected switches that separate different portion of the utility transmission feeders. By the use of remote interconnect switching utilities can manipulate their transmission system to provide the most efficient configuration and also will able to remotely restore power to as many consumers as possible during the time of multiple faults (Yuan, 2011).
5. Capacitor Bank Switching: It is most commonly deployed automation technique in a TS network. The most cost effective capacitor control configuration is to install a number of one-way receivers at the line.

2.12.2 Commercial Transmission Automation Systems

Improving electrical power transmission and distribution in transmission networks would be highly effective if automation is considered according to (Hileman, 1999). Transmission automation products/components can be classified according to their functions: sensors, interface equipment, controllers and actuators which are employed in the modeling of this thesis, and they are as follows:

1) PCD2000 Recloser Control Features:

Under/Over voltage, frequency control and alarming (1phase or 3 phase); Directional specific over current protection, power flow control; Records kW, kVAR & volts per phase, Operation/Fault Records, Power quality recorders per ANSI/IEEE 1159 Standard, and also have Oscillographic capture facility. Open protocols, DNP3.0, Modbus, RS232, RS485, programmable I/O and optical port are all standard.

2) SCD2000 Switch Control Features:

Fault indication that utilizes currents or currents and voltages; Phase imbalance; Switch failure alarm; Number of operations; Sectionalizing function; Automatic source transfer.

3) DCD2000 Communications Gateway Features:

Provides multiple master/slave operation in one integrated box; Provides interface to multiple applications; Provides interface to substation and field devices Support standard protocols (MODBUS and DNP 3.0).

4) SEL-351A Transmission Protection System Features:

Dependable Over current Protection; Innovative Directional Elements; Under/Over frequency Protection; Reclosing Control; Metering and data recording

5) SEL-2411 Programmable Automation Controller Features:

Flexible I/O for automatic control; Sequential events reporting; Station integration; Remote monitoring; Plant control systems

6) SEL-2030 Communications Processor Features:

Two Plug-In Protocol-Processor Card; Automatic Database; Modbus® Slave, DNP 3 Level 2 Slave, and ASCII Serial Protocols; Programmable Logic Controller (PLC).

7) Digital Multifunction System (DMS) Features:

Under/Over voltage, frequency control and alarming (1phase or 3 phase); Directional specific over current protection, power flow control; Event and Oscillography Recorder, Separate local MMIs for P & C.

RS232 port, faceplate accessible for local communication

8) SMOR-B Feeder Management System Features:

Hiset/loset phase, ground, instantaneous O/C and negative sequence TOC; Directional under and over frequency, phase and ground unit TOC; Cold load pickup, breaker failure logic; Records kW, kVAR & volts per phase, Operation/Fault Records and Oscillography.

Front and rear RS232 ports, Optional rear fiber optic port, M-LINK & Modbus protocol (Faradonbeh, 2011).

2.13 Advanced Developments of Transmission Automation System

New technological capabilities for advanced transmission automation are as follows;

a. More widespread communications interface among TAS devices. Further, worldwide accepted standardized communication protocol such as IEC 61850 is available.

b. Advanced integrated and coordinated protection using intelligent electronic devices (IEDs): It includes the functions like intelligent fault location and isolation, auto- restoration systems, contingency analysis, relay protection integration and coordination, restoration of normal connectivity, etc. This requires remotely controlled switching devices and reliable and fast communication systems. This results into improvement of the service reliability.

c. Equipment monitoring and diagnostics: this result in to extension of equipment life- time, reduction of capital and maintenance expenses.

d. Load management schemes: It includes the functions like distribution load forecast for short-term distribution operation studies, planned outage scheduling etc. Advantage of this is improved reliability and quality of service, better utilization of distribution facilities and better utilization of workforce.

e. Coordinated Volt/VAR control schemes: Application of this function requires facilities like remotely controlled voltage controllers of transformers, voltage regulators, distributed generators, power electronic devices and remotely controlled capacitor banks. Benefits of these implementations are improvement of power quality utilization of operational tolerances, non-intrusive load management in near-real-time and better utilization of generation capacity based on Watt-Var relationships.

f. Automated meter reading and analysis: It also includes the functions like power quality monitoring, analysis, and reporting, reliability monitoring, analysis, and reporting. To implement these thing it requires planning of AMR system including automated kWh and multifunctional meters, communication system between the AMR master and the customers, customer information database and AMR analysis computing applications. It also includes real time pricing, to obtain demand side management.

g. Transmission automation should include islanding (micro-grid) scheme as a part of distribution operations and control. The dynamic regulators, universal transformers, more sophisticated voltage and VAR control schemes and algorithms based IED can be used (Faradonbeh, 2011).

CHAPTER THREE

3.0 METHODOLOGY

3.1 Simulation Models

Remedial Action Schemes (RAS) are the key components for any power system utility planning. These are the steps which the thesis employed to take in order to get the system back to its normal operation. Remedial Action Scheme (RAS) as the name suggests are the necessary actions which need to be taken to solve the violations caused by a contingency.

The two approaches to mitigate power quality problems are load conditioning (Model for composite ac–dc Transmission), which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances (Automation switching control).

3.2 Automation Switching Control using IEC

Communication aided transmission automation is the effective mix of local automation, remote monitoring and control capabilities on strategic field devices. This combination of technologies empowers a highly reliable, self-healing (auto-restoration) power system that responds rapidly to real-time events with appropriate actions. Automation does not just replace manual procedures; it permits the power system to operate in a most efficient and optimal way, based on accurate information provided in a timely manner to the decision-making applications and devices.

In particular, IEC61850 (with power electronics extensions for transmission equipment) protocols can provide solutions to automation issues using state-of-the-art object modeling technologies. IEC 61850 based interoperable IEDs are installed to act as controllers and monitors of the power system equipment. The IED is a generic term for intelligence and communication that can be designed into any field device and can serve multiple functions. These IEDs have the compute capacity to execute software applications that can analyze local conditions and make pre-programmed responses to particular local conditions. These IEDs can also interact with each other (using IEC 61850), either within a substation (e.g. protection signals to circuit breakers) or on feeders (e.g. automated reclosers and switches along a feeder responding to isolate a fault) as shown in model Figure 11.

