MAINTENANCE OPTIMIZATION FOR POWER TRANSMISSION SYSTEMS:

A CASE STUDY OF GHANA GRID COMPANY LIMITED

By

BISMARK ANANE

(BEng. Electrical Engineering)

A thesis submitted to the School of Graduate Studies Kwame Nkrumah University of Science and Technology, Ghana in partial fulfilment of the requirement for the Degree of

MASTERS OF ENGINEERING IN INDUSTRIAL OPERATIONS

Department of Mechanical Engineering

College of Engineering

February 2016

TABLE OF CONTENT

LIST OF TABLES

TABLE OF FIGURES

DECLARATION

I hereby declare that this submission is my own work towards the award of MEng and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgment has been made in the text.

Bismark Anane	-----------------------------	-------------------------------
(PG1216213)	Signature	Date

Dr.Gabriel Takyi	-------------------------------	-------------------------------

(Supervisor) Signature Date

Prof. F.K Forson -------------------------------- ------------------------------

(Head of Department) Signature Date

ACKNOWLEDGEMENT

I am most thankful to the Most High God for the wisdom, grace and kindness He has extended to me throughout this project. Many thanks also go to my supervisor, Dr. Gabriel Takyi, for his support, matured counsel and guidance throughout this project. I am highly indebted to GRIDCo for providing me with the necessary information regarding the project .I would also like to express my sincere gratitude to my ever-supporting wife Dinah and our three lovely children Nhyira, Aseda and Nyamedo for their understanding, cooperation and encouragement which were instrumental to the successful completion of this work. My appreciation also goes to my colleagues at GRIDCo for their immense support in the project work as well as people who have willingly helped me with their abilities.

DEDICATION

I dedicate this work to my family. A special feeling of gratitude to my loving and supporting wife, Dinah whose words of encouragement and push for tenacity always ring in my ears. My daughters Nhyira, Aseda and son Nyamedo who have always given me a reason to strive for greater heights. You mean more than the world to me.

ABSTRACT

The focus of this research work is on the optimization of transmission assets at the Ghana Grid Company Limited (GRIDCo). The company's maintenance planning and work schedules are currently anchored on time-based maintenance strategy.GRIDCo has had a number of equipment breakdowns and catastrophic failures since its operationalization in August 2008.These catastrophic failures and the vulnerability of the transmission assets to unpredictable breakdowns have adverse impact on the reliability of Ghana's electricity transmission network. Can GRIDCo manage its assets to achieve the optimum life cycle cost which will deliver the required availability, performance, efficiency and quality to meet business goals and objectives? Can the current method of equipment maintenance in GRIDCo be optimized to improve equipment and grid reliability? To answer these questions, the researcher sought to evaluate GRIDCo's asset management systems and maintenance records on selected power equipment.

Data on eight power transformers which failed catastrophically from 2008 to 2015 in the organization was obtained to facilitate the assessment of the existing maintenance strategy. The results of the research work on the eight failed transformers indicated that prior time-based preventive maintenance activities carried out on the power equipment failed to give asset health and warning of imminent catastrophic failure. The research work carried out to investigate cause of 12T3 20MVA 161/11.5/6.6kV power transformer failure revealed prior maintenance activities carried out in October 2008 before the transformer failed in December 2008 without giving early warnings. The results of my work at Buipe substation also revealed that prior planned, maintenance

activities were conducted on the 33MVA 161/34.5kV power transformer power transformer *codenamed 55T1* before it failed catastrophically in 2013.

On the other hand the research work carried out at Kumasi substation using conditionmonitoring maintenance approach on five power transformers indicated alarming levels of carbon dioxide and ethylene gases in the transformer oil of *13T5 33MVA 161/34.5kV* power transformer. The results of the dissolved gas analysis (DGA) on the transformer oil was used to schedule a timely maintenance on the transformer codenamed *13T5* to avert the catastrophic failure of another power transformer in GRIDCo.

The results of the research work indicate that if GRIDCo had used conditionmonitoring approach for the maintenance of the eight failed power transformers, early warnings of upcoming failure would have been detected.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The Ghana Grid Company (GRIDCo) was established in accordance with the Energy Commission Act, 1997 (Act 541) and the Volta River Development (Amendment) Act, 2005 Act 692, which provides for the establishment and exclusive operation of the National Interconnected Transmission System (NITS) by an independent Utility and the separation of the transmission functions of the Volta River Authority (VRA) from its other activities within the framework of the Power Sector Reforms. GRIDCo was established to undertake economic dispatch and transmission of electricity from wholesale suppliers (generating companies) to bulk customers, which include the Electricity Company of Ghana (ECG), Northern Electricity Department (NED) and the Mines (*GRIDCo,2009*). It is therefore incumbent upon GRIDCo to ensure the transmission network operates effectively and efficiently to achieve its core mandate. GRIDCo must ensure power transmission assets are optimally maintained in order to maximize their efficiency while minimizing maintenance cost.

Maximum asset performance is one of the major goals of GRIDCo.To achieve this goal, minimal life cycle cost and maintenance optimization become crucial while meeting demands from customers and regulators. Condition-based maintenance implies planning the future maintenance actions based on the technical state of the system, the state being assessed on the basis of the estimated reliability indices of the system at the planning moment.

The objective of maintenance optimization is to maximize grid reliability, subject to system constraints such as financial resources or crew resources. The preventive maintenance policies adopted by electric utilities are aimed at apt detection of equipment deterioration for timely interventions. The maintenance activities undertaken by the utility companies can involve equipment inspection, repair, replacement, vegetation inspection, tree trimming, and installation of animal guard and washing of insulators. The cost of preventive maintenance activities performed on a system or system element is determined on the basis of existing statistical information available at each operating unit.

1.2 PROBLEM STATEMENT

Ghana's current energy crisis is mainly due to inadequate electricity production from the generating stations to meet national demand. This has adversely affected all facets of national development. The crisis, codenamed *Dumsor*, to wit, off and on, places more demand on the other operators in the electricity value chain to ensure the already bad situation does not get worse through ineffective and inefficient maintenance and operation of power equipment. Transmission assets must therefore be effectively and efficiently maintained otherwise the grid will also become unreliable for the evacuation of the already inadequate power produced from the generating sources. The Ghana Grid Company, (GRIDCo) has a medium term goal of achieving 99.9 per cent reliability on the National Transmission System by the year 2019 (GRIDCo, 2015). This set target requires a careful evaluation of the existing maintenance practices with the aim of improving it to enhance the reliability of the transmission network at a low cost while meeting stakeholder expectations. The optimization of maintenance schedules is one possible technique to reduce maintenance costs while improving reliability. The Ghana Grid Company (GRIDCo) is relatively new in the power industry and has no doubt inherited vestiges of the old ways of doing things from its mother company, the Volta River Authority. GRIDCo therefore needs to review the outdated maintenance protocols in order to re-strategize for a more effective preventive and corrective maintenance regime. Proper asset management methods also need to be implemented. The huge investment in the transmission sub-sector does require that the equipment are maintained and operated efficiently and effectively to increase uptime and grid reliability. Can the adoption of condition-based maintenance strategy address the shortfalls in the time-based maintenance approach?

1.3 RESEARCH QUESTIONS

1. Can GRIDCo manage its assets to achieve the optimum life cycle cost which will deliver the required availability, performance, efficiency and quality to meet the asset's business goals and objectives?
2. Can GRIDCo's existing maintenance regime facilitate the achievement of its medium term reliability target of 99.9 %?
3. What are the challenges that account for the shortfalls in the time-based maintenance approach?
4. What will be the impact of optimized maintenance management on GRIDCo's operations?

1.4 MAIN OBJECTIVES

The focus of this research work is on the maintenance optimization for transmission systems at GRIDCo.The overall objective of the research work is to carry out an evaluation of GRIDCo's maintenance strategy to improve the reliability and availability of the transmission network. This is intended to reduce risk of catastrophic failures, lower total cost of asset ownership and reduce costs from unplanned outages. A case study on GRIDCo's maintenance strategy will be carried out to determine the asset maintenance challenges with respect to maintenance planning and work scheduling. The ultimate purpose of the research work is to achieve the optimum life cycle cost which will deliver the required availability, performance, efficiency and quality to meet the expectations of GIDCo's stakeholders.

1.4.1 SPECIFIC OBJECTIVES

1. To examine and describe the current state of Ghana's national grid power transmission systems.
2. To examine the adequacy or otherwise of existing preventive maintenance strategy
3. To obtain a list of power transformers in GRIDCo and also determine possible causes of some failed transformers.
4. To propose an optimized approach for equipment inspection and preventive maintenance schedules.
5. To discuss the effects of optimized maintenance of power transmission assets

1.5 ACADEMIC SIGNIFICANCE

1. The research literature will involve discussions on the importance of energy for economic activities and national development. This will require a wide level of reading and presenting literature from various perspectives. This is of academic significance since the researcher, his supervisor, external examiners and anyone

interested in studying this document will have to broaden his knowledge base to appreciate this research.

2. The various eclectic methodological approaches of sampling both human subjects in qualitative research (Individual In-Depth Interviews and Focus Group Discussions) as well as examination of data in quantitative surveys is of academic significance.

3. The documentation of the maintenance optimisation protocols of GRIDCo in relation to the literature is of academic significance since the literature will showcase what should happen and the research will show the reality on the ground.

4. The documentation of the maintenance optimization protocols and procedures for preventive and corrective maintenance is of academic significance because it sets the basis for comparison between time-based and conditioned-based maintenance systems.

5. GRIDCo is a relatively new company which was created out of the Volta River Authority. Besides, it has a very unique mandate of transmitting power. Its modus operandi for executing its mandate has been largely borrowed from its mother company, the Volta River Authority. Some of the methods for equipment maintenance have become outmoded and need to be reviewed and improved upon. Whatever the case may be, a relatively new phenomenon in engineering in Ghana should be of interest to academia. The description of these processes could be used to teach students and the data presented from the company by no less a person than an engineer working in the operations and maintenance division of GRIDCo should prove a valuable resource for further research.

6. The acceptance of the research document will make a significant source of reference material which could be quoted by other members of the academic community and students.

1.6 SCOPE AND LIMITATIONS

The establishment of GRIDCo is intended to develop and promote competition in Ghana's wholesale power market by providing transparent, non-discriminatory and open access to the transmission grid for all the participants in the power market particularly, power generators and bulk consumers and thus bring about efficiency in power delivery. Any system of protocol or procedure in performing preventive and corrective maintenance when not done in collaboration with the producers and distributors will not achieve its ultimate objective. How the other agencies mentioned above perform their preventive and corrective maintenance is not the subject of the research as the work is limited to GRIDCo. The findings and recommendations made in this research is limited to the National Interconnected Transmission System as the study focussed only on maintenance of transmission equipment in the electricity supply chain. There will therefore be a natural gap in the knowledge shared in this document. The response to interviews will also be limited by the need to keep the media and public out of the activities of power supply industry on account of the bad publicity the utilities have received in recent years due to the energy crisis. It is expected that this gap will be reflected in the quality of answers that will be given. It will also reflect in the quality of the data that will be released for analysis and hence the findings.

The eclectic nature of the methodology is such that one procedure may become more thorough and painstaking than others as the researcher stretches his resources of time and finances to complete these various methods of data capturing. The lack of adequate funds to access the latest journal references for an up-to-data literature review is also a major limitation on the quality of the final presentation. The researcher is an electrical engineer working with GRIDCo. He will no doubt have a great advantage in accessing data. Fortunately, data on maintenance systems for transmission equipment is available even though for this level of academic research, there will be some reluctance on the part of officials to release data. The globalised nature of power transmission systems maintenance is such that schedules are planned long in advance so that the consuming public could be notified to make alternate arrangements for power supply in situations which require outage for maintenance. In addition, in advanced economies, there is always an excess of production capacity which ensures that when systems are being repaired or maintenance schedules are being followed, consumers will not face much inconvenience and economic activity can go on uninterrupted. Despite the challenge of assessing maintenance records on transmission assets from different work locations, the researcher will make full use of the representative data to describe in detail what happens in the organization and to recommend optimized methods of cost efficient maintenance plans for the power transmission system.

1.7 ORGANISATION OF THE STUDY

This dissertation consists of five chapters. The first chapter gives a background to the study. It discusses the objectives of the study and gives a background to the nature of the maintenance systems of GRIDCo and other maintenance systems around the globe. Chapter Two presents a summary of the literature that gives the theoretical basis for this study. In this chapter, concepts such as the role of power supply in economic activity, preventive and corrective maintenance are discussed. The last section of Chapter Two is the theoretical framework which discusses the context within which preventive and corrective maintenance takes place. The methodological approaches and techniques used in the process of data gathering for the research are explained together with their theoretical underpinnings in Chapter Three. Both qualitative and quantitative approaches, giving practical details encountered in the field are presented here. The sub topics treated here include sampling frame, sampling method, data collection tools and methods of data analyses. In Chapter Four, the findings are presented alongside with the analyses of those findings. The findings are divided into the various methods by which the data was collected, namely, Surveys, Focus Group Discussions and Individual In-depth Interviews. The analyses are related to the objectives of the study in order to make them more focused and relevant. Where applicable, references are made to the literature where it confirms some of the findings or whether there is a divergence. The last chapter is the Summary of Findings, Conclusions and Recommendations. This chapter highlights some of the key findings in relation to the objectives. The references are presented at the end of this chapter. The appendices of data sampled appear after the references.

CHAPTER TWO: LITERATURE REVIEW

2.0 INTRODUCTION

This chapter specifically presents a summary of related literature of the topic. This involves theoretical and practical research and other studies related to Maintenance Optimization for Power Transmission Systems. The research has its theoretical framework based on the fact that the energy crisis in Ghana has an adverse effect on national growth and GRIDCo being the transmitters of power to consumers are at the forefront of solving any lapses in the distribution process. This literature review has its source materials enlisted at the tail end of Chapter Five with their corresponding references.

2.1 RELATED STUDIES

2.1.1 OPTIMIZED MAINTENANCE PLAN FOR TRANSMISSION

Maintenance is defined as an activity to arrest, reduce or eliminate device deteriorations. The purpose of maintenance is to extend equipment lifetime, increase asset values (equipment conditions), and avoid costly consequences of failures (*IEEE/PES 2001*). Models to create connections between maintenance and the matching lifetime extension, asset condition, and reliability improvement are required in order to make sound decisions related to maintenance activities. Lately many utilities have replaced the scheduled maintenance activities by condition-based maintenance, in which the schedule is based on analysis of periodic inspections or condition monitoring results (*IEEE/PES 2001*).

In relation to maintenance optimization studies, *Hilber and Bertling 2006* presented a concept of applying a multi-objective optimization method for maintenance optimization in transmission systems. The process is similar to that carried out during transmission planning. *Jiang and McCalley 2007* developed a risk-based method for transmission system maintenance optimization, by studying the cumulative long-term risk caused by failure of each piece of equipment, which considers equipment failure probability, deterioration and outage consequence. Yang and Chang 2009 developed several approaches to include stochastic-based equipment models for substation and system maintenance optimizations, and implement evolutionary-based optimization techniques, (Yan et al 2008).

