Addis Ababa Institute of Technology

School of Mechanical and Industrial Engineering

Failure Modes and Effects Analysis to Mitigate Failure of Distribution Transformers in Ethiopia

By

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Approval Sheet

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DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "*Failure Modes and Effects Analysis to Mitigate Failure of Distribution Transformers in Ethiopia*" is original work of mine, has not been presented for a degree in this or in any other university and all the resources or materials used for this thesis have been duly acknowledged.

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ABBREVIATIONS

AC	Alternating Current
AHP	Analytical Hierarchy Process
AM	Asset Management
CI	Critical Infrastructures
CIGRE	International Council on Large Electric Systems
CPI	Critical Public Infrastructures
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
EMF	Electro Magnetic Force
EEPCO	Ethiopian Electric Power Corporation
HRC	High Rupture Capacity
HRC	High Rupturing Capacity
HV	High Voltage
IA	Immediate Attention
IEC	International Electro technical Commission
IEEE	Institute of Electrical and Electronics Engineers
LV	Low Voltage
METEC	Metals and Engineering Corporation
O&M	Operation & Maintenance
OLTC	On-Load Tap-Changers
ONAN	Oil Natural Air Natural
RF	Radio Frequency

ABSTRACT

This study aims to investigate the causes of failure of distribution transformers in Ethiopia as one of the possible causes for the current power interruption and fluctuation in the country.

Failure Modes and Effects Analysis (FMEA) is applied to identify modes of failure, the severity of consequences of those failure modes and detectability of the root causes of failures. Analytical Hierarchy Process (AHP) is also applied to enhance the conventional FMEA process in order to improve the ranking of failure causes. In addition failure classification from various perspectives, unstructured interviewing and questionnaires have been used as an adjunct to complete the study.

The study addresses 1322 prominent failures in distribution Oil Natural Air Natural (ONAN) transformers from year 2013 to 2016 having a repair lead time of more than 18 days and also transformers that could not be restored to normal operations since they failed. The transformers have voltage level of 15 and 33KV and capacity ranging from 10-315KVA.

For the transformers failure analysis covered in this study, the average failure rate is 6%.Failure analysis of prominent failures by sub-systems shows that winding failure constitutes the leading 52.4% of the total failures, analysis of the failures by regions shows that Addis Ababa region registered the highest number of failures followed by central region and north western regions. Further analysis of failures by modes of failure shows that electrical modes of failure constitute the highest modes of failure with 45%.

The output of the FMEA worksheet identifies the most vulnerable parts of distribution power transformers in Ethiopia causing entire damage to the transformers. Thus, the major causes of failure of distribution ONAN transformers in Ethiopia as lack of protective devices, inappropriate testing and diagnosis and inefficient Operation and Maintenance followed by unethical practices with theft of oil and vandalism.

Key words: Distribution Transformers, Failure Modes and Effects Analysis, Failure Analysis, Oil Natural Air Natural, Analytical Hierarchy Process

CHAPTER ONE

INTRODUCTION AND BACKGROUND OF THE STUDY

1.1 Introduction to the Study

Electrical energy is one of the fundamental factors that lay the foundation for social and economic growth of a country. Adequate electrical energy supply, with high quality and reliable supply in an environmental friendly manner must be available to consumers [1].In Ethiopia, since the past few years, electric power interruption has become a serious problem. Electric power problem is quiet common with several interruptions within a day in the capital city and the rest of the regions. The government and the community have controversial feedbacks regarding the problem. Some argue that the electric power interruption is electric demand related with the rapid growth of the country while others admit this has nothing to do with shortage of power supply, it has to do with the failure of aged distribution and transmission lines or power transformers.

Power transformers are the most expensive and dangerous critical public infrastructures in the electricity distribution network. While people demand reliable services from these key infrastructures all the times, they easily forget the fragility and vulnerability and the effort required to restore to the original condition once transformers fail. In reality, the failure rate of power transformers is very low compared to other elements as they are static distribution network equipment. The chance of getting failure in any of the static equipment is very low. However, in Ethiopia, failure of power transformers seems quiet strange with very high failure rate from recent years and it is quiet common to observe failed transformers in nearby residences and the local news media often gives coverage of electric power interruption or damages due to power transformer failures.