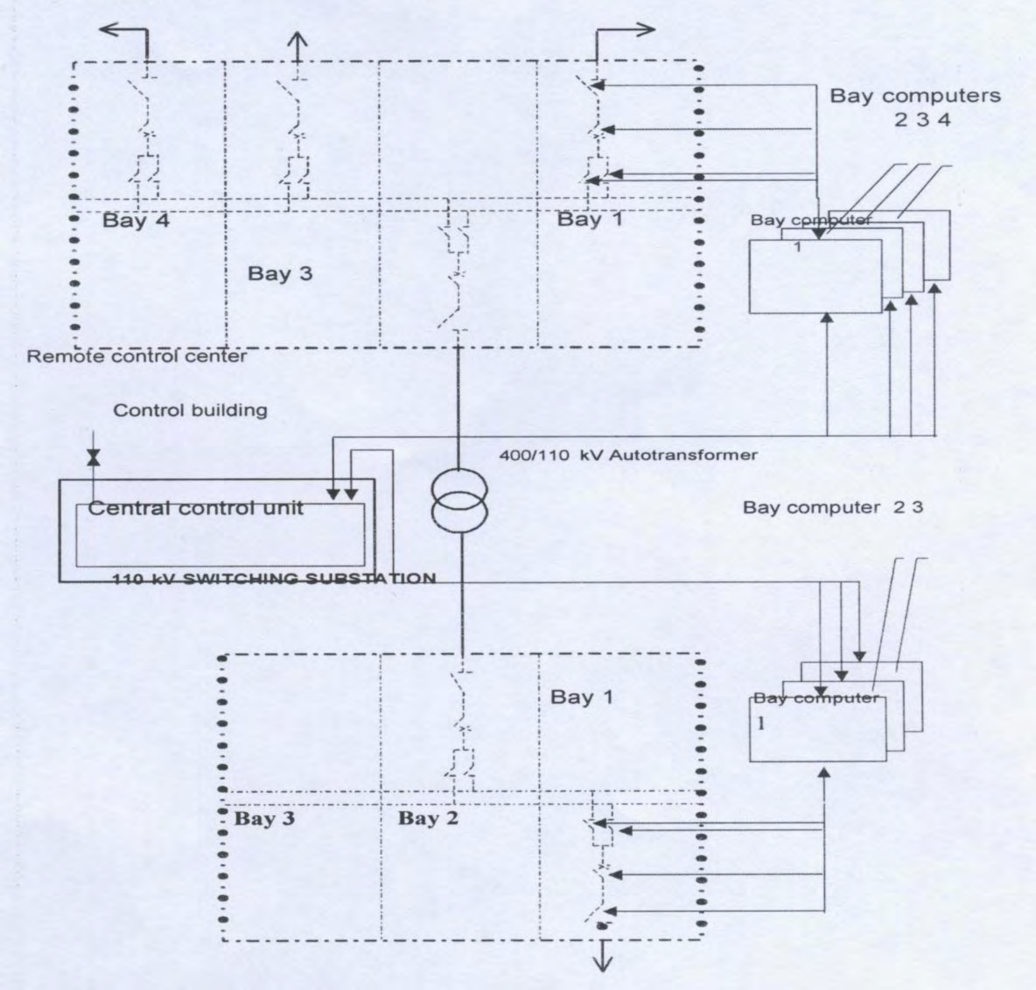

Figure 11: The model of automation switching operations control

3.3 Simultaneous Model of AC-DC Transmission

Figure 11 depicts the basic model for simultaneous ac-dc power flow through a dual circuit ac transmission line. Line commutated 12-pulse rectifier bridge is used in conventional HVDC and the dc power is injected to the neutral point of the zig-zag connected secondary of sending end transformer and is recovered back to ac again by the line commutated 12-pulse bridge inverter at the receiving end side. The inverter bridge is also connected to the neutral of zig-zag connected winding of the receiving end transformer to recover back the dc current to the inverter. The dual circuit ac transmission line carriers both three-phase ac and dc power. Each conductor of each transmission line carries one third of the total dc current with ac current superimposed. Since the resistance is equal in all the three phases of secondary winding of zig-zag transformer and the three conductors of the line, the dc current is equally divided in all the three phases. The conductor of the second transmission line provides return path for the dc current to flow.

The saturation of 400/110 transformer due to dc current can be removed by using zig-zag connected winding at both ends and power electronics components. The fluxes produced by the dc current (Id / 3) flowing through each winding of the core of a zig-zag transformer have equal magnitude and opposite in direction and hence cancel each other. At any instant of time the net dc flux becomes zero. Thus, the dc saturation of the core is removed. A reactor Xd with higher value is used to reduce harmonics in dc current.

In the absence of third order harmonics or its multiple and zero sequence, under normal operating conditions, the ac current flow through each transmission line gets restricted between the zig-zag connected windings and the conductors of the transmission line. The presence of these components may only be able to produce negligible current through the ground due to higher value of Xd (Figure 12). The dotted line in Figure 11 shows the path of ac return current only. The ground carries the full dc current Id only and each conductor of the line carries Id/3 along with the ac current per phase.

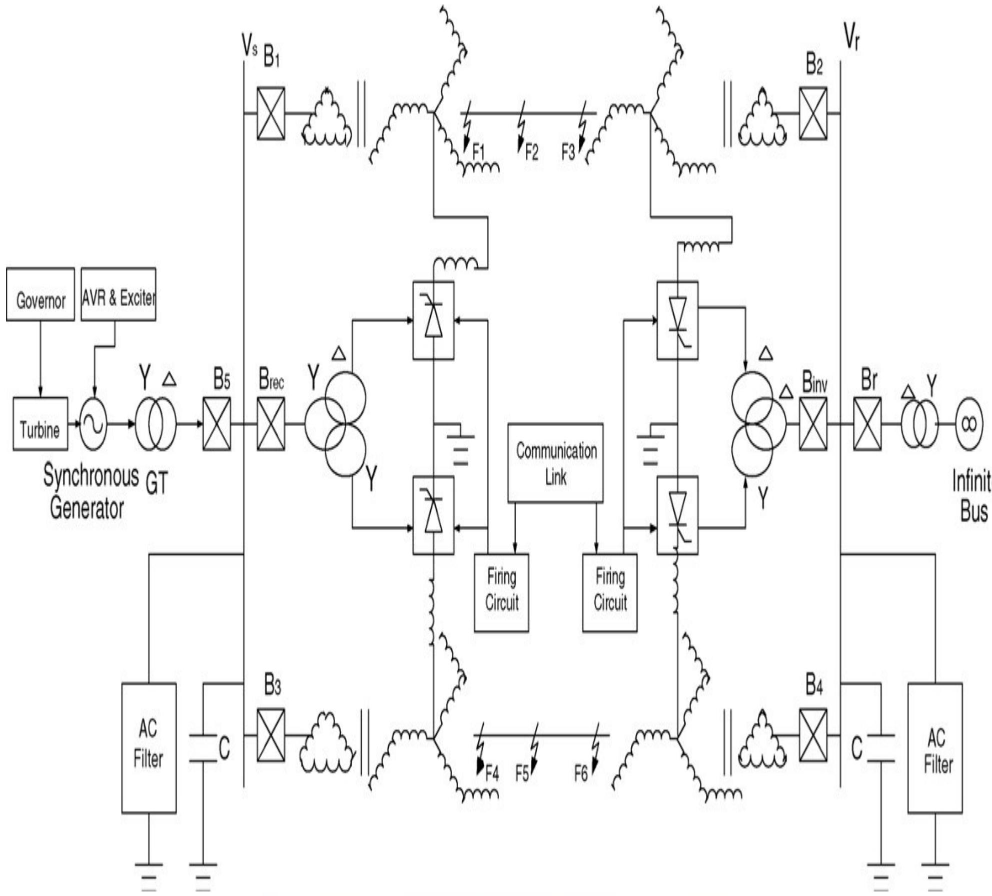

Figure: 12: Model for composite ac–dc Transmission

Detailed analysis of the filter and instrumentation networking which are required for the model scheme and also short current ac design for protective scheme is out of the scope of present work, but preliminary analysis qualitatively presented below says that generally used techniques in HVDC/ac composite system can be adopted solely for this purpose.

Different values of ac filters and dc filters are used in HVDC system and these may be connected to the delta side of the transformer and zigzag neutral respectively to filter out higher harmonics that is (n*p+1)th order and the (n*p)th order from dc and ac supplies. Moreover, filters also may be omitted for very low values of V_d and I_d. In the neutral terminals of zigzag transformer winding dc current and dc voltages can be found out by incorporating common methods that are used in HVDC system. Conventional CVTs or capacitive voltage transformer are used in EHV ac lines to measure stepped down ac component of transmission line voltage. The composite ac-dc voltage in the transmission line does not trouble the working of CVTs. Linear couplers that has high air-gap core may be used for measuring ac component of line current as the dc component of line current cannot saturate high air-gap cores. Thyristor Controlled Series Capacitor TCSC is series compensated device which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.

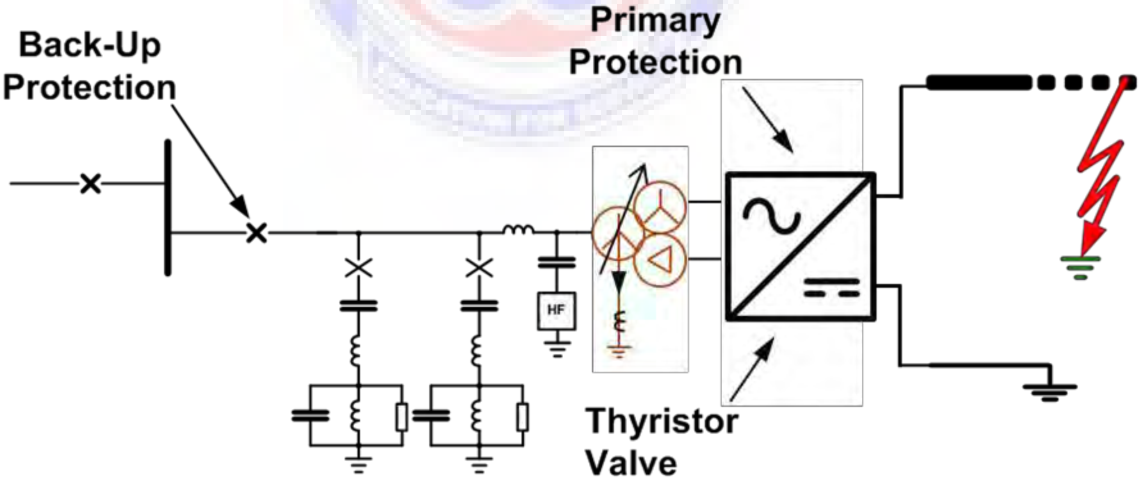

Figure 13: Simulation model of line commutated converters using Power Electronics Protection

Figure 13 shows a circuit diagram of TCSC controller. The TCSC is based on thyristor without gate turn-off capability. In TCSC a variable thyristor controlled reactor is connected across a series capacitor. When the firing angle of the TCR is 180 degrees, the reactor becomes non-conducting and the series capacitor has the normal impedance. As the firing angle is decreased below 180 degree the capacitive reactance increases.