Ebeling (1997) has also pointed out that the purpose of maintenance is to extend equipment life and minimize the frequency of service interruption and undesirable consequences. He also says that, for the purpose of quantifying the effect of maintenance on equipment performance improvement, definitions of reliability indices need to be addressed. Ebeling (1997) defines reliability as the probability that a component or system will perform a required function, for a given period of time, when used under stated operating conditions. Tomasevicz (2006) also emphasizes that in power system engineering, it is the probability of equipment or system that can stay in normal operating conditions.

Maintainability is defined as the probability that a failed component or system will be restored or repaired to reach a specified condition, within a period of time when maintenance is performed in accordance with prescribed procedures.

In the power industry, there are various indices used to measure the reliability of systems. IEEE has developed three standards, for term definitions in outage data reporting and reliability indices: IEEE Standard 762 (2005) for generation reliability indices; IEEE Standard 859 (1987) for transmission reliability indices; and IEEE

Standard 1366 (2004) for distribution reliability indices. Ebeling (1997) further has it that among the reliability indices defined, availability is an important index. Availability is the probability that a system or component is performing its required function at a given point in time, or over a stated period of time when operated and maintained in a prescribed manner.

Availability is the preferred measure when a system or component can be restored, since it accounts for both failures (reliability) and repairs (maintainability). Therefore, availability is a popular adopted index for repairable equipment or systems (ref). Typically, the commonly used term *mean time to failure* (MTTF) index is utilized to measure reliability, because reliability focuses on success or failures. In the contrast, availability includes the consideration of both reliability (quantified by MTTF) and maintainability (quantified by *mean time to repair*, MTTR), and usually calculated by MTTF/ (MTTF+MTTR). Therefore, availability is the most important index to examine the impact of maintenance toward reliability (Ebeling 1997). Improving the overall reliability and reducing the operating cost are the two most important but often conflicting objectives for substation.

A condition-based substation maintenance strategy provides a means of balancing these objectives. This chapter proposes a multi-objective approach to best compromise these two objectives for substations by optimizing the inspection frequencies required for each component .A multi-component model is employed to evaluate the overall reliability of interconnected components.

2.1.2 TYPES OF MAINTENANACE METHODOLOGIES

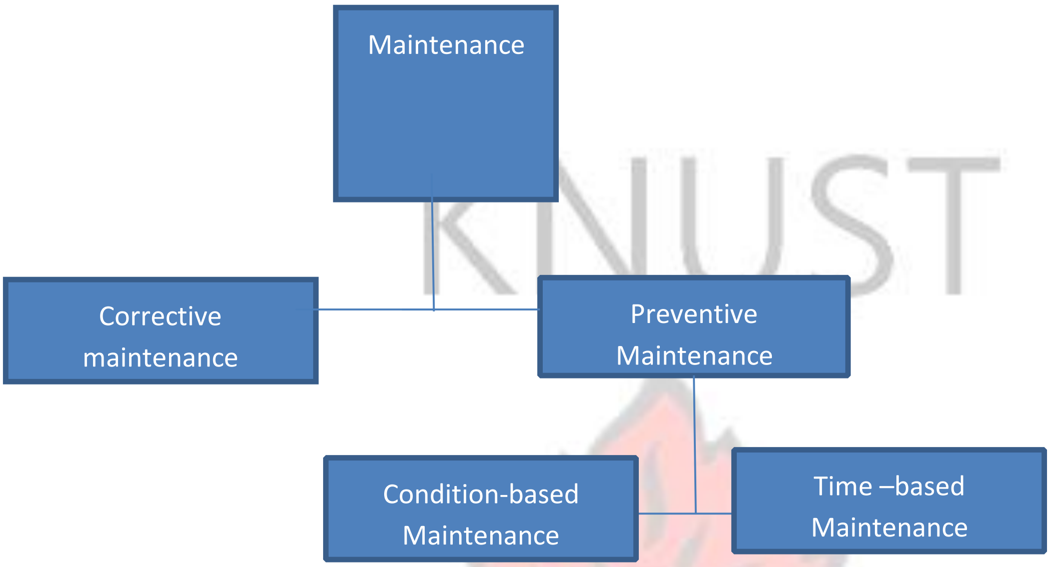


Figure 2.1: The Different Maintenance Methodologies

There are three maintenance methodologies, namely: Corrective Maintenance, Condition Based Maintenance and Time Based Maintenance

2.1.4 SUBSTATION RELIABILITY EVALUATION

According to Allan and Ochoa (1988) the models for maintenance methodologies can be categorized into Network Reduction, Markov Modeling, Minimum Cut-Set and Monte-Carlo Simulation approaches. The following are brief descriptions and comparisons of these methodologies.

1) *Network Reduction*

Brown (2002) has stated that his method uses an equivalent substation model to simplify the original substation, but excludes all feeder breakers. Equations are derived to calculate the equipment failure rates and durations. However, this method ignores the impact of maintenance, and is therefore not appropriate for reliability modelling of substations with aging infrastructure and maintenance.

2) *Markov Modeling*

In the Markov model, each state of the substation is a combination of specific states that are utilized in power transmission equipment models. The reliability indices can then be calculated through solving Markov equations. This method is straightforward and has several applications, especially in small scale substations with limited components. However, the increased number of equipment or states in equipment models will greatly increase the complexity in substation Markov models. (For example, if a substation has *m* equipment, and equipment is modelled by an *n*-state

Markov model, then the substation Markov model contains *nm* states).

3) *Simulation method*

Frimpong (2004) stated that simulation method is widely applied in system level reliability assessment, including substations. Frimpong argues that sequential or nonsequential Monte-Carlo simulation techniques are used to sample the durations of events or the states of equipment, and the system reliability is calculated through the simulated event history.

Again, the increased number states in modelling equipment reliability by Markov process will increase computation burden; the simulation programmes may experience long execution time before converging to a satisfied value. One possible solution to decrease the executing time is using parallel computing techniques, in order to efficiently utilize the capacities of multi-processors and large memory resources.

4) *Minimum Cut-Set*

Billinton (1970) explains that minimum cut-set method is an alternative network reduction method. More importantly, a *cut-set* is a group of components whose failure causes the system to be unavailable. A *minimum cut-set* is a smallest set of components such that if they fail, the system fails. An *nth* order minimum cut-set is identified as those which consist of *n* components. The minimum cut-set method has the following advantages: easy implementation; handles complex networks that cannot be characterized by either serial or parallel connections; gives insight into critical component dependencies. This dissertation implements a minimum cut-set method for substation reliability assessment.

2.2 RENEWALS MODELING

Anders et al (2007) define the action of renewal as: the external intervention performed on a system that restores the system operating status and/or changes the level of its deterioration. From the definition two types of renewal actions that can be performed on systems can be distinguished.

1. Failure Renewal (FR), is performed only at the appearance of some failures and its purpose is to restore the system operation. They are random events generated by the failure of the system.
2. Preventive Renewals (PR), have the purpose of renewing the system before its failure. They can be random or deterministic events, according to the way in which they design their strategies. Thus, the random or deterministic strategy of

preventive renewals is added to a random process of failure renewals. The classification of renewal actions can be performed on several criteria, of which we remind a few: the purpose, timing and costs of their occurrence, distribution and frequency and last but not least, the effects on the system safety (Anders et al 2007).

2.3 ASSET MANAGEMENT

Asset management and maintenance optimization are two related topics. The objective of asset management is to handle physical assets in an optimal way in order to fulfil an organizations goal whilst considering risk (EFNMS, 2011). Eventually, maintenance optimization should be seen as a toolset within the broader concept of asset management.

In a company, there are several things that can be called an asset, for example:

1. Capital
2. Equipment and premises (physical assets)
3. Employees
4. Customer base
5. Corporate structure
6. Brands

According to Hilber (2005), some previous works have shown that asset management literature in the electric power sphere primarily deals with physical assets with a focus towards heavy equipment. This does not exclude other assets entirely from asset management considerations. For example, other assets can be involved as costs and/or constraints in the work with asset management. Usually, physical assets have an expected life of more than one year (typical 20-50 years for electric power equipment) and so represent a big turnover (NAMSG, 1998).

The aim of every company is to maximize of profit at an acceptable risk, asset management therefore becomes a process to achieve this by managing the physical assets. A number of activities are recognized that are closely linked with asset management:

1. Acquire
2. Maintain
3. Dispose
4. Replace
5. Redesign/Rebuild

These actions are what the asset manager can use to align the assets. All the actions are related to each other, for example a replacement consists of a disposal and an acquisition. In the acquisition phase redesign is considered and afterwards the equipment has to be maintained.

Asset management methods are often denoted by the way to keep the risk at a constant level while downsizing cost. This is achieved by a better utilization of the available asset i.e. by performing the best actions at the best possible time. In order to do this, different methods and systems are used.

Graver et al (1964) have stated that, since the aim of any electric utility company is to supply reliable power to customers at low cost, prevention of power system failures is of overriding importance during the design and operation of the system.

Consequently, a proper preventive maintenance program in transmission systems can have a significant effect on the achievement of high reliability. The preventive maintenance policies adopted by electric utilities are aimed either at detecting deterioration of the equipment before it fails or are based on the priori assumption that the equipment has deteriorated and requires replacement without proof of deterioration (Cumming et al 1965).The timing of preventive maintenance involves trade-offs between the requirement for reliable power supply at all times and the cost of performing maintenance activities. Bertling in his report said that in recent times, utilities have conducted pilot applications of the Reliability Centred Maintenance (RCM) on various power plant systems. RCM is a qualitative method for determining applicable and effective preventive maintenance procedures.

2.4 POWER SUPPLY AND EFFECTS ON NATIONAL DEVELOPMENT

Currently, Ghana is experiencing electricity crisis, popularly known as *"dumsor"*, which is having a monumentally bad effect on people, industries and the country's economy in general (Africa-Confidential 2015).

Some research have been done and have come out with results believed to be the uses, disadvantages and possible solutions to the energy crisis in Ghana. There are currently three hydro-electric dams in Ghana namely the Akosombo Dam, the Bui Dam and the Kpong dam. These dams are not operating up to their full capacity due to hydrological challenges. The dams presently have low water levels. A minor reason for this is the insufficient amount of rainfall from the year before, and the major reason being a fall in the flow of water from stream following the construction of dams in Burkina Faso, on an important water source to the Volta Lake (Africa-Confidential 2015).

The poor state of grid electricity supply has a negative impact on the economic performance of a developing economy such as Ghana. Energy supplies have a significant impact on economic activities (Velasquez and Pichler, 2010) because it is used for varied purposes ranging from production, storage, powering of office equipment and product display. The Institute of Statistical, Social and Economic Research (ISSER) of the University of Ghana has revealed in its 2014 economic outlook report that Ghana is estimated to lose between $320 million and $924 million a year in terms of decline in productivity and economic growth due to the current energy crisis facing the country .

Using the case of Malaysia taking energy consumption as dependent variable and GDP, financial development, population as independent variables, results shows that economic growth and financial development influence energy consumption in shortrun as well as long-run. (Islam, Shahbaz, Ahmed, & Alam, 2013).

2.5 THEORETICAL FRAMEWORK

Optimization is based on calculations of customer interruption costs and component importance derived from reliability calculations that are inherently costly in terms of computation time. This pushes the optimization approach toward a method that requires few calls on calculation of objective function and other outputs. Another aspect of the optimization is that the reliability calculation constitute a “black box” that an optimization routine cannot see through. However, the concept of component reliability importance indices allows for a certain degree of visibility into this “black box”.

It is assumed that the caused interruption cost is linearly dependant on the failure rate of the component, when no other data are changed, that is, assuming that a relative change in failure rate results in the same relative change in customer interruption cost caused by the specific component. Given maintenance actions and estimates of failure rate changes and maintenance cost/savings caused by these, a cost-benefit ratio can be developed. This is the ratio between the change in interruption cost and the cost/savings of the investigated action. By doing this for all available actions for all transmission components in GRIDCo, the available actions can be ranked. The cost change of a preventive maintenance action depends on the specific maintenance activity considered, and the activity is assumed to give an estimate of the change in the failure rate for the actual component. It is assumed that the cost of corrective maintenance is linearly dependant on the failure rate, e.g. if the failure rate is reduced with 50% the expected cost of corrective maintenance is reduced with 50% for the specific component.

As an objective, equipment failure is used to estimate the cost of supply interruptions. It is expected that when power systems are maintained more regularly according to the best practices of protocol for maintenance established, grid reliability will improve which consequently shall give confidence to the distribution companies and the general population. GRIDCo's maintenance regime has not been optimal hence the incidence of preventable faults and equipment failures in the transmission network which aggravates the current energy crisis whenever they occur. It can further be argued that GRIDCo inherited its maintenance protocol from Volta River Authority and has not evolved and optimized its maintenance system in accordance with industry best practice since it became operational in 2008. Electrical power systems consist of transmission and distribution networks for the transport of electrical power from producers to customers. The operation of these networks requires several assets. An asset can be a person, object or other entity with a value that makes monitoring and controlling its usage desirable in order to achieve the core business objectives. In electrical power systems, we can define asset as the physical component of a manufacturing, production or service facility, whose value, enables services to be provided and has an economic life of greater than one year. Assets can be classified into different types: physical assets, human assets, intellectual assets, financial assets and intangible assets (Soemeer 2010). In this research, assets will be limited to physical assets (components) of a network. Physical assets are assets such as cables, circuit breakers and transformers. The focus of this research is on Ghana's transmission network with a voltage level of 161 kV. To operate physical assets in a more technically and economically efficient way, asset management is required (Soemeer 2010). In the electrical power business, asset management involves the planning and operation of the electrical power system. Asset management can have different definitions depending on the application. Asset management in the power transmission business can be defined as developing and implementing an integrated set of strategies and decisions as well as managing the relationships with key internal and external parties (Soemeer 2010). Asset management involves many aspects, for example: life cycle assessment, risk analysis, condition monitoring, maintenance

strategies, reliability, financial, legal, regulators etc.

Risks have to be taken into account during the implementation of asset management. One of the major risks that are taken into account in asset management is the probability of failure occurrence and its consequences (Soemeer 2010). The goal is to ensure maximum asset value or minimal life cycle cost while considering the risk.

This can be achieved by proper maintenance planning. Proper maintenance planning can be managed by including several factors such as the condition indexing of components and failure statistics of components. During condition indexing, parameters (condition indicators) indicating the technical condition of the asset are assessed after the execution of preventive inspections (regular maintenance). Based on the assessed condition indicators, the condition of the asset and the health index of a component can be determined. The condition index gives the overall technical state of the asset. The health index gives the state of the asset based on its remaining lifetime.

In this thesis, we will make a distinction where maintenance can be divided into extra maintenance and regular maintenance. Regular maintenance involves preventive inspections in order to assess the condition indicators and the required extra maintenance. The purpose of extra maintenance is to improve the condition of the asset.

2.5.1 Scientific challenges

High voltage transmission networks contain many physical assets. Time constraints make it difficult to optimize the condition and health indexing process for the whole population. Based on available FMECA data (Failure Mode Effect and Criticality Analysis), the relevant components are selected for the appropriate maintenance actions.