Nowadays, power transformers are being produced in the country for power distribution and special purposes with average production capacity of 6000 transformers per annum, while the current demand of transformers in the country is estimated to be 15,000 per annum with expected rise to 20,000 transformers after the opening of Gibe 3 power generation plant. The capacities of locally produced transformers range from 15,000 to 33,000V.

The in-house production of power transformers is expected to prevent shortage of power transformers in the country as well as failures related to imported substandard transformers but the problem still pertains with the in-house produced transformers.

In Ethiopia, the electric power utility is solely governed by two state owned electricity utilities; Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU).It has been over 60 years since these two institutions started operation in Ethiopia originally as one entity, Ethiopian Electric Power Corporation (EEPCO), but recently splitted in to two.

EEPCO has more or less contributed to the current growth of the country but compared to the years of operation in Ethiopia, the institution failed to build its capacity in terms of technology, manpower and asset management systems as has been demanded from today's operation and service requirements. These contribute to difficulties to manage critical public infrastructures such as power transformers through organized asset management or reliability centered maintenance.

However, there are techniques to analyze and mitigate the risks of failures of power transformers and determine the root causes of failures of these critical public infrastructures through the using of Failure Modes and Effects Analysis (FMEA).

Failure Modes and Effect Analysis is a powerful tool that helps to study the possible causes of failure of power transformers and to identify vulnerable elements of the asset that can cause further faults.

This study aims in particular to investigate power transformer failures as one of the factors contributing for the overall electric power interruption and to study the causes of transformer failures through Failure Modes and Effects Criticality Analysis (FMEA) in all the regions in Ethiopia.

1.2 Problem Statements

Ethiopia has the largest electric power generation capacity in Africa next to Democratic Republic of Congo [2]. Despite this significant power generating capacity, from recent years, electric power interruption is becoming a serious challenge in the country.

Frequent power interruption and fluctuation cause underutilized capacities of different industries and production of inappropriate products from machineries and also failure of electric operated machineries themselves. Though electric power supply improves the lifestyle of societies, during power supply problems, the same society, especially those whose lives are strongly linked with electric power supply will suffer. In this aspect, Ethiopians, consuming high electric power supply, micro and small enterprises and commercial and service institutions are being affected and are in loss of their businesses.

Frequent electric power interruptions are mainly caused by transformer failures, worn out distribution, transmission and power carrying lines, overloads, manmade and natural disasters (wind, rain), and inefficient maintenance.

One of the aforementioned causes, power transformers, are critical, expensive and dangerous assets in the transmission and distribution network of electricity. Power transformers may fail due to human errors, acts of nature, hardware failures, software failures, overloads, vandalism and old ages.

When power transformers fail in any of the above cases, electric power will get interrupted until they are replaced or until power sharing operation is carried on from a nearby transformer. And also, due to the high voltage working in contact with oil, failures of power transformers also cause serious injuries on lives and damage of properties.

This research focuses on investigating power transformers failures as possible major contributing factors for the current power interruption in Ethiopia.

1.3 Objectives

General Objective:

The main objective of the study is to investigate failure modes and effects in power transformers to identify root causes of failures so as to devise strategies to address the most frequent modes of failures and improve the reliability of power transformers.

Specific Objectives:

- To examine failures and causes of failures in power transformers to propose remedies for the root causes of the failures to be identified
- To investigate the trend of failures in distribution transformers from various perspectives to have a baseline for further studies.
- To identify vulnerable elements of power transformers that are causing further failures to address problems related to various elements of power transformers.
- To suggest ideas to mitigate failures and risks of failures of power transformers through assigning reasonable RPNs for each causes and improve the reliability of power transformers.

1.4 Scope of the Study

The failure of any one of the power generation, transmission or distribution transformers in the electric grid contributes for electric power interruptions. This study, however, exclusively focusses on failure causes related with distribution transformers failures.