3.4 Simulation Parameters

In the composite ac-dc transmission line, a standard 12 pulse HVDC system under the MATLAB environment is used for the analysis and simulation (Figure 12).

The simulation is based on the comparison between the response under no fault and fault response conditions of the HVDC transmission (double circuit line). A comparison between the sending end and receiving end voltages and sending end and receiving end currents for the two cases has been done. The active and reactive power changes during fault and no fault conditions are also observed.

The simulation parameters/model is a 200 MW (170KV, 1.2 KA) DC line proposed to transmit power over a 100 km transmitter line from a 170 KV, 200MVA, 50Hz network to a 153KV, 200MVA and 50Hz Network.

Operating in its steady state with the following conditions:

Equal power tap on each line, midway at the line Pt = (50+50) =100;

Receiving-end ac power Pac = 216.8 MW;

Sending-end ac power Pac = 277.8 MW;

DC power at the receiving end Pdc = 6.23 MW; transmission angle =60^0 at time t = 0.5s, a solid three-phase-to-ground fault occurs between the tap transformer and the load.

The HVDC system is designed to acquire data at a sampling frequency of 50 kHz. The HVDC system model is simulated for DC line fault. The DC line data is recorded at the rectifier side for the analysis. The data recorded from the rectifier side is then used to determine the voltage magnitude of the Reverse Voltage Travelling Wave (RVTW). The RVTW is also used for the analysis and location of faults on the system using Signal Processing method.

3.5 Effect of Distorted Signals on Major Components of the Power Transmission System, under Fault Conditions

In recent times, customers demand not only continuity of power supply, but also quality and stability in times of transient faults. Customer loads are now sensitive to power quality and any deviation from normal condition of the root mean square (rms) value of voltage and current waveforms result to outage or trip of their system that leads to huge financial loss.

Some of the causes of these waveform distortions are capacitor switching, single line to ground fault, switching ON and OFF of loads, single phase loads, power electronic converters and non-linear loads in the system. The poor power quality, as a result of these distorted waveforms adversely affect the whole equipment connected to the power system. During simulation under fault response condition and without transmission line conditioners, some of the cases mentioned below were revealed.

Transformers: Power transformers experienced overheating that will lead to increased losses and affect power quality to customers.

Capacitor Banks: Capacitors will experience reduced life span due to the detrimental effect of harmonics caused by distorted waveforms.

Disconnect Switches: The various disconnect switch contacts will experience increased heating, thus reducing the life span of their contact materials.

Electrical Motor: Electric motors will operate at reduced ratings and increased loss, thus reducing their life span.

Conductors: Conductors will experience increased heating which will then affect their respective insulations and shorten their useful life span.

Power electronic equipment (Meters, relays, communication Equipment): Most of these items in service at the time of the fault will malfunction.

Using the automation switching controls (Figure 11) and composite ac-dc transmission (Figure 12) models on the power transmission system would result to delivery of power quality, system stability, reliability and cost effectiveness to customers.

3.6 Cable Test using Needle Method

A needle test (Figure 14) will provide comparative breakdown data but not the degree of correlation with actual in-service performance. Needle testing can be applied for short cable samples – a sample length of about 10 cm is enough. For this type of testing it is important to select a test procedure that provides consistent and reproducible conditions of electrical stressing. Selected needle testing is based on the ASTM D 3756-97 standard (ASTMD, 2004).

The test procedure involves placing a well-defined sharp needle electrode inside the insulation at a predetermined depth. A needle with a tip radius of 2±1 μm is inserted into the insulation using a needle drive. Before insertion, the needle must first be washed with alcohol to remove foreign particles and then silicon oil should be applied to the tip of the needle. The purpose of the silicon oil is to fill up any micro cracks that might be introduced to the insulation while inserting the needle. A voltage is then applied to needle. The conductor of the test cable is grounded during this procedure. Initially the step voltage is linearly increased with a steepness of 500 V/s up to 4 kV. Then the voltage is increased step by step until breakdown occurs. The magnitude of step is 1 kV and the duration 1 minute. The same procedure has been used in previous studies and showed that differences in insulation performance can be detected by needle testing. The applied voltage and time to breakdown were recorded for future analysis. Needle test results can be analyzed using various statistical methods.

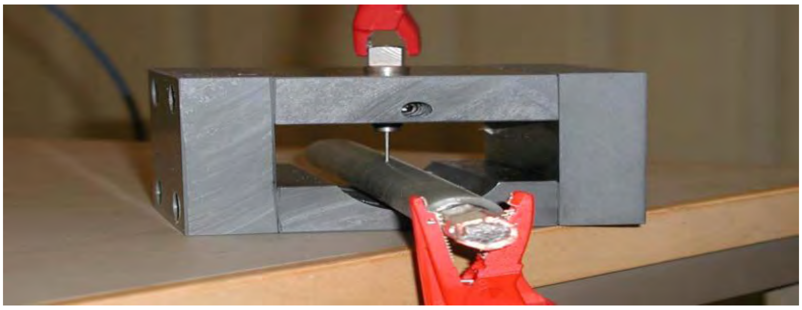

Figure 14: Cable (Needle) test set up

Figure 14 shows the test set up for needle testing. Voltage is applied to the needle and the cable conductor is grounded.

3.7 Inventorying Components

The overall purpose of this section is to help the Tamale operational area, GRIDCo to improve its record keeping processes, so the department will be able to manage and maintain the existing electrical system and better understand how it is currently working. In order to achieve this goal the following actions were taken:

1. Inventory the components within the system
2. Estimate the cost of updating aging and inefficient components
3. Create an efficient system for keeping the database up to date.
4. Investigate future expansion of the system

Microsoft Access software was used to organize the information of the electrical system. The entire electrical system of the substation, including individual components, was cataloged using the existing software available. Once the current state of the system was outlined within the database an updating process was designed in order to keep all cataloged data current. Then, information pertaining to each component was entered into the corresponding database fields.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

From the simulation carried out in Chapter three on the automation switching controls (Figure 11) and composite ac-dc transmission (Figure 12), signals with and without fault conditions have been investigated and simulated by using MATLAB program. Under normal response without fault conditions, the waveform magnitudes for voltage, current, active P and reactive Q powers remained constant. However, during normal response under fault conditions, voltage waveforms suddenly dipped, and recovered to original waveforms after trancient fault cleared, while current waveforms rose in magnitude and then recovered gradually after the fault. This means the system recovered from its disturbances. Active power P decreased in magnitude while the reactive power Q increased in equal magnitude, to compensate for system stability. These means the system conditioners (rectifier and inverter) reacted to stabilized the system.

The cable insulation (needle) test carried out in chapter three, under electron microscopic observation, has shown many small voids and cracks in deteriorated regions and the lamellar structure of polyethylene were destroyed in the insulation. Maintenance budget for the operational area was evaluated. Approximately 50 percent of a maintenance budget is spent on spare parts and material consumption. In organizations that are reactive, up to 20% of spare parts costs are wasted. As Tamale operational area, GRIDCo employs data management module (DMM), spare parts and materials consumption are better planned and controlled, thus waste is eliminated. Analysis of maintenance practices were also carried out for improving equipment reliability and efficiency.