Questions which may arise during the optimization are:

- How can the condition indicators be weighted quantitatively?
- How can the detection chance be determined for the condition indicator and the related failure modes?
- How can an optimal maintenance time interval for each condition indicator be determined?

2.5.2 **Asset failures**

Asset failure simply means the inability of the component to perform the expected function. Asset failures can be triggered by deterioration of the component or external causes such as intrusion of animals like crows.

2.5.3 Deterioration

Components are subjected to deterioration as a result of usage and aging. During operation, components undergo electrical, mechanical, thermal and environmental stresses, which lead to a deterioration of the component (Krontiris and Balzer 2008). Furthermore, deterioration also occurs due to components interaction such as chemical reactions. Deterioration occurs over time and can worsen the reliability of the components.

2.5.4 **Failure Modes and Effects Analysis (FMEA)**

FMEA involves determining the different ways a component might fail (failure modes), and what the consequences might be (failure effects). Furthermore, FMEA determines the probability of the occurrence of each failure mode, as well as the potential severity of consequences. The probability of the occurrence of each failure mode strongly depends on the ageing and degradation state of the asset. Besides the FMEA, a Failure Mode Effect and Criticality Analysis (FMECA) is also possible. In this case, the probability or frequency of the occurring failure modes and the consequences of the failure modes are weighted and expressed in a rank.

A specific component can be divided into several types of components. Failure modes can differ for the several types of components. Failure modes can be divided in two types, maintainable failure modes and non-maintainable failure modes. In contrast to maintainable failure modes, non-maintainable failure modes cannot be countered by preventive maintenance

***2.5.5* Components of a circuit breaker system in a transmission network** A

circuit breaker system can be divided into three components, namely:

- Circuit breaker
- Grounding
- Control circuit.

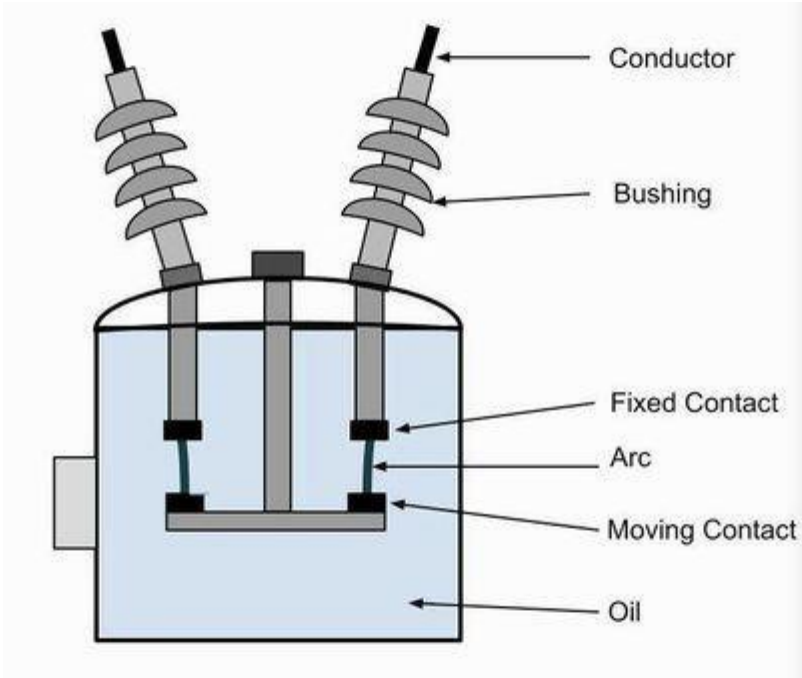
2.5.6 The circuit breaker

The quality of electricity delivery depends on several aspects such as the reliability of the components. The development of networks, increase of power generation, rise in service voltage and the increasing importance of interconnections, results in an increasing importance of the reliability of circuit breakers (CIGRE 2004). The circuit breakers have various and essential duties. The main task of a circuit breaker is to interrupt fault currents and to isolate faulted parts of the system (van der Sluis, 2001). There are indoor and outdoor circuit breakers. Condition indicators and maintainable failure modes of the indoor and outdoor circuit breaker are equal, therefore, no distinction will be made between them in this research.

In high voltage, three types of circuit breakers can be categorized according to the extinguishing medium, namely:

- Air-blast circuit breaker Gas circuit breaker (mostly SF6)
- Oil circuit breaker.

Figure 4.1: An Oil Circuit Breaker



These three types of circuit breakers can be subdivided in 3 types based on the operating mechanisms (Lou van der Sluis 2001):

- Hydraulic mechanism
- Pneumatic mechanism
- Spring operated mechanism.

2.5.6 Grounding

The electrical power system consists of overhead lines and underground cables which are required for transfer of the electrical energy on different voltage levels. These conductors must be isolated with respect to the ground (Popov, 2011). Grounding is a conducting connection, by which an electric circuit or equipment is connected to the earth, or to several conducting body of relatively large extent that serves in place of the earth. Groundings are used for establishing and maintaining the potential of the earth or approximately that potential (Gruzs and Melhorn 1999). Grounding is required, because of the safety in the network for the persons who work or walk nearby and the continuation of the electricity delivery.

2.5.7 Condition-based maintenance

Condition-based maintenance is gradually replacing time-based maintenance as a more effective approach to compromise the operating cost with reliability of substations. In recent years, many diagnostic techniques, such as transformer oil analysis and circuit breaker trip coil current signature have been proposed to inspect conditions of the equipment and determine the need and extent for its subsequent maintenance. Frequent inspections usually give rise to high chances of detecting deterioration but at the expense of high inspection and subsequent maintenance costs.

Furthermore, a lack of proper maintenance or excessive maintenance after each inspection could result in failure rather than improvement. It is thus necessary to optimize the frequency of inspection as well as the extent of maintenance

CHAPTER THREE

METHODOLOGY

3.0 INTRODUCTION

In this chapter, the methodology and a discussion on the approaches to data collection is presented and discussed. The methodology is very important in research because it provides the avenue for anyone interested in the research to judge the validity and reliability of the approach used which has a direct effect on how the findings and conclusions are accepted. Babbie e tal (2001) have stated that validity is the extent to which an empirical measure adequately reflects the real meaning of the concept under consideration. This Chapter therefore includes the research design, sampling technique, sources of data, population and methods of data analysis.

3.1 RESEARCH DESIGN

This research is a case study of the Maintenance Optimization for Power Transmission Systems processes of GRIDCo. It is therefore imperative to combine both qualitative and quantitative techniques. The quantitative technique involves a participant observation of the operations at GRIDCo and a survey of human subjects who expressed their views of the Maintenance Optimization process. It also involves analysis of data on a sample of products returned for after sales service and their corresponding quality control check procedures and data prior to their being released.

The task of finding the optimal balance of preventive and corrective maintenance is approached as a multicriteria optimization problem. On one hand, we have the customers' demands for power delivery and on the other hand we have the maintenance cost for the transmission equipment. In the optimization equipment failure and the consequent total customer interruption cost is used as the measure of system reliability performance from the customer perspective. The maintenance costs are closely related to the analyzed network, its components, structure and available resources.

The qualitative data also involve both human subjects and non-human subjects. The human subjects are selected staff of GRIDCo who will take part in a Focus Group Discussion on the Maintenance Optimization process. Individual In-Depth Interviews with the Maintenance Optimization teams will be conducted. Other Individual InDepth Interviews are planned with the officers responsible for maintenance and repairs. The non-human subjects in the qualitative study involve a descriptive narrative of the Maintenance Optimization for Power Transmission Systems procedure or protocol as well as the same descriptive narrative of the reality of the actual maintenance process. Data on transmission systems were sampled and analysed. Yin (2009) asserts that a case study is an empirical inquiry about a contemporary phenomenon, that is, a case, set within its real-world context especially when the boundaries between phenomenon and context are not clearly evident. Case studies involve an up-close or in-depth understanding of a single or small number of cases, set in their real-world contexts (Bromley 1986). The closeness aims to produce an invaluable and deep understanding, which results in new learning about real-world behaviour and its meaning.

3.1.1 SOURCE DATA

Two main sources of data namely, the primary and secondary sources of data were used for the case study. In this context, the researcher acquired primary data via collection of original primary materials from field personnel and equipment manuals.

Part of the research work carried out at Obuasi, Buipe, Aflao, Achimota, Winneba and New Substations investigated the maintenance records on transformers at these locations prior to the failures of transformers at the said substations. This was aimed at verifying the adequacy or otherwise of time-based maintenance techniques in the maintenance of transmission equipment. The results of the work revealed that preventive maintenance schedules were duly carried out on the transformers before failure occurred. The results of the work also revealed that replacement of the failed transformer at Buipe which is a single transformer substation in 2013 cost GRIDCo multiples of 36,000 man-hours, forty drums of transformer oil and a new 33MVA transformer .This explains how costly corrective maintenance can result from ineffective planned preventive maintenance on transmission equipment. The results of the research work exposed the inadequacy of time based maintenance which makes reliability of power supply vulnerable to unexpected equipment failures. Electricity consumers in Winneba and its environs had to suffer power cuts for about one month after the failure of the transformer before it was replaced. Though best practices cannot entirely prevent the occurrence of every equipment failure in GRIDCo, the research work also revealed that early warnings and proactive maintenance can reduce the probability of catastrophic failures.

unique authority in describing the phenomenon of Maintenance Optimization for Power Transmission Systems.

The quantitative analysis of the human subjects involved the use of a semi-structured questionnaire to elicit responses from relevant staff of GRIDCo in a Focus Group Discussion. Focus Group Discussion were held with experienced maintenance staff from protection, line, operating sections to discuss the Maintenance Optimization for Power Transmission Systems. Individual in-depth interviews were also conducted with managers as has been mentioned in the section on research design. The strategy for maintenance optimization for power transmission systems other jurisdiction were also examined to ascertain the workability of the optimization techniques.

3.2 POPULATION

Given that this is a case study involving both human and non-human subjects, the population includes both staff of GRIDCo who are the respondents in the survey, Focus Group and Individual In-Depth Interviews. The population also includes electricity transmission data of GRIDCo. These data were sampled, a few collected and their contents examined. The results were compared with maintenance schedules on selected power equipment and their corresponding pre-maintenance status. The population of data from which the sampling were done include files on:

i. The electricity transmission system data in GRIDCo ii.
The data on power transmission system equipment iii.
The data on transmission equipment maintenance history.

3.3 SAMPLE AND SAMPLING TECHNIQUE

Data on eight power transformers which failed catastrophically from 2008 to 2015 in the organization was obtained to facilitate the assessment of the existing maintenance strategy. The results of the research work on the eight failed transformers indicated that prior time-based preventive maintenance activities carried out on the power equipment failed to give asset health and warning of imminent catastrophic failure. The research work carried out to investigate cause of 12T3 20MVA 161/11.5/6.6kV power transformer failure revealed prior maintenance activities carried out in October

2008 before the transformer failed in December 2008 without giving early warnings. The results of my work at Buipe substation also revealed that prior planned, maintenance activities were conducted on the 33MVA 161/34.5kV power transformer power transformer *codenamed 55T1* before it failed catastrophically in 2013.

On the other hand the research work carried out at Kumasi substation using conditionmonitoring maintenance approach on five power transformers indicated alarming levels of carbon dioxide and ethylene gases in the transformer oil of *13T5 33MVA 161/34.5kV* power transformer. The results of the dissolved gas analysis (DGA) on the transformer oil was used to schedule a timely maintenance on the transformer codenamed *13T5* to avert the catastrophic failure of another power transformer in GRIDCo.

The results of the research work indicate that if GRIDCo had used conditionmonitoring approach for the maintenance of the eight failed power transformers, early warnings of upcoming failure would have been detected.

There are various sampling methods in scientific research. These include simple random sampling, stratified sampling, systematic random sampling, convenience sampling and quota sampling (Osuala 2007). The suitability of each method depends on many factors depending on time, the availability of respondents and the characteristics of the respondents among other factors. This research involves sampling of both human and non-human subjects. The convenience sampling technique is used when it is most convenient due to many constraints to get all your respondents/subjects from one location and on one occasion. In this case, all respondents are busy and only available during working hours. The convenience sampling technique will be used to determine the participants in the Focus Group Discussion. The same technique will be used to sample the data. The Questionnaire for the Focus Group Discussion will involve a set of a five open-ended questions and respondents will take turns to address the same question. The next major question will be directed at the person seated on the right of the person who answered the previous question. This will be done until all the five participants have answered their major question. The use of a consistent and systematic line of questions for even

unanticipated groups is particularly important for reliability and for reliability by other researchers Berg (1989).

3.4 METHOD OF DATA COLLECTION

The researcher went to visited some substations in the GRIDCo network which included but not limited to Obuasi,Achimota,Buipe,New Obuasi acquaint himself with maintenance processes and to document same .Audio recorders, were used to capture responses to questions for transcription. Primary data on maintenance of transmission facilities within the aforementioned substations were also examined.

The following materials were needed to enhance data collection:

- Background information of Ghana’s power supply system
- Data on the power transmission system of Ghana
- Scholarly reference material on maintenance optimization for power systems
- Power system models (software)
- Transport to substations and overhead transmission line locations.

- Journal and textbook reference material on the reliability-centered maintenance optimization of power systems.

3.5 METHODS OF DATA ANALYSIS

The findings from the Focus Group Discussion and the In-depth interviews were analysed using the techniques of descriptive analyses. The findings from the quantitative survey were analysed using Statistical Software for the Social Sciences (SpSS), Regression Analysis and Microsoft Excel. The data was analysed to assess the maintenance plans for transmission equipment and to determine the optimal balance between preventive and corrective maintenance. This enabled a pictorial representation of the data for easy viewing and further descriptive analysis. The findings and observations were compared to the literature where appropriate to enhance the discussions about the methods used in the comparative literature and the relevant findings. The analysis is also related to the objectives and the research questions in Chapter One to show whether what the researcher expected to find is what has been discovered from the answers given and data analysed.

3.5.1 OPTIMIZATION OF PROCESS STEPS INCLUDED IN THE CONDITION INDEXING PROCESS.

In this section, a model is developed for the assessment of the visual inspections of transmission facilities of the grid operator. This model includes guidelines such as question, answers and a transformation matrix in order to minimize the subjectivity in the assessment of the visual inspections. Afterwards, a strategy including the indexing of the condition indicators is constructed for the determination of the condition of the asset. A strategy is created in order to determine the time intervals for the condition indicators. The result and weighting of the condition indicator were included in this new strategy. The impact of the process steps in determining the condition of the assets which are optimized is also described. Based on the impact of the process steps, it can be evaluated to determine whether the maintenance programmes can be planned more optimally or not.

3.5.2 GUIDELINES FOR VISUAL ASSESSMENT OF TRANSMISSION ASSETS

A number of questions have to be answered during visual inspections. These standard questions which have to be answered during inspection of transmission assets are aimed at establishing the condition of assets or determining the severity of defects.