For all the fifteen geographically divided regions in Ethiopia for the purpose of managing electric power, transformers failure data have been collected from a centralized database available at the capital city, Addis Ababa.

Data analysis against age has been done for four regions where their failure database included the age of the transformers when failure occurred.

1.5 Significance of the Study

Electric power supply improves economic growth of countries. On the other hand, electric power interruption and shortage cause negative impact on the economic growth and the productive contribution of the society towards the growth of the economy.

In Ethiopia, at present, electric power interruption is causing negative impact on day to day activities of people. The power interruption stays for days, sometimes for weeks that makes the situation very worse. This study, therefore, contributes to improve reliable supply of electric power in the country by investigating one of the possible causes of power interruption, power transformers failures.

The research points out ideas for the electric utilities on how to manage power transformers failures, how to keep their critical assets safe enough and how to watch risks of failures. These contributions will lead to strategies to improve the reliability of transformers that will realize the reliable supply of electric power.

Improved and reliable electric power supply creates safe, happy and productive society and profitable industries. This will definitely contribute to the overall economic growth of the country.

1.6 Research Methodology

The research begins with review of literatures to summarize and conceptualize researches conducted on power transformers` Failure Modes and Effects Analysis by previous researchers. The written documents have been also used to analyze and evaluate failure categories and risk priority numbers associated with each failure modes by the different authors to develop best failure categories and Risk Priority Numbers (RPNs).

Secondary data about power transformers have been collected from EEU centralized failure database. Work procedures, policies and constraints of EEU have been carefully assessed for possible impact on power transformers functionality and weak links.

Data gathered from traditional failure reports include transformers failures, operating assumptions, status of the transformers (normal, stressed, repaired).

Data from traditional failure reports have been further cleared and filtered to create failure database.

Other inputs on failures and severity of impact of failures have been collected from own observations, newspapers, questionnaires for EEU maintenance staff and unstructured interviews.

Failure database have been analyzed using conventional Failure Modes and Effects Analysis (FMEA) and Analytical Hierarchy Process (AHP).

1.7 Organization of the Study

This study applies Failure Modes and Effects Analysis (FMEA) to identify the causes of power transformers failures in Ethiopia. The study is organized in the following way:

Chapter one discusses the existing problems related with electric power interruption and fluctuation in Ethiopia. Chapter Two, Related Literature Review, explains the relevance of FMEA for power transformers based on other relevant scientific works. Chapter Three discusses the methodology engaged to create and analyze transformers failure database. Chapter Four discusses the data collected and the background of Ethiopian Electric Utility, its working procedure in relation to the management of power transformers, transformers suppliers. Chapter Five discusses a description of analysis of the FMEA study and analysis of chosen most critical failure causes using Analytical Hierarchy Process (AHP) and interpretation of the results. Chapter six discusses the remedies as conclusions and recommendations.

CHAPTER TWO

RELATED LITERATURE REVIEW

2.1. Power Transformer-Critical Distribution Network Equipment

Power Transformer is the most critical, vulnerable and dangerous asset in the electric power distribution network. A Transformer facilitates the reliable and quality supply of electric power as well as its efficient distribution and transmission. Transformers make long distance transmission of electricity economically feasible. The transformer does not require movement of its parts while serving these functions.

The reliability of power systems depend on the reliability of power transformers;therefore,Power transformers are the most important equipment in the distribution network [1, 3].Unless encountered with a fault that causes premature failure, insulation paper aging is the main cause of transformers deterioration. Heat is the main factor that facilitates Polymerization of the cellulose chains that leads to weakening of the tensile strength of the papers or the papers will have low degree of polymerization (DP) [4].

Sudden failure of a transformer can cause severe production interruption and machinery failure [5].

2.2. History of Power Transformers

The basic elements of modern power transformers were the results of Michael Faraday's experiments on electromagnetic induction in 1831 to produce electricity from magnet. Faraday's experiment demonstrated that an alternating current induced to a winding around a magnetic permeable core produces a magnetic flux and induced electromagnetic force due to a varying magnetic flux in a secondary winding.