4.1. Normal Response without Fault:

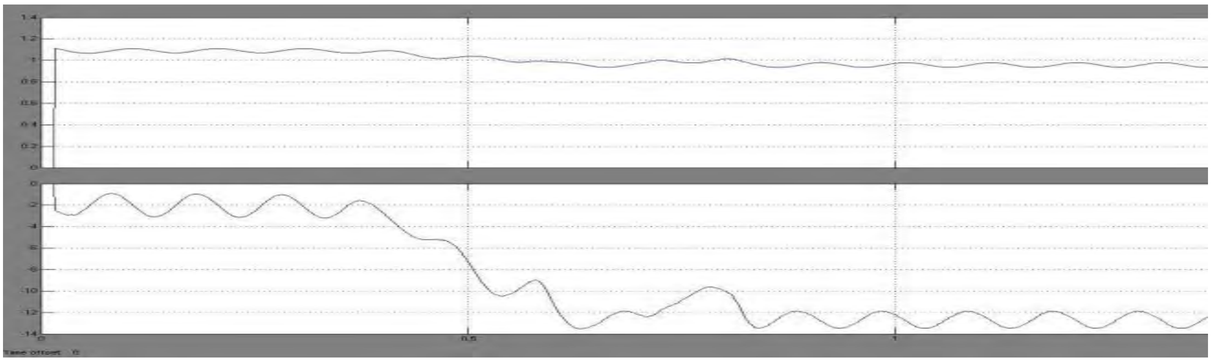

Figure 15(a): Sending end voltage magnitude and phase

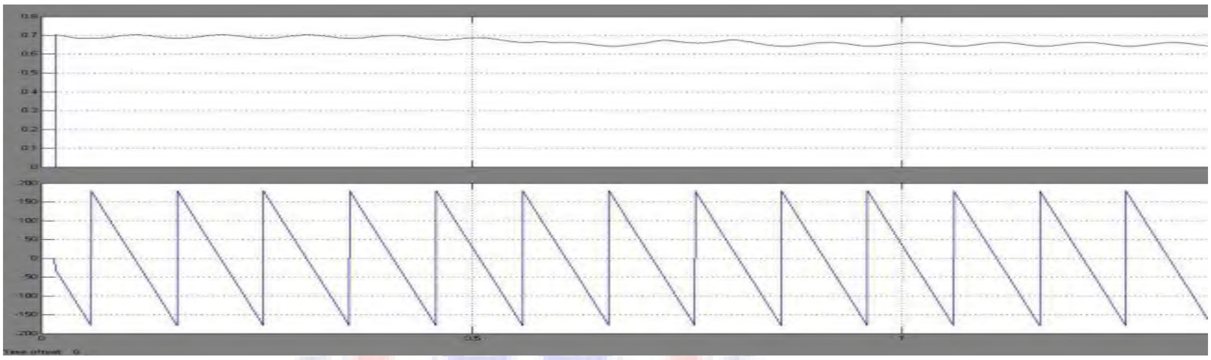

Figure 15(b): Receiving end voltage magnitude and phase

Under no fault conditions, the sending and receiving end voltage waveforms remains constant as shown in Figure 15(a) and Figure 15(b) above, which means normal operating condition.

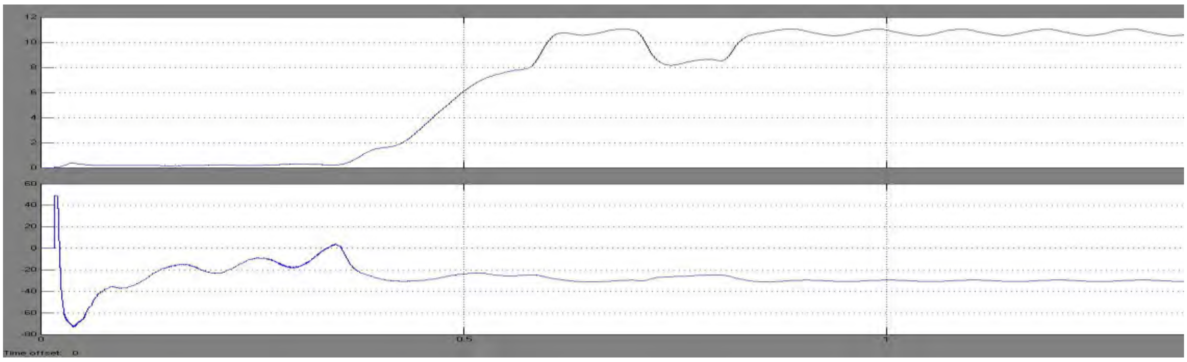

Figure 15 (c): Sending end current magnitude and phase

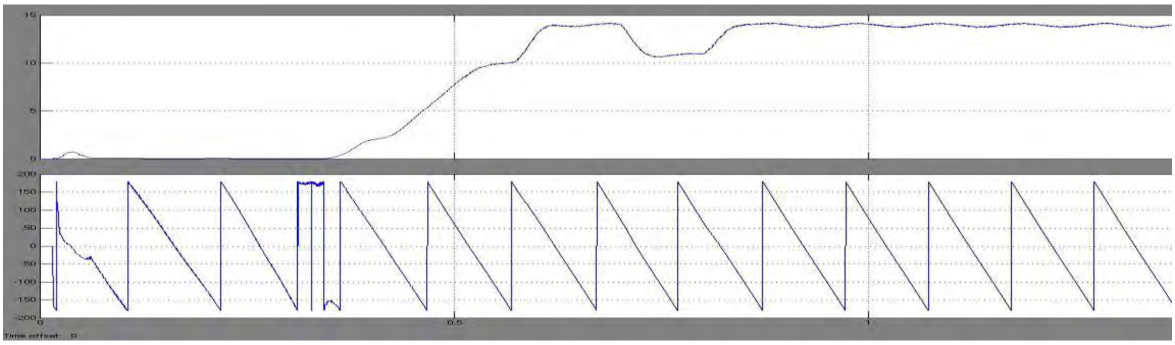

Figure 15 (d): Receiving end current magnitude and phase

Under no fault conditions, the sending end current Figure 15(c) and receiving end current Figure 15(d) waveforms rise to a certain spike and then remains constant, which means normal operating condition.

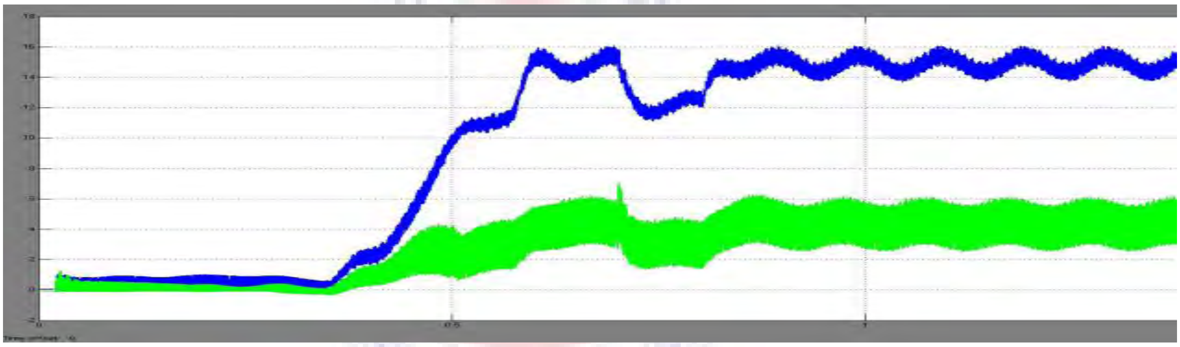

Figure 15 (e): Active power P (blue), and reactive power Q (green), at sending end waveforms under no fault condition

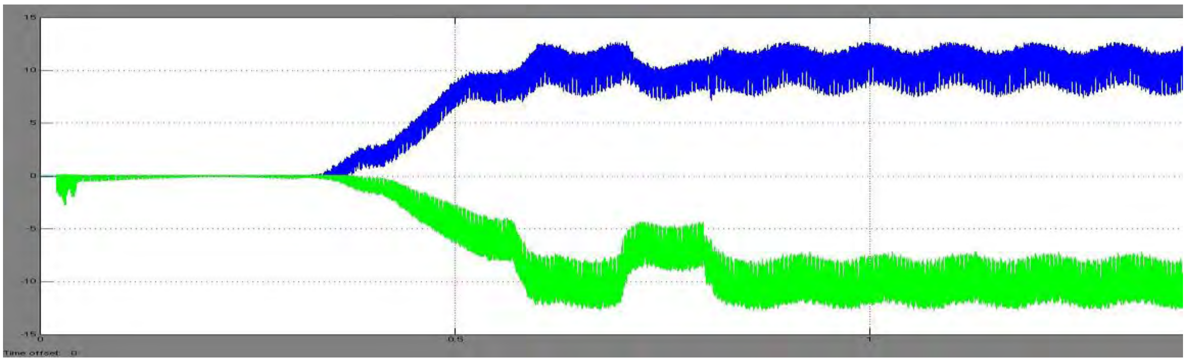

Figure 15 (f): Active power P (blue), and reactive power Q (green), at receiving end waveforms, under no fault condition

Under no fault conditions, sending end active power P and reactive power Q waveforms increase to a point and remains constant in magnitude as seen in Figure 15(e). As the reactive power Q, is utilized in the circuit, its receiving end waveform is lowered in magnitude to a point and then increases in value gradually, before settling down as seen in Figure 15(f). The above figures signifies normal operating conditions.