The six standard questions and related answers are shown in table 3.1

Table 3.1: Six inspection questions and corresponding multi choice responses

Questions	*Answers*	*Rank*	*Lay-out in practice*
What is the size of the deviation?	*Nothing Small Medium Large*	*Nothing =0 Small = 1 Medium = 2 Large = 3.*	***Size deviation***
What is the severity of the deviation?	*Nothing Less Moderate Many*	*Nothing =0 Less = 1 Moderate =2 Many = 3.*	***Severity deviation***
What is the intensity of the defect?	*Nothing Beginning Advanced End*	*Nothing = 0 Beginning = 1 Advanced = 2 End = 3.*	***Intensity deviation***
Can the defective sub-component be repaired?	*Yes No*	*Yes can be repaired No has to be replaced*	
			Yes □ No □
Are subcomponent spares available?	*Yes No*		***Sub-component spares available***

Is the checklist satisfied?	*Yes No*		*Checklist subcomponent satisfied*

3.5.3 TRANSFORMATION MATRIX

Based on the results of the questions of each visual inspection, a transformation can be made to one of the four categories in table 3.2. At each visual inspection usually two questions are asked, therefore, a matrix can be handy for the application of the transformation. The categories in the matrix are determined on basis of interviews of maintenance personnel. This matrix can be applied for a visual inspection of power transformers, circuit breakers, disconnect switches and all other substation equipment.

Table 3.2: Matrix for the Transformation of the Parameters Size and Intensity.

Size / ***Intensity***	*0*	*1*	*2*	*3*
0	*Good*	-	-	-
1	-	*Fair*	*Fair*	*Poor*
2	-	*Fair*	*Poor*	*Bad*
3	-	*Poor*	*Bad*	*Bad*

3.5.4 **APPLICATION OF THESE GUIDELINES TO THE ASSESSMENT OF ELECTRICITY TRANSMISSION COMPONENTS.**

With the aid of several examples (components), the designed model will be illustrated. In table 7.2, the inspection sheet for a power transformer as one of the major transmission system components is shown.

3.5.5 **ADVANTAGES OF THE NEW MODEL FOR ASSESSING THE VISUAL**

INSPECTION

The advantages of the model for assessment of visual inspections are:

- The assessment of the visual inspection will be uniform for each specific inspection. The same questions, answers and transformation matrix will be used for each specific inspection.
- Different maintenance personnel perform the visual inspections, there is therefore a high possibility of subjectivity in the assessment. However, using guidelines the subjectivity can be minimized. The guidelines in this model are the question, answers and the transformation matrix. The maintenance personnel are all required to answer the same questions. Based on the transformation matrix, the transformation to the categories such as good, fair, poor and bad will be independent of the maintenance personnel. Subjectivity during the transformation is accordingly minimized

3.5.6 STRATEGY FOR THE DETERMINATION OF THE ASSET CONDITIONS

In order to determine the condition of the asset, there should be possibility to transform the condition indicators levels to the condition level as illustrated in figure 3.1. The results of the dissolved gas analysis (DGA) carried out five power transformers at Kumasi substation (Table 4.5) further illustrate the use of inspection and pretest results was used to schedule maintenance activities on the transformer codenamed *13T5* to avert the catastrophic failure of another power transformer in GRIDCo.

The results of the test on the transformer indicated alarming levels of carbon dioxide and ethylene gases in the transformer oil of *13T5 33MVA 161/34.5kV* power transformer.

The interpretation of the condition indicator levels and the condition levels includes aspects such as:

1. The requirements of extra maintenance (yes or no)
2. Noticing of deterioration (deterioration or no deterioration)
3. The interval for the next extra maintenance (earlier or much earlier).

The classification of the condition indicator levels and the condition levels, and the transformation of the condition indicator levels to the condition levels are shown in figure 3.1.

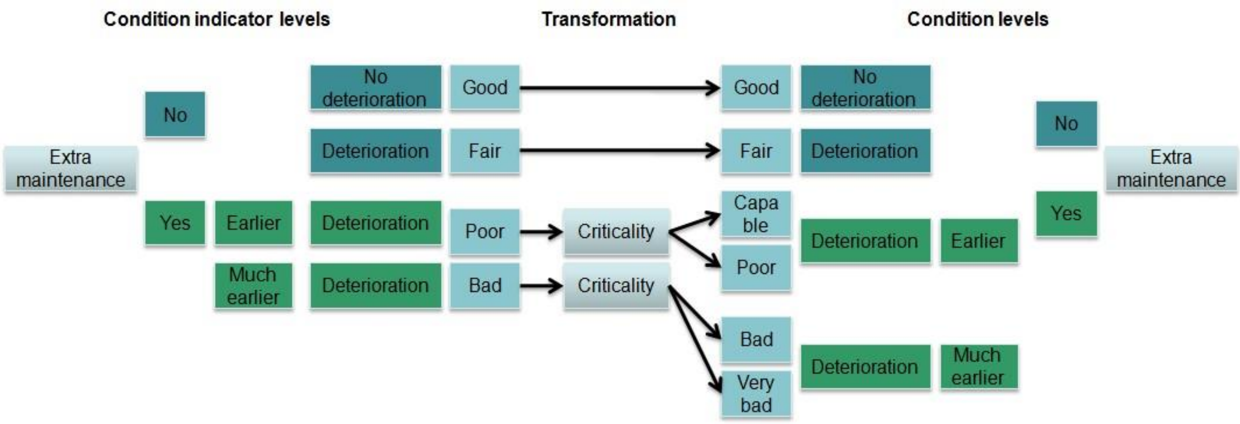


Figure 3.1: Classification of the Condition Indicator Levels and the Condition Levels.

As described in the preceding page, the worst condition indicator on the five transformers at Kumasi occurred on 13T5.The results was therefore used to determine the next maintenance schedule. In this case, the worst condition level is bad. After that, the weighting of that condition indicator was matched in the diagram (see figure 3.2). Based on the diagram, bad (high weighting) is related to unusable. The condition of the asset is unusable. Once the weighting of each condition indicator was determined and given on the inspection form, only the diagram was included in order to determine the condition of the asset. The determination of the asset condition is uniform for each transmission component, therefore, the strategy of determination can be programmed leading to a more user friendly application of this method.

As indicated, a number of condition indicator levels can directly be transformed into a condition level. A number of transformations are assumed to be based on the weighting (criticality) of the condition indicator. This is shown in figure 3.2.

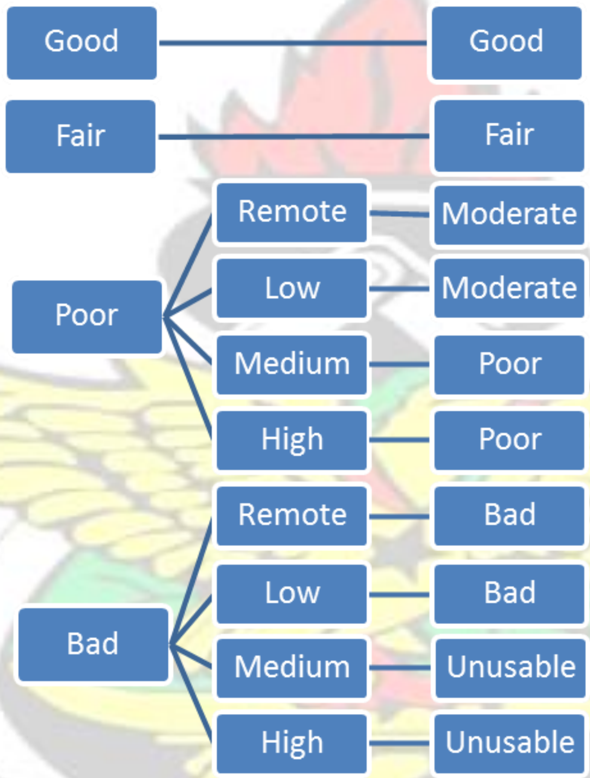
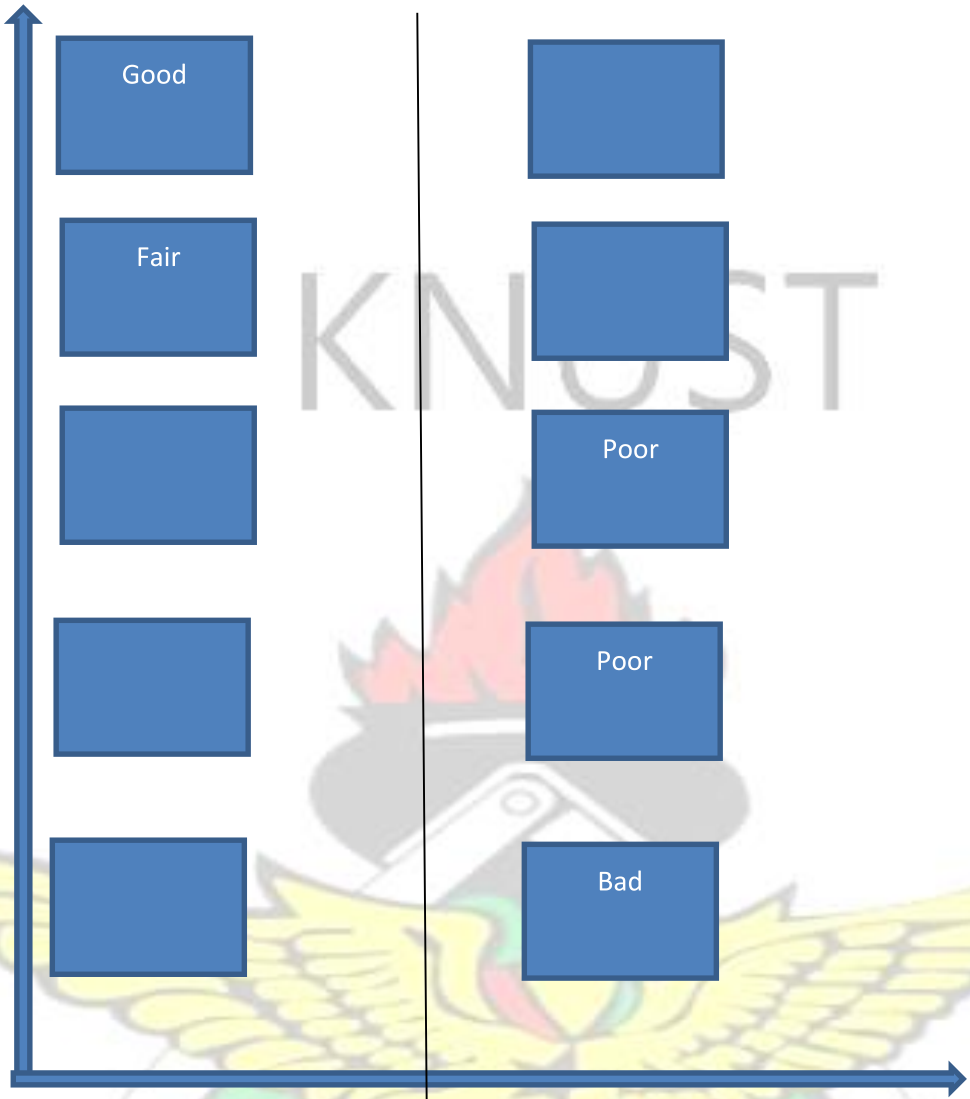


Figure 3.2: A Transformation of Visual Inspection Indicators of Transmission Equipment

Good

Capable



Additional maintenance not required | *Additional maintenance required.*

Moderate

Poor

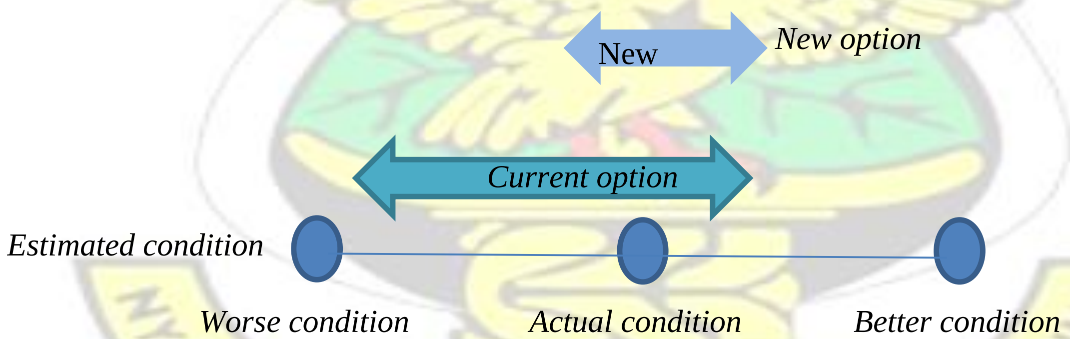
Very poor

Figure 3.3 Matrix indicating an interpretation of condition levels of inspected equipment

Based on the transformation in figure 3.2 in relation to 13T5 (table 4.5) a strategy for selecting the appropriate maintenance schedule in accordance with the condition indicator level was appropriately selected. For the achievement of a proper reliability of a component, the weakest part of the component should be involved. Based on this, the worst condition indicator level on 13T5 was prioritized in the new strategy for quicker attention.

In figure 3.4, the range of the estimation of the condition of the asset with respect to the actual condition of the component is shown for the current and new strategy.

Figure 3.4: Estimation of Condition



Based on the ranges indicating the estimations of the condition of the asset it can be concluded that the range in which the estimation of the condition of the asset can be inaccurate is smaller for the new strategy (option). From this it is found that a narrower estimation of the condition of the asset can be determined with the new

strategy.

3.5.7 EVALUATION OF THE TRANSFORMATION MODEL

In the new strategy that has been described throughout the previous sections, the weighting of the condition indicators is included in the transformation. Compared to the current system of facility inspection in the transmission network, the new transformation model has a greater chance of revealing defects on transmission equipment to facilitate a more effective maintenance planning. The transformation of the good level and fair level remains the same in the new transformation model. Based on the condition of asset, analyses will be performed in order to determine the extra maintenance. For the good level and fair level no extra maintenance is required, that is why it does not matter that these levels do not change in the new strategy.

3.5.8 PRACTICAL EXAMPLE

With the help of an example, the new strategy for the determination of the condition of the asset will be illustrated. Table 3.3 gives the results of the condition indicators of an inspected component in the transmission network. As described in the preceding sections, the worst condition indicator level will be selected for urgent attention. In this case, the worst condition level is bad. After that, the weighting of that condition indicator will be matched in the diagram as presented in the transformation model in figure 3.2. Based on the diagram, bad (high weighting) is related to unusable condition .In other words condition of the asset is unusable. Once the weighting of each condition indicator is determined and given on the inspection form, only the diagram has to be included in order to determine the condition of the asset and as basis for subsequent decision-making processes on maintenance actions. The determination of the status of an asset is uniform for each component, therefore, the strategy of determination can be programmed which can lead to a more user friendly application of this method.