Faraday demonstrated the basic principles of magnetic induction, while the first practical transformer was believed to be released by Lucien Gaulard and John Dixon Gibbs in 1881.In 1876 Pavel Yablochkov produced lighting with an alternating current source at the primary end and loads in the secondary ends to deliver varying outputs, as in lamps with different luminaire intensities. Ever since the discovery of the principles of electromagnetic induction by Michael Faraday, Many others took the patent of power transformers afterwards. William Stanley designed the first commercial transformer in 1886 from an E-shaped interlocking iron plate as cores. William Stanley, an engineer for Westinghouse, who built the first practical 1885 after George Westinghouse bought Gaulard and Gibbs' patents. The core was made from interlocking E-shaped iron plates. This design was first used commercially in 1886. Mikhail Dolivo-Dobrovolsky in 1889 produced the first three-phase transformer, Tesla in 1891 invented the Tesla coil for generating very high voltages at high frequency [6].

2.3. Technological Advancement

Over the years, manufacturers improved the quality of distribution network transformers and accessories. The technological advancement in transformers is becoming more painstaking for technicians to spot faults immediately. To avoid these technology related challenges, distribution systems must consider a blend of new and old technologies as well as considering upgrade of experiences and skill levels of technicians as an initiative to reduce cost and to improve service delivery [7].

2.4. Working Principles

The basic working principle of power transformers is simple, electromagnetic induction. Transformers are capable of receiving AC power at one voltage and delivering it at another voltage. In this way transformers help achieve better transmission efficiency while transferring the power over longer distances.

A varying magnetic flux associated with a loop will induce an EMF across it. Such a fluctuating magnetic field can easily be produced by a coil and alternating EMF system. A current carrying conductor produces a magnetic field around it. With the fluctuating nature of the alternating current, the magnetic field associated with the coil will also fluctuate. This magnetic flux can effectively link to a secondary winding with the help of a core made up of a Ferro magnetic material. This fluctuating magnetic field will induce an EMF in the secondary winding due to electromagnetic induction. Since the turns are arranged in series, the net EMF induced across the winding will be the sum of individual EMFs induced in each turn. Since the same magnetic flux is passing through the primary and the secondary coils, the EMF per turn for both the primary and the secondary coils will be the same. The EMF per turn for the primary coil is related to the applied input voltage. As a result the induced EMF at the secondary coil is expressed with the following formula.

Where E1 and E2 are primary and secondary EMFs and T1 and T2 are primary and secondary turns then, voltage ratio or turns ratio can be expresses as follows [8]:

$$\frac{E_1}{E_2} = \frac{T_1}{T_2}$$

This implies with few turns with the primary, one can lower the voltage or the reverse case one can increase the voltage [9].

2.5. Parts of the Power Transformer

Power Transformers are composed of the following subsystems:

Winding

Windings carry current in transformers. They are carefully stranded around the core and each strand is covered with insulation material. High voltage and low current flows in the primary winding and with electromagnetic induction voltage is stepped up and current is stepped down in the secondary winding. During this process stresses related with dielectric, thermal and mechanical occur and cause winding failure. These stresses rise from short circuits, mechanically during movement of the transformer from one place to another and lightening. [10]

Bushings

Bushings are used as isolation materials. They are used to isolate the oil carrying tank from the outer parts of the transformer. Bushings may fail when the insulating oil and paper used heated up, over voltage, oil leakage and ages. When the insulation system of bushings break, bushing failure occurs followed by tank rupture, transformer failure and long term outage [11].

Tap Changer

Tap Changers are used to regulate the voltage level by adding or subtracting to the windings of a power transformer. Tap changers are the only moving parts of power transformers, which also make them the most vulnerable parts of power transformers. Springs and capacitors problems may cause tap changer failures in power transformers [12].

Conservator Tank

The tank in a transformers serves multiple purposes. As a container of the transformer oil, as a protection for active part of the transformer and also as support for accessories and control equipment. Oil vapors created as a result of internal arcs can lead to high pressure that can rupture the tank [13].