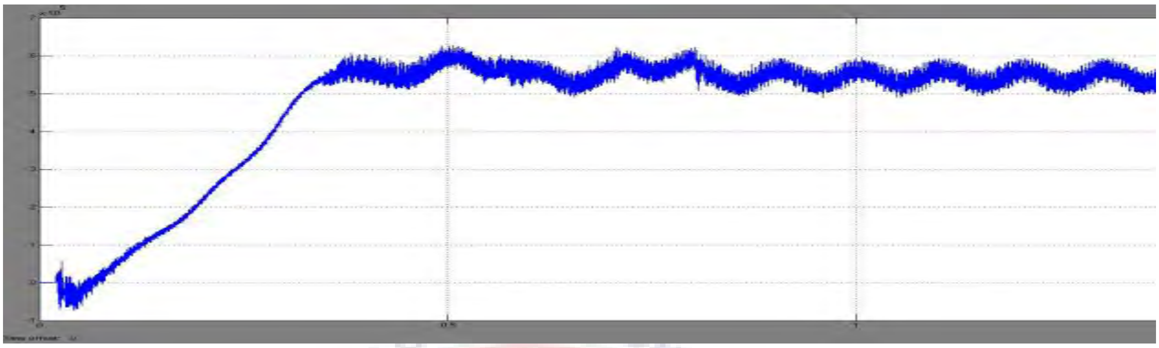

Figure 15 (g): Rectifier dc voltage

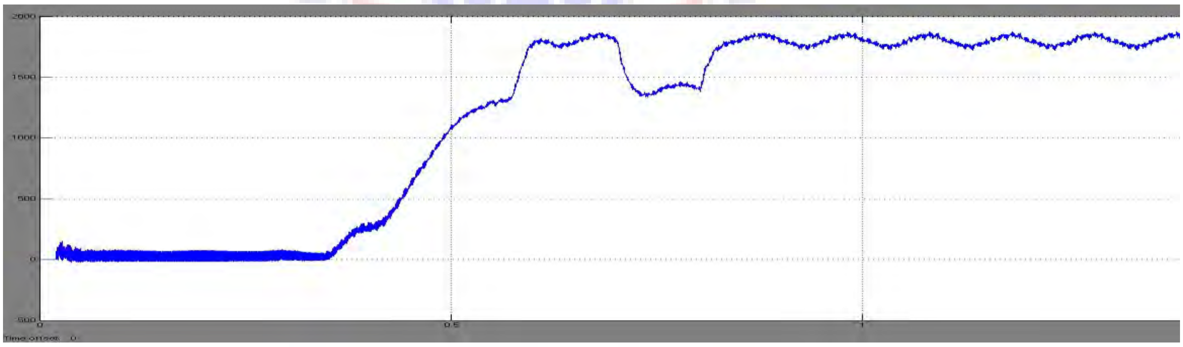

Figure 15(h): Rectifier dc current

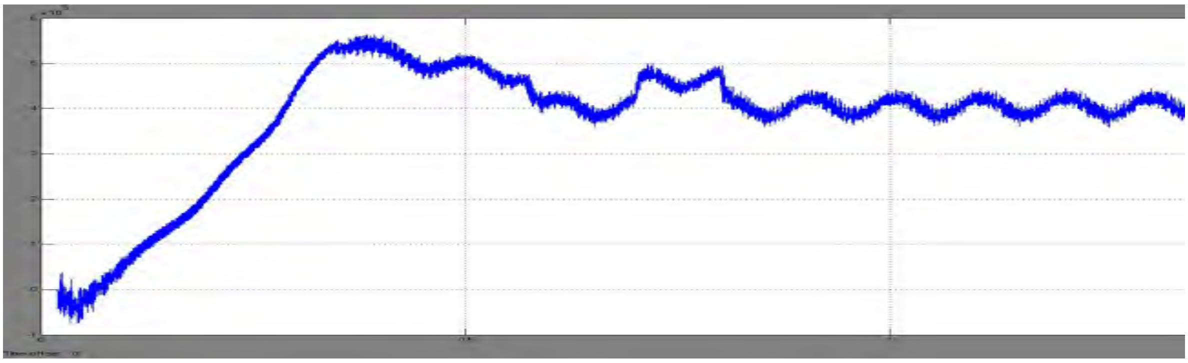

Figure 15(i): Inverter dc voltage

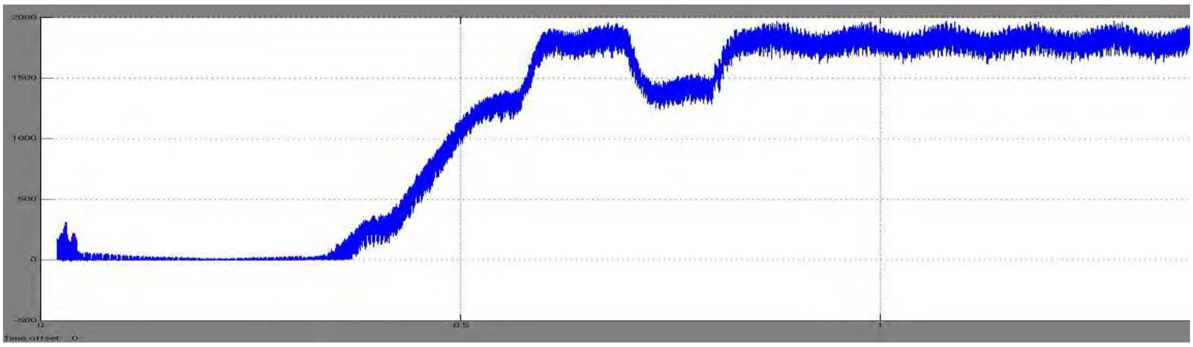

Figure 15(j): Inverter dc current

The voltage waveforms across the rectifier Figure 15(g) and inverter Figure 15(i) remain stable, just as their respective current waveform levels in Figure 15(h) and Figure 15(j), under no fault conditions signifying normal operating conditions.

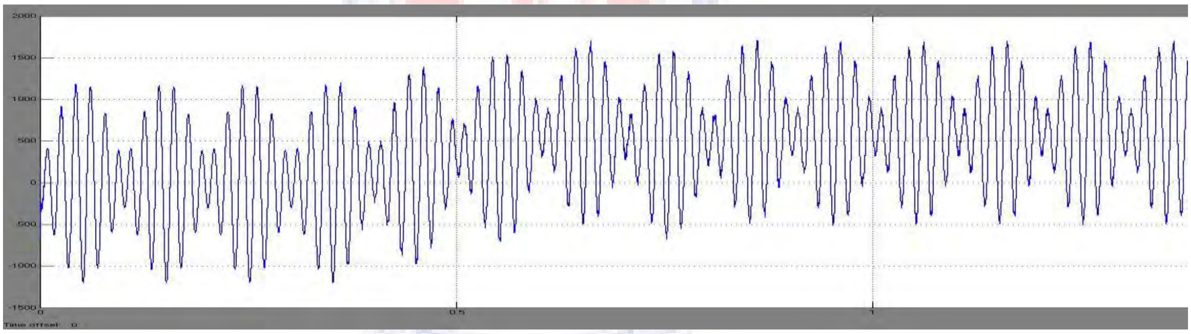

Figure 15(k):Total current under no fault

The Figure 15(k) shows the resultant current waveform, that indicates normal operating condition.

4.2. Normal Response under Fault

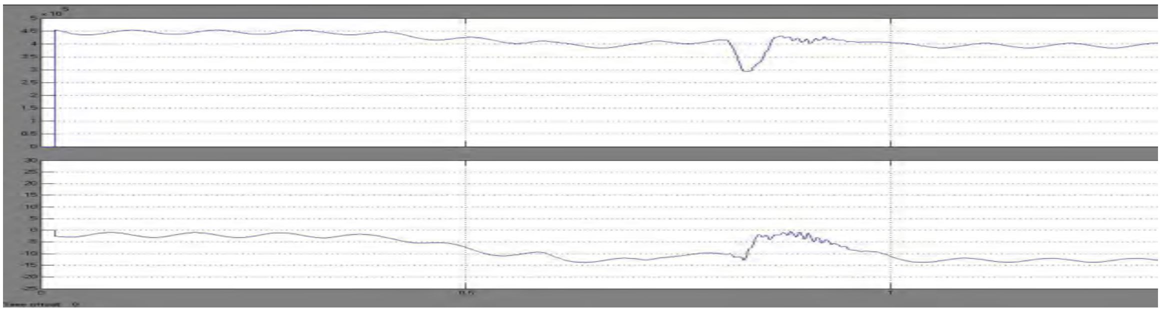

Figure 16(a): Sending end voltage magnitude and phase

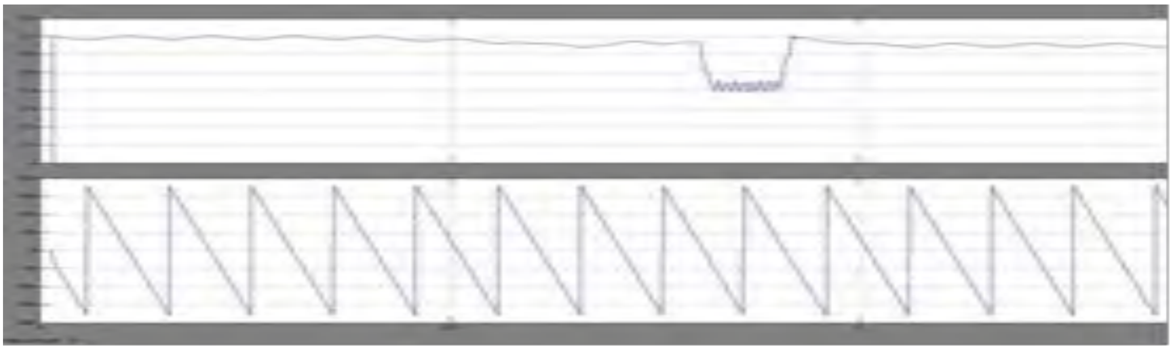

Figure 16(b): Receiving end voltage magnitude and phase

Under fault response conditions, the sending end voltage 16(a) and receiving end voltage 16(b) waveforms suddenly dipped, with recovering of original waveform after the fault was cleared. This means the system recovered from disturbances.