Table 3.3: The Results of the Condition Indicators (CI) of a Component

Component			
Condition indicator *A*	***Weighting of the condition indicator*** *B*	***Result of the condition indicator*** *C*	***Condition of asset***
CI 1	*Low*	*Fair*	
CI 2	*High*	*Bad*	
CI 3	*Low*	*Poor*	*Decision is based on the combination of columns B and C*
CI 4	*Remote*	*Good*	
CI 5	*Medium*	*Fair*	

3.5.9 STRATEGY FOR THE DETERMINATION OF THE TIME INTERVALS FOR THE MAINTENANCE OF TRANSMISSION ASSETS.

A strategy is required to determine an optimal time interval for assessing condition indicators of transmission assets. In this way, the proper moment of the required maintenance can be determined. For condition indicators with a basic time interval (BTI), the determination of the time intervals could be shown in the matrix of table 5. In the matrix the four results of the condition indicators are plotted against the four weightings of the condition indicators. Based on the matrix, there are 16 options. It will be assumed that the BTI will be stated centrally of the matrix. The central of the matrix is: poor-remote and fair-high. Furthermore, it will be assumed that the adjustment of the BTI will be performed with a time interval for each cell compared to the previous cell. The minimum BTI in TOR 2.1 is 1 year, therefore, the minimum time interval in the matrix will be assumed to be 1 year. This will result in a time interval, ∆TI.

∆TI is expressed in years. As shown in table 3.4, the BTI is adjusted with a plurality of ±∆TI based on the result and weighting of the condition indicator. The matrices of these time intervals are shown in appendix L.

In the interpretation of the condition levels, it is given if extra maintenance is required before the next regular maintenance or not. The time intervals for the extra maintenance are not given, but are determined based on experience. The time interval (x∆TI) for the extra maintenance will also be determined in the matrix in table 3.4 where x ranges between 1 and 7.

Table 3.4: Matrix Table for Determination of Time Intervals

Condition indicator	**Weighting**			
Result	**High**	**Medium**	**Low**	**Remote**
Good	BTI + x∆TI	BTI + x∆TI	BTI +x∆TI	BTI + x∆TI
Fair	BTI	BTI + x∆TI	BTI +x∆TI	BTI + x∆TI
Poor	BTI – x∆TI	BTI – x∆TI	BTI – x∆TI	BTI
Bad	1	BTI – x∆TI	BTI – x∆TI	BTI – x∆TI

This will result in a combination of regular and extra maintenance. The time interval for extra maintenance will be determined; therefore, it does not have to be given in the interpretation of the condition levels that extra maintenance is required before the next regular maintenance.

Based on the strategy for the determination of the time interval, it can be expected that the time interval for each condition indicator can differ from each other. After that, the difference between the next lowest time interval will be matched with the difference between the other time intervals. If the difference between the next lowest time interval is the lowest difference, it will be selected in the first group.

- If the difference between the next lowest time interval is not the lowest difference, the next lowest time interval will be the second group. The remaining condition indicator will also be included in the second group.
- If the second lowest time interval differs less than 1 year compared to the lowest time interval, the second lowest time interval will be involved in the first group. In this case the time interval for the second group will be the third lowest time interval.
- If the other time intervals also differ less than 1 year from the lowest time interval, these time intervals will also be included in the first group.

3.6 .0 USER FRIENDLY AND UNIFORMITY

Once the matrices for each BTI are constructed, the time interval for the condition indicators can be determined after each inspection (regular maintenance). By creating guidelines (strategy), the adjustment of the time intervals will be uniform. Because of the uniformity, the determination of the time intervals can be programmed, leading to a more user friendly method.

3.6.1 IMPACT OF THE OPTIMIZED PROCESS STEPS

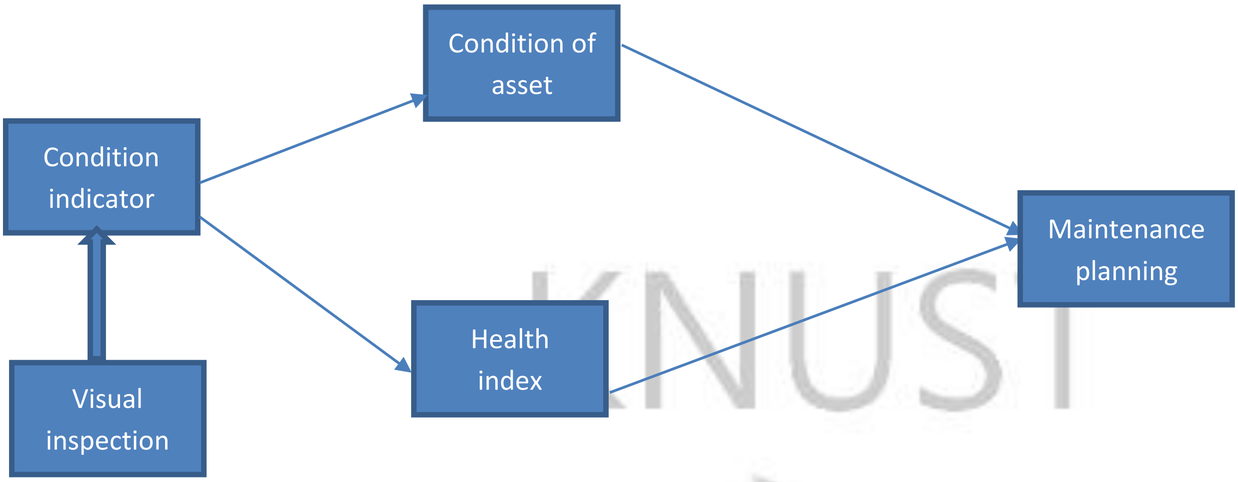
After the optimization of all the process steps, the impact of this optimization can be analyzed.

- By using a more objective assessment of visual inspections, the data quality of the assessment of the condition indicators can be improved.
- From this improved data quality of the assessed condition indicators, the health index and condition of asset can be determined more precisely.

Furthermore, based on the improved data quality of the assessed condition indicators an optimal time intervals of the condition indicators can be determined.

- Based on the updated condition index levels and the inclusion of the weighting of the condition indicators, a narrower estimation of the condition of the asset can be achieved.
- Furthermore, an optimal time interval of the condition indicators can be determined based on the weighting of the condition indicators.
- Based on an optimal time interval of the condition indicators and a narrower estimation of the condition of the asset, the extra maintenance planning can be determined more optimally.
- Based on an optimal time interval of the condition indicators, the regular maintenance planning can be determined more optimally.

Figure 3.5: Resultant Effects of Visual Inspection



In Figure 3.5, the impact of the process steps which are optimized is shown. Based on the optimized aspect included in the condition indexing process, the regular and extra maintenance planning can be determined optimally.

CHAPTER FOUR

FINDINGS AND ANALYSIS OF FINDINGS

4.0 INTRODUCTION

This chapter explains the findings on how best an optimised maintenance system can be realised. In Chapter One, under the section titled The Problem Statement the question was posed thus: "Would the Reliability Centred Maintenance (RCM) methodology help determine the optimal balance between preventive and corrective maintenance?" In this chapter findings on the works done at the eight selected substations are discussed. Condition-based maintenance methodology as well as time-based model are presented and discussed. This is on account of the fact that various models are being implemented by the Ghana Grid Company.

Data on eight power transformers which failed catastrophically from 2008 to 2015 in the organization was obtained to facilitate the assessment of the existing maintenance strategy. The results of the research work on the eight failed transformers indicated that prior time-based preventive maintenance activities carried out on the power equipment failed to give asset health and warning of imminent catastrophic failure. The research work carried out to investigate cause of 12T3 20MVA 161/11.5/6.6kV power transformer failure revealed prior maintenance activities carried out in October 2008 before the transformer failed in December of the same year without giving early warnings. The results of my work at Buipe substation also revealed that prior planned, maintenance activities were conducted on the 33MVA 161/34.5kV power transformer power transformer *codenamed 55T1* before it failed catastrophically in 2013.

On the other hand the research work carried out at Kumasi substation using conditionmonitoring maintenance approach on five power transformers indicated alarming levels of carbon dioxide and ethylene gases in the transformer oil of *13T5 33MVA 161/34.5kV* power transformer. The results of the dissolved gas analysis (DGA) on the transformer oil was used to schedule a timely maintenance on the transformer codenamed *13T5* to avert the catastrophic failure of another power transformer in GRIDCo.

The results of the research work indicate that if GRIDCo had used conditionmonitoring approach for the maintenance of the eight failed power transformers, early warnings of upcoming failure would have been detected.

4.1 IMPROVING RELIABILITY

Improving the overall reliability and reducing the operating cost are the two most important but often conflicting objectives for substation. A condition-based substation maintenance strategy provides a means of balancing these objectives. This chapter proposes a multi-objective approach to best compromise these two objectives for substations by optimizing the inspection frequencies required for each component .A multi-component model is employed to evaluate the overall reliability of interconnected components.

4.2 NEED FOR INSPECTION OPTIMIZATION

The proposed methodology for GRIDCo is the component-specific level Markov model, system-specific reliability model, and a multi-objective evolutionary algorithm. A sound two-level reliability model addresses adequately the costs and benefits of inspection. On the device-specific level, only conditions of individual components are of interest. Therefore, the aim of this level is to obtain the reliability indices for each component, but the topological inter-dependence of components is not considered. The model in the system-specific level mainly focuses on the overall impact of individual components to the substation. Impacts due to changes of substation configuration and operation, as well as inspections on the overall reliability and cost are examined in an easy-to-use system reliability model.

A brief description is given as follows:

- Using inspection frequencies as input, the Markov model will generate reliability indices for individual components,
- Using the system-configuration-related parameters and the load demand as inputs, the system reliability model will then generate the indices of the cost and availability at individual load points, and
- Outputs of the system reliability model are used to calculate the two objectives (expected energy not served and overall cost) to be evaluated by the

optimization method, which will guide the search towards optimal inspection frequencies.

4.3 RESULTS

The results of the research work on the eight failed transformers indicated that prior time-based preventive maintenance activities carried out on the power equipment failed to give asset health and warning of imminent catastrophic failure. The work carried out to investigate cause of 12T3 20MVA 161/11.5/6.6kV power transformer failure also revealed that prior maintenance activities were carried out in October 2008 before the transformer failed *without* giving early warnings in December of the same year. Investigations carried out at Buipe substation also revealed that prior planned, maintenance activities were conducted on the 33MVA 161/34.5kV power transformer power transformer *codenamed 55T1* before it failed catastrophically in 2013.

On the other hand the research work carried out at Kumasi substation using conditionmonitoring maintenance approach on five power transformers indicated alarming levels of carbon dioxide and ethylene gases in the transformer oil of *13T5 33MVA 161/34.5kV* power transformer. The results of the dissolved gas analysis (DGA) on the transformer oil was used to schedule a timely maintenance on the transformer codenamed *13T5* to avert the catastrophic failure of another power transformer in GRIDCo.

The results of the research work indicate that if GRIDCo had used conditionmonitoring approach for the maintenance of the eight failed power transformers, early warnings of upcoming failure would have been detected.

The availability and reliability transformers presented in this study reflect on GRIDCo's policy. Identifying the effects of component failure on the system under analysis, based on the failure rates of transformers from 2008-2015, a maintenance policy can be formulated to reduce their occurrence probabilities. Better aims and specific targets are needed for power transformers in particular and the grid in general to improve maintenance management systems and productivity. This should be based on a new maintenance paradigm that will improve maintenance control and PM activities. The GRIDCo must formulate effective maintenance strategies, make decisions and monitor progress against plans by collecting, retrieving and analyzing data. To reduce downtime and achieve high production capabilities, the aim should be to find ways to increase equipment reliability and extend the equipment's life through cost effective maintenance. To achieve these, GRIDCo must move away from the traditional reactive maintenance mode to proactive maintenance and management philosophies. There should be maintenance processes that fully address Total Quality

Maintenance (TQM) and Total Productive Maintenance (TPM) operating modes. Such change requires a complete shift to a Condition-Based Maintenance (CBM) approach, which is a maintenance and management philosophy that advocates planning all maintenance (i.e. preventive, predictive and corrective), as well as the control of quality in maintenance operations.

4.3.1 EXPECTED ENERGY NOT SERVED (EENS)

Electricity has been the driving force for economies of the world and provides day-today necessity for the population in the world. The generation, transmission and retailing of electricity have existed hundreds of years in providing the much needed electricity. Due to the nature of electricity systems, the variable demand at every moment needs to be met by consistent electricity supply in making sure the continuous availability of the resources. Not meeting the demand in any case will lead to a huge loss of income to all the players in the supply chain as well as to the consumers. The reliability of the generation, transmission and distribution of electricity in this sense is crucial for the continuous supply of electricity to meet the demand.

Since the power systems are in fact energy system, where energy sale is the real revenue for the electric company, one of the most essential and most needed reliability index known called the EENS can be deduced as follows:

EENS=COi x Poi x Toi (MW/year)--4.0

Where COi= Capacity Outage I (kW) Poi=Probability of capacity outage I and Toi = Time of outage I (h/year)

In this section a numerical case study is carried out for reliability evaluation of supply to bulk customers in the transmission system of Ghana. In this section EENS index is calculated for all transformers at 100 hours duration for capacity outage per year (TOi=10hrs/year) and probability of capacity outage POi = 0.2.The procedure presented in table 4.1 is used to compute both EENS and cost of EENS per transformer capacity.

Table 4. 1 shows the capacity of ninety power transformers in the transmission network.