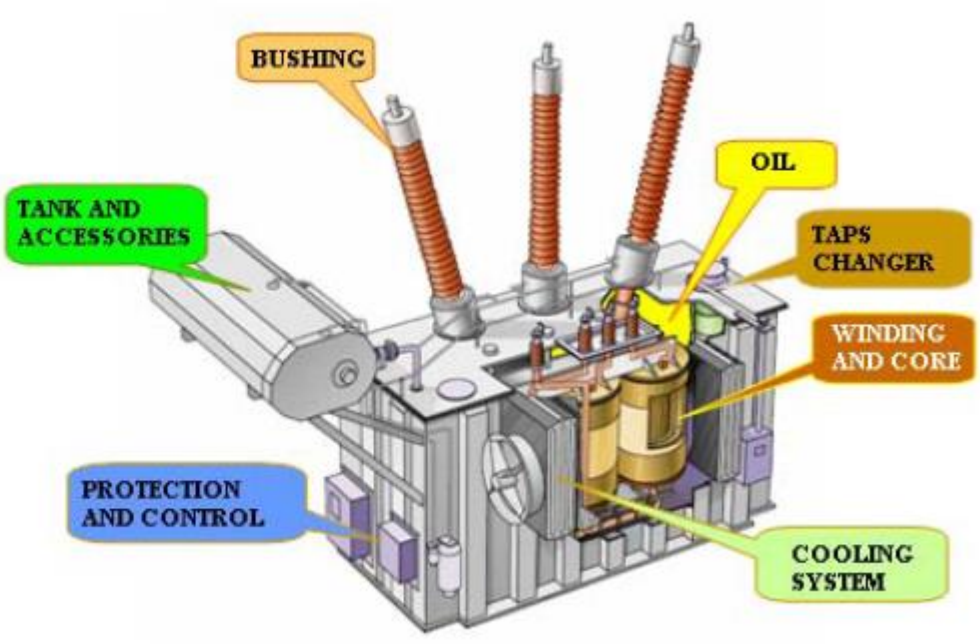

Figure 2.1: Parts of the Power Transformer. Source: *Catterson, VM, (2014*)

2.6. Types of Power Transformers

Power transformers can be classified in many ways based on their location and function in the electric distribution system. Based on their purpose transformers can be classified as distribution, amplifier, and arc furnace. By their application as power supply, impedance matching, circuit isolation, by their frequency range as power, audio, radio frequency (RF). Transformers can further be classified by power, by voltage, cooling type as in air cooled, oil filled, water cooled, fan cooled, etc. By the ratio of the number of turns as in step-up and Step-down [6].

2.6.1. Generation transformers

Generation transformers are used for stepping–up power generated at a generating station from a range of 11KV to 25KV to higher voltages up to 745KV.

2.6.2. Transmission transformers

Transmission transformers reduce the transmission voltage to a sub-transmission voltage level, usually from 220KV to 138KV or 400KV to 345KV. They are usually located between generation station transformer and receiving end transformer, in the transmission line. These transformers are usually installed in groups with at least one additional transformer to backup failure or maintenance of the others. An installed tap changer used to change the winding ratio, therefore the voltage level.

2.6.3. Distribution transformers

These are transformers that reduce the transmitted voltage level to domestic use voltage level, usually to 220v.Distribution transformers are not equipped with tap changers, they, therefore need to be removed from the system to change the voltage level. There is no backup possibility in the distribution transformers unlike the transmission transformers, their maintenance should be watched.

2.7. Reliability of Power Transformers

The reliable operation of the whole distribution network depends on the reliable operation of power transformers. Having failure statistics of power transformers based on proper data collection and a periodic review of the failure statistic is an essential input when considering redesigning, reviewing the technology, improving maintenance and testing procedures for varying loading and network configurations [14].

Power transformers reliability records can show important features that are related with future failure trends as well as to assess the overall reliability of the electric distribution network. The reliability data also contributes to improve existing international standards related to high voltage equipment [15].

A research conducted in 2010 in European substation transformers revealed the most significant failures in substation transformers between the years 2000 to 2010.Substation transformers with ratings from 100 to 500KV have been included in the study. Table 01 shows the population of transformers investigated and the failure rate for the respective voltage rating.