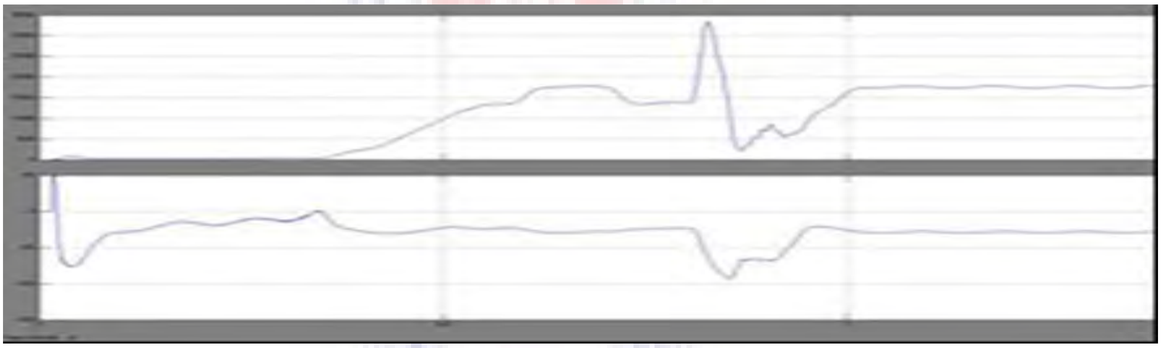

Figure 16(c): Sending end current magnitude and phase

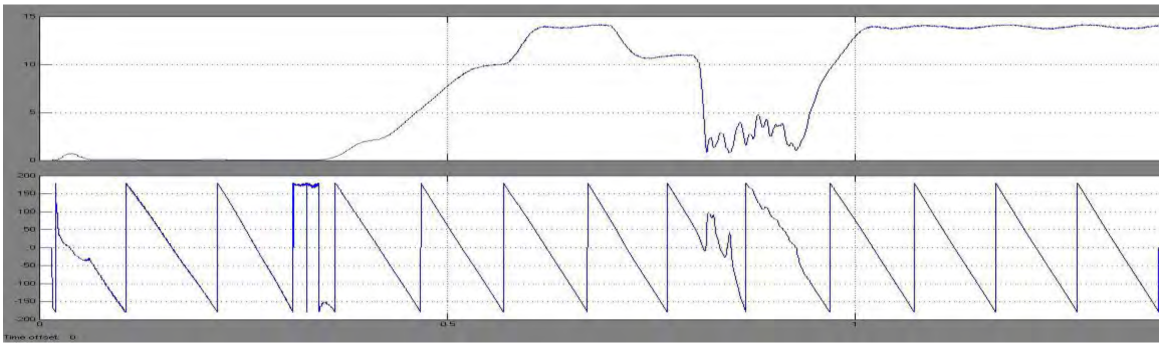

Figure 16(d): Receiving end current magnitude and phase

Under fault response conditions, the sending end current 16(c) and receiving end current 16(d) waveforms, rise to a certain spike or magnitude and then recovered gradually after the fault is cleared.

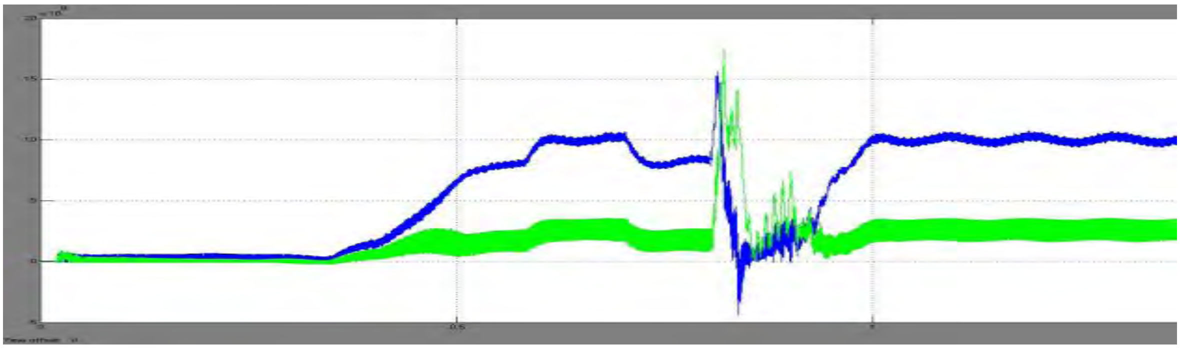

Figure 16(e): Active power P, and reactive power Q waveforms at sending end, under fault condition

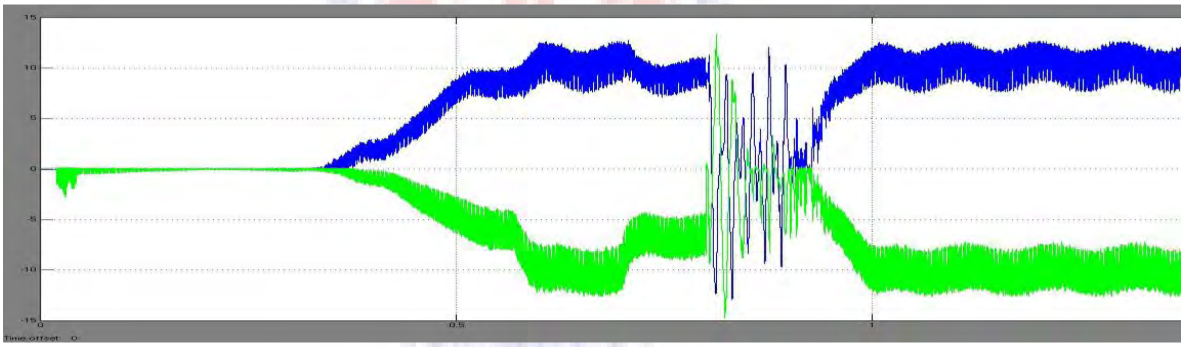

Figure 16(f): Active power P, and reactive power Q waveforms at receiving end, under fault condition.

Under fault response conditions, there are distortions in the active power P, and reactive power Q, in Figure 16(e) and 16(f) waveforms. While active power P decreased in magnitude, the reactive power Q increased in equal magnitude, to compensate for system stability.