SUBSTATION	INSTALLED CAPACITY TRANSFORMERS	RATING	DEMAND (MVA)	DEMAND (MVA)	AVERAGE DEMAND (KW)	EENS	COST OF EESN
		(MVA)	15-Jun	15-Jul			
							(GHS)
TAFO	15T1	13	2.11	2.51	2079	41580	18711

	15T2	33	28.1	32.1	27090	541800	243810
AKWATIA	16T1	33	18.82	18.38	16740	334800	150660
	16T1	33	18.82	18.38	16740	334800	150660
KPONG	17T1	33	27.61	26.76	24466.5	489330	220198.5
	17T2	66	19.88	20.28	18072	361440	162648
ASIEKPE	22T1	33	31.3	30.69	27895.5	557910	251059.5
	22T2	33	11.49	12.17	10647	212940	95823
HO	23T1	7	-		#DIV/0!	#DIV/0!	#DIV/0!
	23T2	13	11.49	10.88	10066.5	201330	90598.5
KPEVE	24T1	7	4.87	4.85	4374	87480	39366
KPANDO	25T1	20	14.06	14.22	12726	254520	114534
SOGAKOPE	33T1	15	11.49	12.17	10647	212940	95823
AFLAO	39T1	33	19.55	18.23	17001	340020	153009
CAPE COAST	7T1	13.3	12.49	12.61	11295	225900	101655
	7T2	33	33.57	35.79	31212	624240	280908

TAKORADI	8T1	33				0	0
	8T2	33	34.05	31.6	29542.5	590850	265882.5
	8T3	33	35.72	31.18	30105	602100	270945
ESIAMA	34T1	33	19.36	17.24	16470	329400	148230
ABOADZE	32T7	200	53.5	50.4	46755	935100	420795
	32T8	200	52.6	85.3	62055	1241100	558495
TARKWA	9T1	33	27.1	29.18	25326	506520	227934
	9T2	33	31.64	26.52	26172	523440	235548
	9T3	33	16.39	19.73	16254	325080	146286
PRESTEA 161KV	10T1	33	6.36	6.67	5863.5	117270	52771.5
BOGOSO	30T1	33	10.1	10.5	9270	185400	83430
	30T2	33	32.18	30.66	28278	565560	254502
NEW TARKWA	41T1	33	19.6	19.6	17640	352800	158760
	41T2	33	19.5	19.5	17550	351000	157950
	41T3	33	0	0	0	0	0
AKYEMPIM	42T1	33	11.86	11.15	10354.5	207090	93190.5

ACHIMOTA	5T1	66	55.2	58.9	51345	1026900	462105
	5T2	66	52.6	81.2	60210	1204200	541890
	5T3	66	54.2	80.9	60795	1215900	547155
	5T4	66	47.5	52.7	45090	901800	405810
	5T5	66	69.1	51.9	54450	1089000	490050
ACCRA EAST	59T1	66	67.7	69.5	61740	1234800	555660
	59T2	66	23	30	23850	477000	214650
MALLAM	37T1	66	61.1	55.2	52335	1046700	471015
	37T2	66	53.8	45.4	44640	892800	401760
	37T3	66	58.7	63.7	55080	1101600	495720
	37T4	66	62.5	45.7	48690	973800	438210
CAPE COAST	6T1	13	12	12.2	11500	230000	103500
	6T2	33	30.49	30.59	27486	549720	247374
SMELTER	3T2	20	6.2	5.6	5310	106200	47790
	3T3	85				0	0

	3T4	85	64	72.6	61470	1229 400	553230
	3T5	85				0	0
	3T7	85	74.4	72.9	66285	1325 700	596565
	3T8					0	0
WINNEBA	6T1	33	26.6	30.4	25650	5130 00	230850
KUMASI	13T1	66	58.2	67.9	56745	1134 900	510705
	13T2	66	73.8	69.6	64530	1290 600	580770
	13T3	66	66.7	69.2	61155	1223 100	550395
	13T4	66	57.8	65.7	55575	1111 500	500175
OBUASI	12T1	33	3.77	3.52	3280.5	6561 0	29524.5
NEW	12T3	18.2	18.8	18.87	16951.5	3390	152563.5

OBUASI						30	
	21T1	33	9.91	9.08	8545.5	1709 10	76909.5
	21T2	33	20.7	10.7	14130	2826 00	127170
	21T3	33	11.04	11.04	9936	1987 20	89424
DUNKWA	11T1	6.5	5.63	5.81	5148	1029 60	46332

ASAWINSO	20T1	33	20.26	20.5	18342	366840	165078
	20T2	33	28.12	27.37	24970.5	499410	224734.5
KONONGO	18T1	20	10.94	10.55	9670.5	193410	87034.5
NKAWKAW	14T1	33	0	2.6	1170	23400	10530
	14T2	33	12.76	11.45	10894.5	217890	98050.5
AYANFURI	57T1	33	19.12	19.28	17280	345600	155520
ANWOMANSO	58T1	66	20	16.6	16470	329400	148230
	58T2	66	42.8	23.5	29835	596700	268515
NEW ABIREM	60T1	53	12.8	25.5	17235	344700	155115
	60T2	53	12.9	14.8	12465	249300	112185
TECHIMAN	26T1	20	15.6	14.4	13500	270000	121500
	26T2	20	15.7	14.4	13545	270900	121905
SUNYANI	27T1	20	9.81	9.6	8734.5	174690	78610.5
	27T2	33	31.95	34.4	29857.5	597150	268717.5
SAWLA	38T1	13.3	0	0	0	0	0
KENYASI	43T1	53	0	0	0	0	0

	43T2	53	31.4	35.9	30285	605700	272565
KINTAMPO	56T1	33	0	0	0	0	0
	56T2	33	2.31	2.17	2016	40320	18144
MIM	62T1	33	11.9	11	10305	206100	92745
WA	68T2	33	11.2	11.2	10080	201600	90720
TAMALE	28T1	33	29.6	22.8	23580	471600	212220
	28T2	33	33.1	21.4	24525	490500	220725
BOLGA	29T1	20	11	10.5	9675	193500	87075
YENDI	35T1	13.3	15.4	15.3	13815	276300	124335
ZEBILLA	53T1	33	12.4	10.1	10125	202500	91125
	53T2	20	8.9	6.2	6795	135900	61155
BUIPE	55T1	33	5.4	5.2	4770	95400	42930
TUMU	69T1	33	0	0	0	0	0
TOTAL							**18040950**

Source: **GRIDCo**

Table 4.2: Existing Time-based Preventive maintenance Schedules on Transformers and their Associated Protection Devices

EQUIPMENT	MAINTENANCE ACTIVITIES	DAILY	MONTHLY	QUARTERLY	SIX MONTHS	ONE YEAR	TWO YEARS
TRANSFORMER	Temperature and load monitoring						
	Silica Gel Monitoring						
	Cooling Fan Maintenance						
	Water Content Analysis						
	Oil Dielectric Analysis						
	On-Load Tap Changer Maintenance						
	Insulation Resistance Test						
PROTECTION RELAYS	Calibration Of Differential Relays						
	Calibration Of Winding & Oil Thermometers						
	Calibration Of Back-Up Protection Relays (Over Current)						
	Testing Of Alarm System						

Source: GRIDCo

Table 4.2 above shows the existing maintenance schedule for power transformers and their associated protection systems. The table shows that temperature and load monitoring on transformers are done daily. Silica gel and cooling fan maintenance are however done on a monthly basis. Annual maintenance works on power transformers include water content analysis, on-load tap changer maintenance, and calibration of differential and overcurrent protection relays and testing of alarm systems. Every two years, GRIDCo carries out calibration of winding and oil thermometers, insulation resistance test and oil dielectric analysis. These schedules were strictly adhered to. The researcher sighted documents from the operations and maintenance department that show the nature of work that was done and the persons responsible. There were appropriate signatures and all the relevant documentation that show that the works were carried out as planned. Despite all these strict adherence to maintenance protocols Table 4.3 below show that these transformers failed in a way that was totally unexpected.

Table 4.3 Data of eight failed power transformers in GRIDCo (2008-2015)

STATION	TRANS. ID.	MANUFAC-TURER	YEAR OF MANF.	SERIAL NUMBER	RATED VOLTAGE KV			YEAR OF FAILURE
					I	I I	I I I	
ACHIMOTA	T2	AEG	1994	310070-01	161	34.5		2015
ACHIMOTA	T5	ALSTOM	1999	315600-01	161	34.5		2013
NEW OBUASI	T2	ASEA	1983	7288 081	161	11.5	6.58	2011
OBUASI	T2	NUOVA	1985	32346	161	6.64	11.5	2012
OBUASI	T3	C. G. E.	1963	14076	161	6.64	11.5	2008
WINNEBA	T2	C. G. E.	1963		161	11.5	6.64	2014
AFLAO	T1	ALSTOM	2001	316163	161	34.5		2012
BUIPE	T1	ABB	1993	1.112.054/U	161	11.5		2013

Source:GRIDCo

Table 4.4 Replacement of failed 33MVA transformer at Buipe Substation-Summary of activities and resources used

Activity	**Year of installation**	**Resources used**	**Man-hours**
Replacement of Buipe transformer	2013	33MVA transformer, 25,000 litres of transformer oil, treatment plant	3,600

As presented in table 4.3, two power transformers codenamed 5T1 and 5T5 failed catastrophically in 2013 and 2014 respectively at Achimota substation. It is worthy to note that transformer 5T1 with a serial number 310070-01 which was manufactured by AEG underwent scheduled annual, quarterly and monthly preventive maintenance prior to failure. The time-based maintenance activities on the transformer did not reveal any warning of catastrophic failure.5T5 power transformer with a serial number 315600-01 manufactured by ALSTROM in 1999 also failed catastrophically in 2013 after all planned preventive maintenance schedules had been conducted on the equipment. The time-based preventive maintenance on the assets failed to give the health status of the transformer and warning of catastrophic failure. At the New Obuasi substation, the transformer codenamed 21T2 with serial number 7288081 also failed catastrophically in 2011 after all time-based maintenance schedules had been duly carried on the equipment. Two other power transformers codenamed 12T3 and

12T2 also failed catastrophically at Obuasi substation in 2008 and 2012 respectively.

Transformer T1 with serial number 316163 located in Aflao and manufactured by ALSTOM in 2001 also failed catastrophically in 2012 after all planned preventive maintenance schedules had been duly carried out on the transformer. The results at Buipe which is a single transformer substation also shows that the planned annual, quarterly and monthly maintenance activities conducted on the power transformer *codenamed 55T1* neither revealed equipment malfunction nor upcoming failure before the 33MVA 161/34.5kV power transformer failed catastrophically in 2013.

The common factor among these failed transformers is that all planned time-based maintenance schedules were strictly adhered to by maintenance personnel. It is also important to indicate that it takes about one year from the point of placing an order for a power transformer to the point of delivery and installation in Ghana. The catastrophic failure of power transformers particularly in single transformer substations therefore brings serious financial, economic and social and challenges and difficulties to both GRIDCo and the affected electricity consumers.

Table 4.5 Results of dissolved gas analysis on power transformers at Kumasi Substation.

EQUIPMENT USED: Transport X																			
									TEST RESULTS										
No.	**LOCATION**	**NOMENCLATURE**	**SERIAL NUMBER**	**MANUFACTURER**	**MVA RATING**	**VOLTAGE RATING**	**YEAR OF MANUFACTURE**	**DATE TESTED**	**GAS**	**Hydrogen H_2**	**Water H_2O**	**Carbon Dioxide CO_2**	**Carbon Monoxide CO**	**Ethylene C_2H_4**	**Ethane C_2H_6**	**Methane CH_4**	**Acetylene C2H2**	**TDCG**	**RSOF OIL**
									CAUTION	***100***		***2500***	***350***	***50***	***55***	***120***	***2***	***700***	
									WARNING	***700***		***4000***	***570***	***100***	***100***	***400***	***5***	***1900***	
5	**Kumasi**	13T1	315610-01	Alstom	50/66	161/34.5	Jul-99	20/8/2014		5	14	1274	58	6	19	<1	<0.5	89	
6	**Kumasi**	13T2	112958	Hyundai	50/66	161/34.5	2007	20/8/2014		8	15	988	86	2	8	5	<0.5	107	
7	**Kumasi**	13T3	316515	Areva Energies	50/66	161/34.5	Jul-04	20/8/2014		<5	14	1513	33	2	14	<1	0	53	
8	**Kumasi**	13T4	ET09977/1	Crompton Greaves	50/66	161/34.5	2011	20/8/2014		7	18	1083	60	3	14	2	0	85	
9	**Kumasi**	13T5	B-357266	Westinghouse	25/33	161/34.5		5/2/2013		81	26	5238	405	126	45	35	194.8	888	

It is evident from table 4.5 that the alarming levels of carbon dioxide and ethylene gases in the transformer oil of 13T5 33MVA 161/33.5kV power transformer at Kumasi substation was revealed by dissolved gas analysis (DGA). Dissolved gas analysis (DGA) is the study of dissolved gases in transformer. Performing a dissolved gas analysis (DGA) of the transformer insulating oil is useful in evaluating transformer health. It is a diagnostic technique for maintenance planning and work scheduling. The result of the diagnostic test on 13T5 was used to schedule a timely maintenance which averted another catastrophic failure of power transformer in GRIDCo.

4.5 OBSERVANCE OF PROTOCOL

The research work at Obuasi, Buipe, Aflao, Achimota, Winneba and New Obuasi Substations revealed that planned preventive maintenance activities carried out on the transformers failed to give early warnings before failure occurred. It was also observed that the cost of deploying staff and resources to replace the failed transformers at Obuasi, Buipe, Aflao, Achimota, Winneba and New Obuasi Substations was extremely high.

There was an examination of maintenance guidelines which was obtained from GRIDCo. The contents were corroborated by participant observation of the researcher who is a staff of GRIDCo. The protocol is in various parts according to the table of contents. The Table of Contents shows the major items in the checklist and how they should be handled. The document begins with an Introduction, Procedure, Responsibilities and a Reference. It is followed by a checklist form. It is titled Transformer Oil Test Results Summary and Analysis. At the end of the checklist, a determination of either Gas-In-Oil Analysis or Basic Oil Test ought to be made. The officer who carried out the survey is expected to tick either one or the other. The document shows how to sample for basic transformer oil tests, how to flush sampling valve and how to sample for a dissolved gas in oil analysis. The frequencies of testing and acceptable ranges of results are also listed. The observance of the researcher is that these guidelines are strictly followed.

4.6 COST OF 2014 PLANNED TRANSMISSION SYSTEM IMPROVEMENT PROJECTS

The 2014 planned transmission system improvement work consisting of transmission lines, capacitor banks, transformers, spare towers, major maintenance works, replacement and upgrade of obsolete equipment is estimated to cost the company **USD 514,860,274.00.** This is illustrated in Table 4.4 below.

Table 4.6: Cost of 2014 planned transmission system improvement projects

No.	Project	Estimated Cost US$
1	Smelter II Substation	22,000,000.00
2	Kumasi 2nd BSP	15,000,000.00
3	Supply improvement to Ho	980,604
4	Tumu-Han-Wa	50,000,000.00
5	Mim Substation (Sunyani-Mim Upgrade)	15,000,000.00
6	Mallam Substation Upgrade Project	10,000,000.00
7	Substation Reliability Enhancement Project	45,000,000.00
8	Tamale Voltage Improvement Project	18,000,000.00
9	Power System Re-enforcement	50,000,000.00
10	Supply improvement to Brekum	28,000,000.00
11	Supply Improvement to Western Region	65,000,000.00
12	Kumasi to Bolga 330kV Transmission Line	67,000,000.00
13	Prestea-Kumasi 330kV Transmission Line	65,000,000.00
14	Tafo Substation Upgrade Project	2,000,000.00
15	Volta-Togo 330KV Transmission Line	13,000,000.00
16	A3BSP	10,000,000.00
17	Kpone Thermal Power Evacuation	30,000,000.00
18	Right-Of-Way Management (ROW)	8,879,670.00
	TOTAL	**514,860,274.00**

Source: GRIDCo

4.7 ADDITIONAL RECOMMENDED CHECKLIST FOR TRANSFORMER MAINTENANCE AT ALL GRIDCo SUBSTATIONS DEVELOPED BY THE RESEARCHER

Preventive maintenance done regularly by trained, professional and experienced electrical workers on electrical equipment helps to detect problems before they become serious issues. By scheduling a comprehensive maintenance check that utilizes advanced technology and expert electrical skills, the power equipment on which GRIDCo runs its business can continue working efficiently, thereby reducing the risk of a catastrophic failure that can cost time and money. Based on the researcher's working experience at GRIDCo, it is recommended that a checklist template (table 4.7) be adopted as an additional inspection protocol throughout the entire lifespan of new transformers and the remaining lifespan of in-service power transformers.