Table 2.1: Failure Rates of Substation Transformers. *Source J.A. Trappey, et.al.*

POPULATION INFORMATION OF SUBSTATION UNITS	HIGHEST SYSTEM VOLTAGE [kV]			
	100 ≤ U < 200	200 ≤ U < 300	300 ≤ U < 500	All
Number of utilities	22	18	14	32
Number of transformers	2775	2124	1214	6113
Number of major failures	90	72	49	211
Transformer-Years	20915	15221	9271	45407
Failure rate p.a.	0.43%	0.47%	0.53%	0.46%

In order to achieve reliable and durable transformers as well as to reduce life cycle related costs, it is important to monitor the condition the transformers are operating, their insulation system as well as the condition of their the accessories if they are in proper working order [16].

2.8. Failure Modes and Effects Analysis

FMEA was recognized in the 1940's to study failures that might occur from dysfunctions of US military equipment. FMEA technique can be used both in the design and functional stage of a system. In the design phase FMEA can be used to proactively study or evaluate consequences of design problems and to make modifications and changes on time. In the functional phase, FMEA systematically analyses occurred modes of failures, their root causes and consequences to identify the most vulnerable parts that need urgent action [17].

FMEA is a tool for assessing risk associated with the different modes or ways in which a component or system can fail, identifies the effects of those failures, and provides structure for revising the design to mitigate risk where necessary. FMEA is an inductive process and constantly asks questions, if a failure occurs then what could possibly happen? Searching for the consequences of those failure modes. It provides an approach for quantitative analysis of risk and which failure modes and effects are worth paying attention to. This is useful to compare designs and refine designs and as a decision tool for which action precedes which and further refine designs. It is an important tool to document safety review in an easy format [18].

FMEA can be classified as System FMEA, Design FMEA and Process FMEA.

System FMEA: deals with system composed of multiple sub systems. The main concern lies on the integration of the sub systems and their contribution into the functionality of the whole system. It includes failure modes related with the interaction of sub systems that cause dysfunction of the entire system.

Design FMEA: design FMEA focuses on product design and failures that might hinder the functionality of the product or its components while it is in the design stage.

Process FMEA: considering that the product is well designed, process FMEA deals with the manufacturing process of the product in order to identify spots in the process that could later have an impact on failure of the product.

2.8.1. Failure Mode and Effects Analysis (FMEA) -procedures

There are a number of standards in doing an FMEA, the principles applied in the different standards are similar [19]:

- The system to be investigated should be broken down to its components
- Identify modes of failures associated with each component
- Identify consequences / end effects for each failure mode
- Identify potential root causes for each failure modes

- The end effects /consequences of each failure mode should be assigned with a Severity level (S)
- Each root cause must be assigned with a probability of Occurrence (O) and Degree of Detectability (D)
- Calculate the Risk Priority Number by multiplying Severy,Occurrence and Detection (S*O*D)
- Identify process controls and indicators as a way of mitigating high RPNs
- Calculate a new RPN value

2.8.2. Drawbacks of Traditional Failure Modes and Effects Analysis

FMEA is a very powerful tool used to analyze potential failure modes within a system and it has been used to examine the power transformer’s performance in different failure scenarios. The FMEA method, however, has several setbacks; for example failure modes with different sets of risk factors may produce the same RPN values and impossible to identify the actual risk among RPNs that on the surface are equal. And also the traditional FMEA does not take the relative importance of S, O, and D into account.

FMEA based on Fuzzy set Theory

Significant efforts have been made by researchers in order to overcome the drawbacks of traditional Failure Modes and Effects Analysis. Vikramjit et al., 2010 introduced FMEA incorporated with fuzzy set theory.

FMEA blended with fuzzy approach uses FMEA team to forward their knowledge and experience associated with S,O,D. Experts judgment and experience about the S, O, D can be used to define degree of membership in the Fuzzy model of the process by using fuzzy linguistic terms [20].