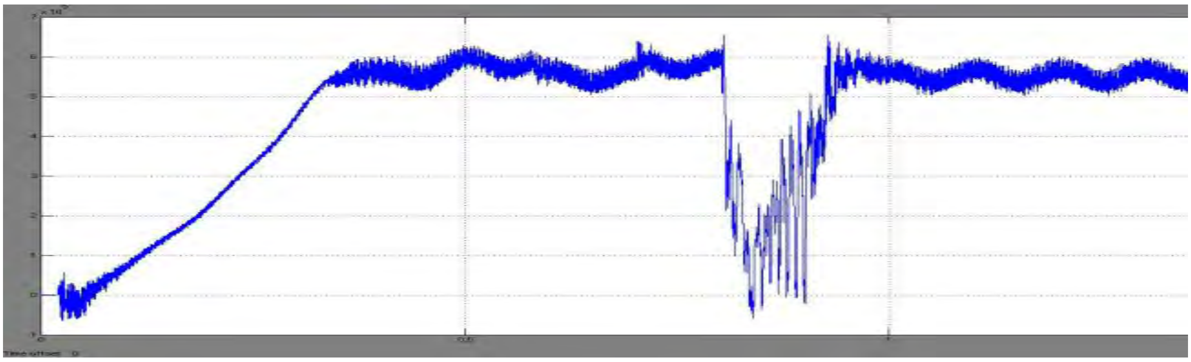

Figure 16(g): Rectifier dc voltage

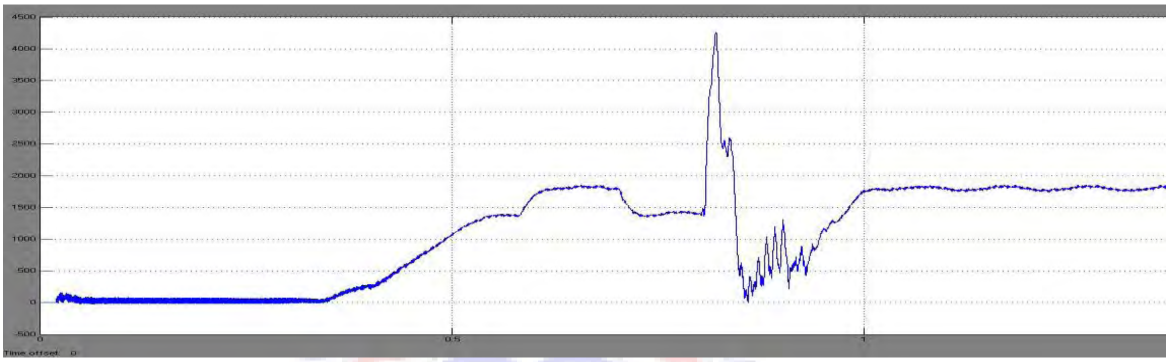

Figure 16(h): Rectifier dc current

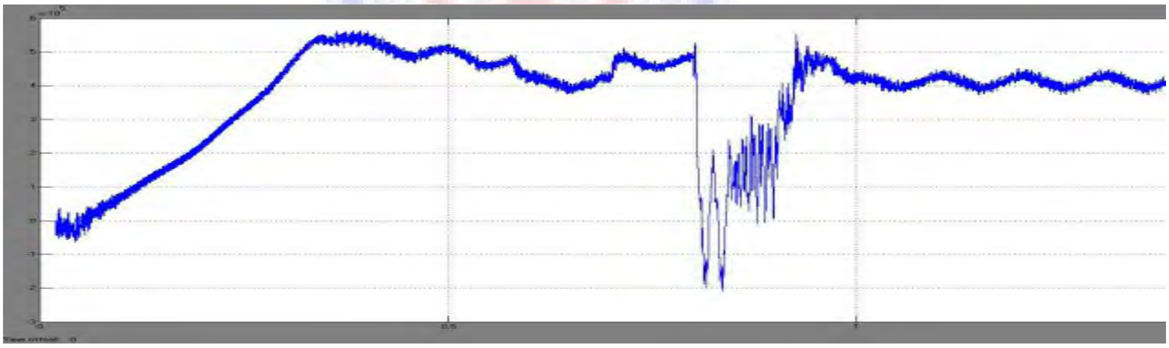

Figure 16(i): Inverter dc voltage

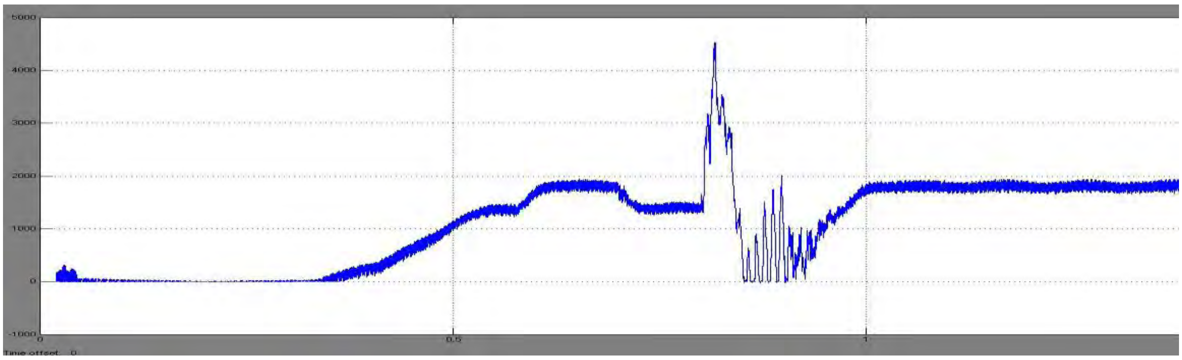

Figure 16(j): Inverter dc current

The voltage waveforms across the rectifier, figure 16(g) and inverter, figure 16(i) dipped on the occurrence of fault whereas their respective current levels surged or increased in magnitude in figure 16(h) and Figure 16(j), under fault conditions. The voltage and current waveforms above regained stability. These means the system conditioners (rectifier and inverter) reacted to stabilized the waveforms.

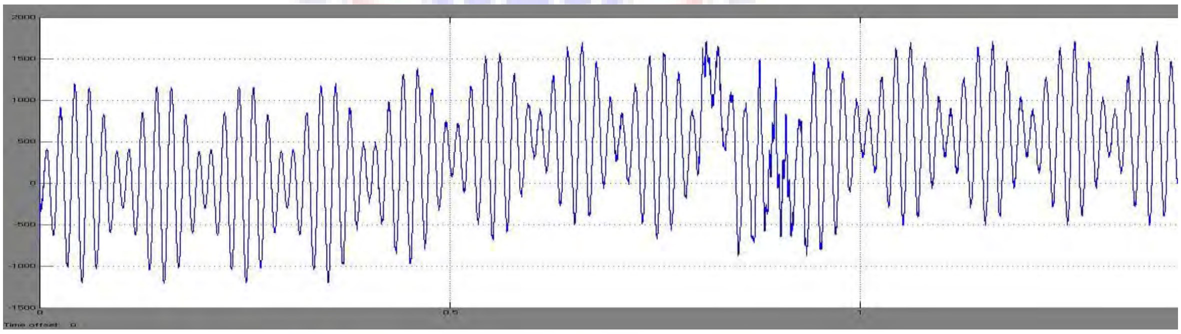

Figure 16(k): Total current under fault

The figure 16(k) shows the resultant current waveform distortion during fault and later normalised. The above results are obtained by using a single line to ground fault in the transmission parameters for the circuit and automation control line models as shown in the Figures 11 and 12.

The single line circuit model uses ground as return path in Figure 12. Hence the use of unipolar dc link for simultaneous ac-dc transmission can pose threats to the equipment located nearby in the ground since using ground as return path can corrode the metallic material if it is in its path.

Another thing is that the sluggishness in the system is removed. If we consider an EHV line and on occurrence of a fault the transient response of the system, for example the voltage profile, the current or the sudden surge in the reactive power requirement has inherent sluggishness, the system requires a long time to recover. But by using the simultaneous ac-dc model the transient response is increased and hence the transient stability. The stability is further enhanced because of quicker current control mechanism of HVDC blocks that is the rectifier, inverter blocks and line commuter converter backup protections (Figure 13). In the control mechanism there is a master control and separately there is inverter and rectifier protection which works on VDCOL power electronics control procedures. Whenever the voltage dips on occurrence of a fault the current is restricted so the fault current is also decreased and the most significant thing is that, it has a very small time constant that works very fast.

4.3 Cable (Needle Test) Insulation

In the needle test (Figure 14), it is the maximum electric field strength that determines the breakdown phenomena. The maximum electric field strength is several orders higher than the average electric field strength. The cable insulation thickness is 2 mm, the needle tip radius is 1.5 μm and the test voltage level is 22 kV, the maximum electric field according the test is 3420 kV/mm whereas average electric field strength is 11kV/mm. Microscopic imaging of the test needles showed that variation in the tip radius is negligible. Insertion of the needle into the cable insulation will cause uncertainty in the measurement results. The total uncertainty in the insulation thickness *d* is 1 mm, meaning that the real insulation thickness varies from 1 mm to 3mm, the maximum electric field strength varies from – 4, 5% to 8, 8% from its nominal value.

The total uncertainty may contain factors such as the bending of the cable and needle, the thickness of the insulation and conductor screen, the asymmetry of the insulation, etc. Variations are smaller than the standard deviation of the measured breakdown voltages. In a needle test a deteriorated region (increased carbonyl content) in polyethylene increases the treeing resistance for AC ramp voltages and positive impulse voltages. The changes of polyethylene structure in the deteriorated region may be responsible for this. Deteriorated areas can improve insulation performance locally. Electron microscopic observation has shown many small voids and cracks in the deteriorated region and the lamellar structure of polyethylene is destroyed in the deteriorated region of the insulation. The number of chain scissions is accumulated at low density during long periods of AC voltage application in the deteriorated region, forming small voids and destroying lamellar structure thereby destroying the cable.