4.6 Maintenance Schedules template for power transformers

This template (table 4.7) is intended to establish standard practice as well as to give general advice and guidance in the maintenance of power transformers owned and operated by GRIDCo. Maintenance recommendations are based on industry standards and findings from the research work. However, equipment and situations vary greatly, and sound engineering and management judgment must be exercised when applying these recommendations. Other sources of information must be consulted (e.g., manufacturer's recommendations, unusual operating conditions, personal experience with the equipment, etc.) in conjunction with these maintenance recommendations

Table 4.7**:** Recommended checklist for Transformer Maintenance at all GRIDCo

Substations

SUBSTATION NAME-- DATE---------------------
TRANSFORMER NOMENCLATURE/ID------------------------VOLTAGE RATIO---

S/No	Activities	Carried out	Remarks
1	Check for oil leakages		
2	Check for oil level in the conservator tank is up to 3/4th mark		
3	Check for Breather condition		
4	Check for Silica Gel condition		
5	Clean the body		
6	Open the terminal box and check the following a. Tightness of terminal connection b. Condition of bushings c. Any sign of overheating.		
7	Check for any unplugged opening, missing bolts		
8	Check all terminal box tightness		
9	Check oil/winding temperature setting		
10	Check if Earth wiring system is proper & intact		
11	Check cable support		
12	Any other abnormality		

Table 4.8: Maintenance Instructions for Power Transformers

MAINTENANCE INSTRUCTIONS FOR POWER TRANSFORMERS

Inspection frequency	Items to be inspected	To be checked	Actions required if inspection shows unsatisfactory condition

Hourly	Oil and winding temperature	Ensure that temperature rise is within specified limits	-
Hourly	Loads (Amps)	Check against rated figures given on the name plate	-
Hourly	Voltage		
Daily	Oil level in transformer	Check oil level gauge	If low, top with dry oil find whether there is any leak.
Daily	Oil level in bushing		
Daily	Dehydrating breather	Check that air passages are free. Check colour of active agent	If silica gel is pink, change by new charge. The old charge may be reactivated for using again.
Daily	Oil level in OLTC conservator	Check oil sight window or oil level gauge	If low, top with new dry oil
Daily	Relief diaphragm of	-	Replace if broken or cracked
Daily	Cooler fan, bearing motor & operating mechanism	Check the bearings. Examine contacts, check manual control and interlock	Lubricate the bearing. Replace burnt or worn contacts.
Quarterly	Bushing	Examine for cracks and dirt deposit	Clean the dirt. If cracked or broken replace the bushing
Quarterly	Oil in transformer	Check for dielectric strength and water content	Take suitable action to restore quality of oil
Half yearly or at the end of 5000 operation	Oil in the diverter switch of OLTC	a. Dielectric strength	Filter or replace if BDV is less than specified value
		b. Water content	Measure the water content Replace/ recondition if exceeds that specified limits
Yearly	Oil in transformer	Check acidity	Filter or replace oil
		resistivity, tan delta and sludge	
Yearly	Gasket joints	-	Tighten the bolts evenly to avoid uneven pressure

Inspection frequency	Items to be inspected	To be checked	Actions required if inspection shows unsatisfactory condition
Yearly	-	Check sealing arrangements and find out whether there is any leak	Replace gasket if leaking
Yearly	Relays alarm and other circuits	Examine relay and alarm contacts, their operation fuses etc. check relay accuracy.	Clean the components. Replace contacts and fuse if necessary
Yearly	Earth resistance	-	Take suitable action if earth resistance is high
After 50000 operations of the OLTC	1.Arcing contacts	-	Replace if necessary
	2.Lubricating oil in the gear box of driving mechanism	Low oil level	Add or replace with lubricating

Source: GRIDCo

CHAPTER FIVE

SUMMARY OF FINDINGS,

CONCLUSION AND RECOMMENDATION

5.0 INTRODUCTION

This chapter discusses the summary of the findings, conclusion and recommendations. It is divided into three sections. The summary of findings which is the first section is linked to the major objectives of this research. Three major findings are discussed and related to the key objectives of this research.

5.1 SUMMARY OF FINDINGS

The work carried out at Obuasi, Buipe, Aflao, Achimota, Winneba and New Substations shows preventive maintenance was duly carried out at all the transformers before failure occurred. Secondly, the deployment of staff and resources to carry out corrective maintenance is costly. For instance the replacement of the failed transformer at Buipe which is a single transformer substation in 2013 cost GRIDCo multiples of man-hours, revenues and logistics. GRIDCo's current scheduled maintenance system also lacks the capacity and adequacy to timely detect equipment deterioration. The results of the research work reveals prior annual, quarterly and monthly planned maintenance activities carried out on the failed transformers at Obuasi, Buipe, Aflao, Achimota, Winneba and New Substations did not give early warnings of malfunctions and upcoming failure. Time based maintenance makes reliability of power supply vulnerable to unexpected equipment failures. Electricity consumers in Winneba and its environs had to suffer power cuts for about one month after the failure of the transformer before it was replaced. Though best practices cannot entirely prevent the occurrence of every equipment failure in GRIDCo, the research work reveals early warnings and proactive maintenance can reduce the probability of catastrophic failures. The researcher's participant observer status makes his contributions a unique authority in describing the phenomenon of Maintenance

Optimization for Power Transmission Systems in GRIDCo. A combination of Reliability-Centered and Condition-based substation maintenance provides a means of balancing these objectives. Frequent inspections usually give rise to high chances of detecting deterioration but at the expense of high inspection and subsequent maintenance costs. Furthermore, a lack of proper maintenance or excessive maintenance after each inspection could result in failure rather than improvement. The reliability of a power supply system can be compromised by the failure of any of its assets. With respect to transmission, one has to observe that components such as power transformers are very expensive equipment. When one fails it takes a lot of time to place an order, build the transformer, ship it, take delivery and install it at the designated location. The average cost for each of GRIDCo's power transformers is about one million United States Dollars. This explains why failure of power transformers poses serious financial challenges to GRIDCo. Its resultant social and economic impacts on electricity consumers are incalculable. Failure of power transformers in areas without an embedded redundancy in the substation design can be more costly as the outage period can last for a very long time. The consequent loss of productive hours of work for offices, production facilities, residential facilities and other users is invaluable. Every effort must therefore be made to prevent invaluable electricity transmission assets such as transformers from failing.

It has been established through this research work that even though scheduled maintenance regimes are followed under the time-based maintenance regime, as described in Chapter Four, the transformers failed without early warning signals. It is therefore concluded that time-based maintenance protocols, whether they originate from Original Equipment Manufacturers' specification or GRIDCo's internal maintenance programmes, lacks the capacity to accurately diagnose ''health'' status of transmission assets.

Condition-based maintenance strategy is therefore recommended to replace the existing time-based maintenance regimes in order to effectively maintain GRIDCo's assets. This will reduce the occurrence of preventable failures of assets and improve the reliability of the National Interconnected Transmission System (NITS).

5.2 CONCLUSION

The Ghana Grid Company has well trained technical staff who perform regular servicing and maintenance of its transmission assets. Their work always follows timebased maintenance protocols. This methodology however lacks the adequacy to timely detect equipment deterioration. Condition-based maintenance which is anchored on detailed equipment inspections and diagnostic techniques is recommended for implementation in GRIDCo to enhance effective maintenance planning for transmission assets. This is more economical as it will adequately detect equipment deterioration for timely intervention. It will also prevent over-maintenance which is a problem with the existing time base maintenance system.

The major conclusions from this research work can be summarised as follows:

1. The work carried out at Obuasi, Buipe, Aflao, Achimota, Winneba and New Obuasi Substations shows preventive maintenance was duly carried out on all the transformers before failure occurred.
2. GRIDCo's time-based maintenance schedule lacks the capacity and adequacy to timely detect equipment deterioration. Prior annual, quarterly and monthly planned maintenance activities carried out on the failed transformers at Obuasi, Buipe, Aflao, Achimota, Winneba and New Substations did not give early warnings of malfunctions and upcoming failure.

3. Deployment of staff and resources to carry out corrective maintenance is costly. For instance the replacement of the failed transformer at Buipe which is a single transformer substation in 2013 cost GRIDCo multiples of man-hours (3,600 man-hours), revenues and logistics.
4. Time based maintenance makes reliability of power supply vulnerable to unexpected equipment failures. Electricity consumers in Winneba and its environs had to suffer power cuts for about one month after the failure of the transformer before it was replaced.
5. The existing maintenance strategy and lack of redundant transformer capacities to meet N-1 criteria at Konongo,Dunkwa,Ayanfuri,Mim,Buipe and Yendi substations impact adversely on security and reliability of power supply.
6. Cost of maintenance is high due to over-maintenance of transmission equipment under the time based maintenance approach. The results of the work revealed that powers transformers, circuit breakers and protection equipment installed within the last three years at Nkawkaw, New Abirem, Kintampo and Mim undergo extensive annual, quarterly and monthly maintenance despite the good status of the equipment.
7. Periodic inspection, cleaning, servicing, part replacement activities are not adequately carried out under the time based maintenance regime to give scientific basis for effective maintenance planning.

8. GRIDCo's set target of 99.9% grid reliability will require the adoption and implementation of condition monitoring, inspections and functional testing as maintenance strategy.

5.3 RECOMMENDATION

Currently, preventive maintenance on power transmission assets in GRIDCo is anchored on the time-based approach. For instance the overhaul of a power transformer is carried out after a certain number of in-service hours. This approach lacks the capacity to give conditions of the transmission assets before maintenance is carried out. To address these shortfalls in the existing strategy, reliability centered maintenance (RCM) which is condition-based, with maintenance intervals based on actual equipment criticality and performance data is recommended for maintenance planning in GRIDCo. Optimized maintenance on power transmission assets will increase their availability and ultimately improve grid reliability as a result of faster reaction times as well as professional fault analysis and elimination. It is thus critical for the grid operator to adopt a systematic approach to the evaluation, design and development of cost effective maintenance programmes for power transmission assets. This is needed to enhance the effectiveness of operations and maintenance programmes. An additional check list is also designed and recommended for adoption in the inspection of transmission assets before maintenance is scheduled. The checklist will be used to thoroughly examine the transmission equipment and find out possible additional indicators that will suggest that some servicing or repair work need to be done to forestall any future breakdowns.

REFERENCES

1. Allen RN & Billinton R 1993, *Power System Reliability and Its Assessment*: *Part 3 Distribution*, IOSR Journal of Computer Engineering (IOSR-JCE), Vol 11, issue 2 pp 58

2. *Systems and Reliability Costs*1993, Power Engineering Journal, vol. 7, no.

4.pp141

3. Anders GJ1990, *Probability Concepts in Electric Power Systems,* John Wiley & Sons,New York.

4. Dai L&Christie RD1994, *The Optimal Reliability-Constrained Line Clearance Scheduling Problem,*Proceedings of the Twenty-Sixth Annual North American Power Symposium,vol. 1, pp. 244-249, September 26-27, Manhattan, KS.

5. Jensen J, Bertling L, Hilber P, Setréus J &Wallnerström CJ2007, *RADPOW Development and Documentation,* TRITA-EE, School of Electrical Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden.
6. Endrenyi J 1978, *Reliability Modeling In Electric Power Systems*, Wiley and Sons, New York.
7. Billinton R &Allan RN 1996, *Reliability Evaluation of Power Systems*, 2nd Edn, Plenum Press, New York.
8. Anders G 1990*, Probability Concepts in Electric Power Systems,* John Wiley & Sons, USA.
9. Brown R 2002, *Electric Power Distribution Reliability,* Marcel Dekker Inc, New York.

10. *IEEE Guide for Electric Power Distribution Reliability Indices*2006, IEEE Standards 1366, Viewed 14 October 2015.
11. Heinz F, 2003, Risk-*Based Asset Management*, Paper No 36. CIRED, Barcelona, Spain.

12. Hällgren B &Hilber P, 2004, *An Optimal Plan for Overhead Line Replacement in Kristinehamn – Background Material"*, Department of Electrical

Engineering, KTH, Sweden.

13. *New Zealand Infrastructure Asset Management Manual*, 1998, National Asset Management Steering Group, New Zealand.

14. Gaver DP, Montmeat FE &Patton AD 1964, *Power System Reliability-I. Measures of Reliability and Methods of Calculation*, IEEE Transactions on Power Apparatus and Systems, vol. 83. pp. 727-737

15. Cumming DJ, Montmeat FE, Patton AD and Zemkowski J, 1965, *Power System Reliability-II. Applications and a Computer Program*, IEEE Transactions on Power Apparatus and Systems, vol. 84.pp 397-403

16. Bertling,L n.d,*Reliability Centered, 2003 Maintenance for Electric Power Distribution Systems*, PhD Thesis, KTH, Dep. of Electric Power Engineering, KTH, Stockholm.

17. Hilber P, 2005, *Component Reliability Importance Indices for Maintenance Optimization of Electrical Networks*, Licentiate thesis, School of Electrical Engineering, KTH, Stockholm.

18. Billinton R & Allan RN, 1992, *Reliability Evaluation of Engineering Systems*, Plenum Press, New York.

19. Allan RN & Ochoa JR, 1988, *Modeling and Assessment of Station Originated Outages for Composite Systems Reliability Evaluation*,IEEE Transactions on Power Systems,vol.3, no.1. pp 309-316

20. Ebeling CE, 1997, *An Introduction to Reliability and Maintainability Engineering*, McGraw Hill, NewYork.

21. Tomasevicz CL, 2006, *Optimal Maintenance Policy with Markov and SemiMarkov Processes*, Master’s Thesis, University of Nebraska-Lincoln.

22. Anders GJ, 1990, *Probability Concepts in Electric Power Systems*, Wiley,

New York.

23. *Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity*, 2005, IEEE Standard 762. Viewed 28 October, 2015.

24. *IEEE Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities*1987, IEEE Standard 859. Viewed 17 October 2015.

25. Brown RE, 2002, *Electric Power Distribution Reliability*, Marcel Dekker, New York.

26. Kerlinger F, 1986, *Foundations of Behavioral Research*, 3rd Edn, Harcourt Brace & Company Orlando, FL.

27. McCombs ME & Shaw DL, 1972, *Functions of Mass Media* in The Public Opinion Quarterly, Vol. 36, No. 2. Pp 176-186

28. Cooper DR and Schindler PS, 2006, *Business Research Methods*, McGraw-Hill, Irwin.

29. Wimmer RD & Dominick JR, 2003.Mass *Media Research: An Introduction*. Wadsworth Publishing Company.Belmonth, CA.

30. Black K, 2004, *Business Statistics for Contemporary Decision Making*, 4th Edn,Wiley Student Edition for India. Wiley-India.

31. Energy Backup & Standby Power for Schools & Hospitals, NTT DOCOMO, Viewed 12 July, 2015. Technical Journal Vol. 15 No. 3 pp 35-41

32. Africa Confidential (http://www.africa-confidential.com/article preview/id/6036/The_politics_of_dumsor-dumsor. Viewed 15 July, 2015.

33. *Energy Sector Management*: Assistance Programme Report on Nigeria (APR) 1993b, World Bank, Working Paper.

34. Evans M, Hastings N & Peacock B, 1993, Statistical Distributions, 3rd Edn, John Wiley & Sons, New York.

35. Deming WE, 1986,*Out of the Crisis*, Technology, Cambridge.

36. Soemeer A, 2013, *Optimized Maintenance Planning for Transmission Power System*, Delft University of Technology, Netherlands.

37. Krontiris A & Balzer G, 2008, *Condition assessment of power system equipment, the impact of ageing and deterioration* in Soemeer A 2013,Optimized Maintenance Planning for Transmission Power System, Delft University of Technology, Netherlands.