4.4 Inventory and Stores

In the benchmarked Tamale operational area, inventory management is supported by the Data Management Module (DMM). The total number of parts, in addition to the stores" policies, purchasing policies and overall inventory management practices are supported by this software and contribute to the overall maintenance materials costs. It includes selecting spare stock items, determining quantity requirements, establishing stock levels, reordering quantities, and initiating procurement and replenishment actions. Correct parts and materials in good condition should be available for maintenance activities to support both planned and forced outages. Procurement of services and materials for outages must be performed in time to ensure that materials are available to avoid negative impacts on maintenance schedules.

The timely availability of parts, materials, and services is a key element of a strong and effective maintenance programme. Correct parts and materials in good condition are necessary to maintain design configuration and maintenance requirements for activities during normal operating periods and to support both planned and forced outages. Special services are needed periodically to provide unique or supplementary maintenance support.

Storage of parts and materials provides for maintaining quality and the shelf life of parts and materials. Good inventory control enables plants to lower the value of the inventory and continue to maintain a high maintenance service level. This enables the maintenance department to be responsive to the operations group, while increasing the maintenance department"s own personal productivity. Successful computerized maintenance management system users have less material costs. Minimizing inventory on hand helps maintenance organizations eliminate waste. Approximately 50 percent of a maintenance budget is spent on spare parts and material consumption. In organizations that are reactive, up to 20% of spare parts cost may be waste. As organizations become more planned and controlled, this waste is eliminated.

4.5 Analysis of Maintenance Practices

Maintenance management engineers do not adequately differentiate between preventive, predictive, corrective, or reactive work. This was observed during the study collection in the Tamale operational area, GRIDCo. However, a combination of all types of maintenance management systems was used in the study area. From Table 3, it is clearly seen that the benchmarked power transmission operational area mainly focused on predictive, constant monitoring and condition-based maintenance. The five years‟ average maintenance types used by the operational area are shown below:

Table 3: Maintenance types used by GRIDCo, Tamale Operational Area

Types of maintenance (occurrence in %)	Years				
	2011	**2012**	**2013**	**2014**	**2015**
Emergency maintenance	10	10	10	10	15
Preventive maintenance	35	30	30	25	27
Predictive maintenance	40	40	45	40	40
Planned corrective maintenance	15	20	15	25	18

Table 3 shows the analysis of maintenance management practices performed by the Tamale operational area. From the five years‟ average results, we see that preventive and predictive maintenance approaches have been widely adopted. The operational area mainly utilized the Reliability Centered Maintenance (RCM) approach to work out the content and the mix of its preventive and predictive maintenance activities. The 2013 year was the highest level of predictive maintenance practices. The dominant maintenance practice was Predictive (45%), followed by Preventive (30%), and Planned corrective (15%) whereas Emergency (10%) had the least maintenance practice. The power transmission operational area is using a combination of different maintenance managements. The reason is connected with the age, working condition and the complexity of the substations and their equipment.

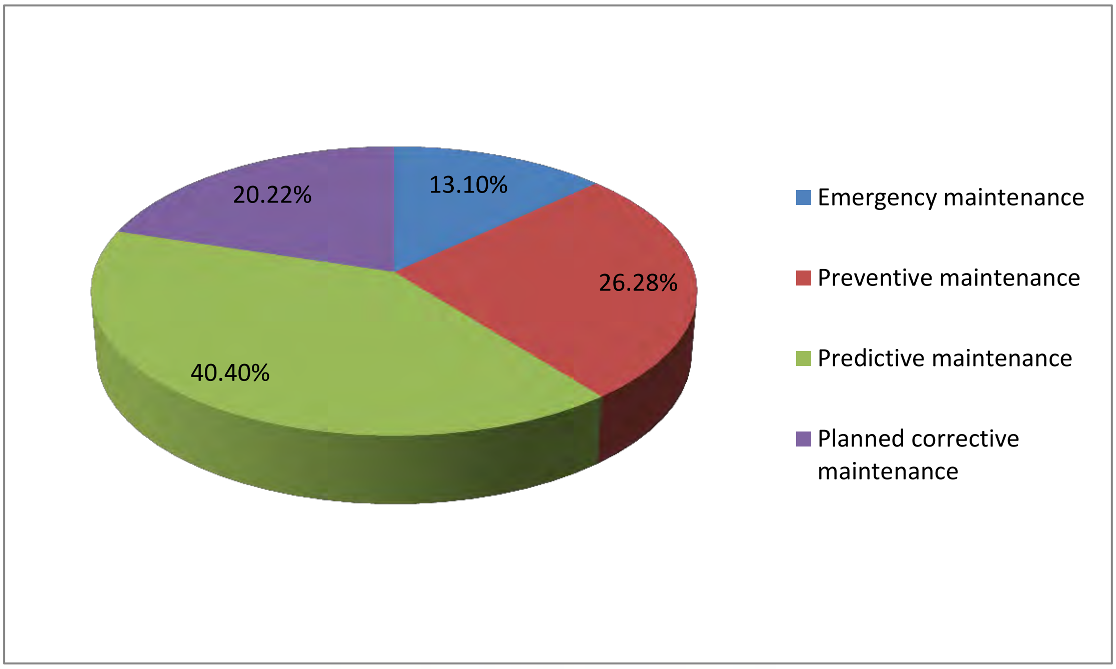

Figure 17: Maintenance scheduled and cost

Clearer information on the maintenance cost distribution, based on the implemented percentage of a combination maintenance system is presented in Figure17. Predictive maintenance (40.4%) had the highest scheduled maintenance and cost whereas Preventive, Planned and Emergency maintenance had, 26.28%, 20.22% and 13.1% respectively. Based on the costs and the history of the equipment, the transmission operational area needs to focus on predictive maintenance. 26.28% preventive maintenance in the benchmarked operational area is high. Also, emergency maintenance seems to be high in the area. In order to reduce the excessive preventive works, the benchmarked operational area needs to rely more on planned corrective maintenance without affecting the reliability of the system. With better condition- based fault diagnosis and better prediction of the deterioration of equipment, more planned corrective maintenance could be achieved.

In the overall, predictive is the preferred system in delivering a flexible, dynamic and proactive maintenance procedure, achieving high reliability, safety, system security and ensuring high availability, minimum down time and repair time. By reducing the percentage of emergency and time based preventive maintenance and maximizing the predictive and planned corrective maintenance, the operational area might achieve more maintenance cost savings by utilizing precision maintenance technologies such as vibration analysis, thermal imaging, laser alignment, moisture and temperature transmitter (MMT 330) and dynamic balancing to improve equipment reliability and efficiency.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The findings of this thesis present a general overview of improving power maintenance and management in an electrical transmission networks in the GRIDCo Tamale Operational Area. In addition, the report explores maintenance practices that promote energy efficiency improvement in transmission networks in the area. The general findings of the thesis are as follows:

The study reveals that automation has seen an improvement in transmission systems. The stability is further enhanced because of quicker current control mechanism of HVDC blocks that is the rectifier, inverter blocks and line commuter converter backup protections.

The study evaluated a number of maintenance performances in transmission systems through benchmarking. Corrective, preventive, predictive and proactive maintenance strategies were needed to boost the transmission system reliability. One of the major contributions of this thesis is to connect component reliability performance to the overall objectives in order to establish the right level of maintenance for every major component.

The study assessed the performance of substation equipment (transformers, motors, cable insulation, capacitor banks, disconnect switches and circuit breakers) and revealed that with corrective maintenance, improved power quality and reliability is assured.

The study revealed that HVDC blocks incorporated has improved faults observability and location in electrical power transmission systems.

5.2 Recommendations

This study recommends that more automation equipment should be acquired by major stakeholders such as the Ministry of Power (Energy), Ghana Grid Company Limited (GRIDCo), Volta River Authority (VRA), Electricity Company of Ghana (ECG), Northern Electricity Distribution Company (NEDCo), Independence Power Producers (IPPs) and other relevant agencies in the power sector.

Due to the interconnections to our neighboring countries like Togo and Burkina Faso, the need to improve power maintenance and management in transmission systems to achieve efficiency, cost effectiveness, stability and reliability of the power transmission system in Ghana and GRIDCo Tamale operational area, in particular is paramount.

Again, the thesis recommends that more research should go into maintenance and management practices (corrective, preventive, predictive and proactive) to promote energy efficiency and improvement in transmission substations and networks. Studies could be done to determine the impact of Reliability Centered Maintenance (RCM) in electrical transmission and distribution networks as well.

Besides, the study recommends that more research should be done on power safety management and practices to safeguard the lives of people and property. Lastly, it is recommended that extension of this research work should be to incorporate the views of external stakeholders like researchers, high-tech equipment dealers, financial organizations, government etc. on the barriers and drivers for improving power maintenance and management.

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