38. *Final report of the second international enquiry on high voltage circuit breaker failures and defects in service 2004*, Working Group 06 (Reliability of HV circuit-breakers) of Study Committee 13 (Switching Equipment), International Council on Large Electric Systems (CIGRE). Viewed 18 January 2016.

39. Van der Sluis L, 2001, *Transients in power systems*, 1st Edn, Wiley, New York.

40. Power system grounding – Marjan Popov, 2011.

41. Transmission masterplan for Ghana-GRIDCo,2011.

42. Gruzs TM & Melhorn CJ, 1999, *recommended practice for powering and grounding electronic equipment*, Institute of Electrical and Electronics Engineers, Viewed 18 January 2016.

43. *Failure survey on circuit breaker control systems,* 2004, CIGRE Working Group 13.06, Later Working Group A3.06. Viewed 18 January 2016.

44. *https:www.gridcogh.com*

APPENDIX 1 GRIDCo MAINTENANCE PROTOCOL

INTRODUCTION

Transformer failure is a very costly event for GRIDCo and its customers.

Replacement cost can exceed 1 million US dollars and may take up to two years.

Transformer failure can be predicted, often years in advance, by systematic analysis of routing test results, allowing plenty of time for corrective action. Following the procedure below will facilitate the desired results.

Transformer test results come in four separate reports from the commercial test laboratory and field staff:

(a) Transformer Gas Analysis

(b) Inhibitor Analysis (c) PCB Analysis

(d) Basic oil Analysis

Normally, each report indicates the test results, date of test, operating designation and serial number of the unit tested.

PROCEDURE

- A separate file folder will be set up for each transformer receiving oil tests and labeled with the Operating Designation, Manufacturer, serial number, oil volume and year of manufacturer.
- Test results received from the laboratory will be filed in reverse chronological order, all four reports grouped by date of test.
- An analysis summary sheet will be kept on the inside front cover of every file folder.
- When test results are received the will be transferred to the summary sheet by the administrative officer who will take the folder to the Section Head, Electrical Maintenance for Analysis.
- The section head, Electrical Maintenance will perform the analysis reporting the results to the appropriate maintenance department for action as required.
- The administrative officer will keep files of test results up to date and maintain an effective retrieval system.

Analysis of Test Results

The blank form, appended will be used for analysis of test results. Test results will be analyzed as outlined in IEEE Standard 104.

RESPONSIBILITIES

- Field staffs in the O&M departments are responsible for taking oil samples as specified by Technical Services Recommended Maintenance Program for Electrical Maintenance.
- Technical Services is responsible for analyzing test results and flagging potential problems on all power transformers in the test program.

REFERENCE

For further information see:

(a) TPEM004 "Power Transformer Insulating Oil Sampling Procedure and Guideline for Test Program".

(b) "Administration of Basic Oil and Gas In Oil Test Program"

APPROVAL

DIRECTOR (S), NETWORK SERVICES DEPT.

Table 2 Transformer Oil Test Results Summary & Analysis

TRANSFORMER OIL TEST RESULTS SUMMARY & ANALYSIS

Operating Nomenclature:______________________ Oil Volume: ________________________

Manufacturer: ______________________________Year of Manufacturer________________

Serial No: __________________________________

Transformer Oil Analysis				1st Test	2nd Test		3rd Test	
				Date:	Date:		Date:	
Gas	Formula	Unit	Maximum	Result	Result	% change	Result	% change
Hydrogen	H2	PPM	100					
Oxygen & Argon	O2 + A	PPM						
Nitrogen	N2	PPM						
Carbon Monoxide	CO	PPM	250					
Methane	CH4	PPM	100					
Carbon Dioxide	CO2	PPM	20000					
Ethylene	C2H4	PPM	100					

Ethane	C_2H_6	PPM	60					
Acetylene	C_2H_2	PPM	5					
Total Dissolved Gas		PPM	700					
Water	H20	PPM	30					
Inhibitor Test		Unit	Minimum	Date:	Date:		Date:	
				Result	Result	% Change	Result	% Change
DBP		%	0.3%					
DBPC		%	0.3%					
PCB Test		Unit	Maximum	Date:	Date:		Date:	
				Result	Result	% Change	Result	% Change
PCB Content		PPM	50					
Basic Oil Test		Unit	Maximum	Date:	Date:	Date:		
				Result	Result	% Change	Result	% Change
Dielectric Strength		KV	30					
Neutralization Number		mgKOH	0.3					
Interfacial Tension		Dynes/cm	40					

Source: GRIDCo

GRIDCo MAINTENANCE PROTOCOL PURPOSE

To provide sampling procedure and guidelines for two types of diagnostic test carried out on transformer insulating oil:

(a) Gas-In-Oil analysis
(b) Basic Oil Test

SCOPE

This procedure must be followed by Electrical Maintenance staff in the operations & Maintenance Dept.

INTRODUCTION Insulating oil used in GRIDCo power transformers obtained by fractional distillation of mineral oil which consist of over two thousand hydrocarbon compounds. However, only nine of these compounds in the gaseous form are considered important in the analysis of dissolved gas in insulating oil. These are acetylene, carbon monoxide, ethane, ethylene, hydrogen, methane, nitrogen and oxygen.

Furthermore, six of these gases are combustible, the presence of which is an indication that overheating, loose connection, break in cellulose integrity, arcing, partial discharge or corona has taken place in the transformer. When dissolved in oil these gases reduce the flash point of the oil and cause premature failure. Analysis of dissolved gas-in-oil is the most powerful non-invasive diagnostic method available for transformer.

Basic-oil test determine dielectric strength, neutralization number is interfacial tension (Soluble contaminants) and moisture content of oil. Basic Oil test also provide important information. Regular testing of oil and rigorous monitoring of test result is a proven and cost effective method for early detection of insulation system problems in transformers. The two methods used by the Authority are Basic Oil Tests and Dissolved Gas-In-Oil Analysis.

PRECAUTION

Do not take oil sample for test in windy, rainy or cloudy weather.

MATERIALS REQUIRED

Sampling jars, syringe, adaptor plug and labels.

SAMPLING PROCEDURE

FLUSHING SAMPLING VALVE Open bottom sampling valve on the transformer to flush inside of valve into a suitable container (e.g. empty pail), to avoid spilling oil into the environment.

SAMPLING FOR BASIC OIL TEST

(a) Rinse the inside of a clean and dry sampling jar with oil taken directly into the jar from the transformer. Fill the jar with oil through the sampling valve while holding the jar in such a manner that as few bubbles as possible are created in it.

(b) Flush top valve and take oil sample through the top sampling valve of transformer.

(c) Label the jars correctly. Indicate whether it is bottom or top oil.

SAMPLING FOR DISSOLVED GAS IN OIL ANALYSIS

(a) Fit a clean adaptor plug, with a drilled hole off-center made to accept the tapered inlet of the syringe, to the transformer sampling valve, see figure attached.

(b) Turn syringe valve to flush position, open the transformer sampling valve and allow the oil to run until all trapped air is eliminated. (figure 2.1)

(c) Turn the syringe valve to fill position and allow approximately ten (10) cc of oil to enter the syringe. Close the transformer valve and remove the syringe (fig. 2.2).

(d) Hold the syringe vertically with the mouth upwards and expel any air bubbles. Depress the piston to the zero mark and shut off the syringe valve. (Figs 2.3A & 2.3B).

(e) Refit the syringe, which is now free of bubbles and with its dead volume filled with oil, into the hole in the plug.

(f) Re-open the transformer sampling valve and allow the oil to flush through the flush port of the syringe valve. (fig. 2.4)

(g) Turn the syringe valve to fill position and allow the oil pressure to push the syringe valve to fill position and allow the oil pressure to push the piston back until the syringe contains about 26cc of oil. (fig. 2.5)

NOTE: If possible, don't pull back the piston manually as it may result in atmospheric leakage and bubble formation.

Do not fill syringe to more than 26cc to ensure adequate seal along the piston.

(h) Close the syringe and transformer valves. Remove the syringe and drilled plug. Plug entrance of sampling valve.

(i) Fill the identification tag provided giving such information as transformer serial number, rating, year of manufacture, syringe serial number, date sampled, etc.

(j) Shipping

Pack samples into Syringe Carton provided. Pack the syringe carton into a second carton and fill all empty space with dust free packing material. As soon as possible, air freight samples to accredited testing authority recommended by Electrical Maintenance Section, Technical Services Department.

FREQUENCY OF TESTING

Once manually or more frequently as may be recommended by Electrical Maintenance Section, Technical Services.

STANDARDS ACCEPTABLE RESULTS FOR GAS-IN-OIL ANALYSIS

Principle combustible gases generated in transformer oil and their causes are as follows:

Gas Cause

Acetylene – Arcing

Carbon monoxide – Overheating Cellulose Ethylene,
ethane – Overheating joint etc.
Hydrogen – Coran

Guideline for Individual Gasses

As a guide, acceptable level of individual combustible gases in oil, the Authority has adopted standards set by the Doble Society:

Table 7.1 Acceptable Levels of Individual Dissolved Gas

ACCEPTABLE LEVELS OF INDIVIDUAL DISSOLVED GASSES	
GAS GENERATED	MAXIMUM VOLUME IN PPM (Based on 20,000 Gallons of Insulating Oil)
Acetylene	5
Carbon dioxide	2000
Carbon Monoxide	250
Ethane	60
Ethylene	100
Hydrogen	100
Methane	100

Source: GRIDCo

Guidelines for Total Dissolved Gas

The total pm of all gases dissolved in oil should not exceed 700, based on 20,000 gallons of oil. Higher totals indicate incipient problems.

Volume Conversion

The above figures are based on a twenty thousand (20,000) gallons volume of transformer tank.

To convert to a different volume, use above figure x actual volume / 20,000

Rat of Accumulation

In addition to guide lines listed above, the rate of gas generation also provides critical information about changes occurring in the transformer. Rapid build-up indicates internal problems.

Monitoring of Dissolved Gas Levels

It is necessary to establish a computerized data base as a means of monitoring the absolute levels and rate of dissolved gases. Rigorous monitoring will provide ample warning of incipient faults.

ACCEPTABLE RESULTS FOR BASIC OIL TESTS

a. Neutralization number is a measure of acids present in insulating oil usually as a result of oxidation.

    (a) Acceptable level is equal to or less than (≤) 0.4mg (KOH)/g.

    (b) If neutralization number is between 0.4 and 0.7 then reclaim using fullers earth and vacuum treatment or completely replace oil, whichever is cheaper.

    (c) If level is more than 0.7 the replace oil.

b. Dielectric strength determines the insulating ability of oil. This test is very sensitive to the presence of impurities such as carbon, lint, fibre and metal chips.

    (a) Oil dielectric strength is good if it is equal or greater than 40kV by **ASTM D1816**.

    (b) Minimum level for treatment is 25kV by **ASTM D1816**.

    (c) Scrap if dielectric strength is less than 25kV after treatment.

c. Interfacial tension (IFT) measures presence of soluble contaminants in oil.

(a) Minimum acceptable IFT for new oil is 40 dynes/cm

(b) Minimum level of IFT for treatment is 17 dynes/cm

(c) Scrap oil if IFT is 15 dynes/cm or less.

d. Moisture content of oil (in ppm) indicates the quantity of moisture in insulating oil measured in parts per million.

(a) A moisture level of 10ppm or less is acceptable.

(b) If moisture level is more than 15ppm then treat oil.

ADDITIONAL RECOMMENDED CHECKLIST FOR TRANSFORMER MAINTENANCE AT ALL GRIDCo SUBSTATIONS DEVELOPED BY THE RESEARCHER

Preventive maintenance done regularly by trained, professional and experienced electrical workers on electrical equipment helps to detect problems before they become serious issues. By scheduling a comprehensive maintenance check that utilizes advanced technology and expert electrical skills, the power equipment on which GRIDCo runs its business can continue working efficiently, reducing the risk of a catastrophic failure that can cost time and money. Based on the experience of this researcher working at GRIDCo, this checklist should be adopted as an additional protocol for the expected lifespan of selected transformers. The results can then be analyzed in the course of time by comparing the selected transformers with others that did not follow this additional recommended protocol.

SUBSTATION NAME-- DATE-----------------------

TRANSFORMER NOMENCLATURE/ID-------------------------------- VOLTAGE RATIO--------------

Table **7.2**: Recommended Checklist for Transformer Maintenance

S/No	Activities	Carried out	Remarks
1	Check for oil leakages		
2	Check for oil level in the conservator tank is up to 3/4th mark		
3	Check for Breather condition		
4	Check for Silica Gel condition		
5	Clean the body		
6	Open the terminal box and check the following d. Tightness of terminal connection e. Condition of bushings f. Any sign of overheating.		
7	Check for any unplugged opening, missing bolts		
8	Check all terminal box tightness		

9	Check oil/winding temperature setting		
10	Check earthing system is proper & intact		
11	Check cable support		
12	Any other abnormality		

Table 3Maintenance Instructions for Power Transformers

Inspection frequency	**Items to be inspected**	**To be checked**	**Actions required if inspection shows unsatisfactory condition**
Hourly	Oil and winding temperature	Ensure that temperature rise is within specified limits	-
Hourly	Loads (Amps)	Check against rated figures given on the name plate	-
Hourly	Voltage		
Daily	Oil level in transformer	Check oil level gauge	If low, top with dry oil find whether there is any leak.
Daily	Oil level in bushing		
Daily	Dehydrating breather	Check that air passages are free. Check colour of active agent	If silicagel is pink, change by new charge. The old charge may be reactivated for using again.
Daily	Oil level in OLTC conservator	Check oil sight window or oil level gauge	If low, top with new dry oil
Daily	Relief diaphragm of	-	Replace if broken or cracked
Daily	Cooler fan, bearing motor & operating mechanism	Check the bearings. Examine contacts, check manual control and interlock	Lubricate the bearing. Replace burnt or worn contacts.
Quarterly	bushing	Examine for cracks and dirt deposit	Clean the dirt. If cracked or broken replace the bushing

Quarterly	Oil in transformer	Check for dielectric strength and water content	Take suitable action to restore quality of oi
Half yearly or at the end of 5000 operation	Oil in the diverter switch of OLTC	a. Dielectric strength	Filter or replace if BDV is less than specified value
		b. Water content	Measure the water content Replace/ recondition if exceeds that specified limits
Yearly	Oil in transformer	Check acidity resistivity, tan delta and sludge	Filter or replace oil
Yearly	Gasket joints	-	Tighten the bolts evenly to avoid uneven pressure
Inspection frequency	**Items to be inspected**	**To be checked**	**Actions required if inspection shows unsatisfactory condition**
Yearly	-	Check sealing arrangements and find out whether there is any leak	Replace gasket if leaking
Yearly	Relays alarm and other circuits	Examine relay and alarm contacts, their operation fuses etc. check relay accuracy.	Clean the components. Replace contacts and fuse if necessary
Yearly	Earth resistance	-	Take suitable action if earth resistance is high
After 50000 operations of the OLTC	1.Arcing contacts	-	Replace if necessary
	2.Lubricating oil in the gear box of driving mechanism	Low oil level	Add or replace with lubricating