While the FMEA based on fuzzy set theory captures the uncertainty to a certain degree, it also ignores some uncertainties that could occur in the process.FMEA based on fuzzy theory also lacks the capacity to translate qualitative evaluation to quantitative evaluation.

FMEA based on Cloud Model of Weight

Jianpeng Bian, et.al /TELKOMNIKA, 2015 proposes cloud weight analysis to prioritize the apparently equal RPNs that traditional FMEA analysis generally produces. Every element in the proposed cloud matrix of contrast is constituted by the cloud model. The element C_{ik} represents the contributing degree of the sub-index f_i to the prior index which is relative to f_k.Assuming the sub- index is *n*.Through analyzing the characteristics of the pair-wise comparison, cloud matrix, it is clear that the diagonal element C_{ii} represents the important degree of comparisons, that is Ex_{ii}=1, En_{ii}=0,He_{ii}=0.Again, the element C_{ik} represents the contributing degree of the sub-index f_i to the prior-index, which is relative to f_k and the symmetrical element C_{ki} is the contrast [21].

$$C = \begin{bmatrix} C_{11}, \cdots, C_{1n} \\ \cdots \quad \cdots \\ C_{n1}, \cdots, C_{nn} \end{bmatrix} = \begin{bmatrix} C_{11}(Ex_{11}, En_{11}, He_{11}), \cdots, C_{1n}(Ex_{1n}, En_{1n}, He_{1n}) \\ \cdots \quad \cdots \quad \cdots \\ C_{n1}(Ex_{n1}, En_{n1}, He_{n1}), \cdots, C_{nn}(Ex_{nn}, En_{nn}, He_{nn}) \end{bmatrix}$$

$$c_{ki} = \frac{1}{c_{ik}} = C(\frac{1}{Ex_{ik}}, \frac{En}{(Ex_{ik})^2}, \frac{He}{(Ex_{ik})^2})$$

When constructing the cloud matrix of contrast, the mutually important degrees of the different should be determined first to form the cloud model, that is, the cloud`s pole. Experts must also determine the degree of each sub index`s importance relative to the cloud`s pole. Finally the results are synthesized. The degree of mutual importance of FMEA`s three risk factors (S, O, D) is divided into five ranks. Experts determine the mutually important degree of each factor relative to the cloud model`s pole. The qualitative results are quantified through the application of synthesized, multi-expert quantification to determine the value of each factor.

FMEA based on Analytical Hierarchy Process (AHP)

Vaibhav, et.al 2014 suggests Analytical Hierarchy Process (AHP), also known as, pair wise comparison to prioritize equal RPN values generated as a result of traditional Failure Modes and Effects Analysis (FMEA).AHP methodology is established by setting up decision hierarchy out of the decision problem into a hierarchy of interrelated decision elements. The input data are collected by pairwise comparison of the decision elements. In the pairwise comparison respondents are forced to prioritize between two alternatives. By comparing factors, it is possible to identify the extent or ranking of the compared factors. An AHP pairwise comparison starts with the construction of n*n matrix. Then respondents compare two factors at once by using a relative scale measurement. Each alternative is matched one-on-one with the other alternatives. Reciprocals are automatically assigned in each pairwise comparison.

When all the pairwise comparisons are made, the priority vectors (eigenvectors) can be can be calculated as follows: each element of the matrix is divided by its column total ad then the priority vector can be obtained by finding the row averages. Then, the consistency of comparison is determined by using eigenvalue (λmax) to calculate the consistency index (CI), CI= (λmax-n)/ (n-1).After that, the consistency ratio (CR) can be calculated by dividing CR with the appropriate value of the random index (RI).If CR does not exceed 0.10, it is acceptable, but if it is more than that, the judgment matrix is inconsistent and should be reviewed and improved [22] [23].

2.8.3. Failure concepts and definitions

The following definitions of terms are according to IEC.

Failure: loss of ability to perform as required

Fault: inability to perform as required, due to an internal state

Failure Modes: manner in which failure occurs

Reliability: ability to perform as required, without failure, for a given time interval, under given conditions

2.8.4. Classification of Failures

Failures can be categorized according to various dimensions in order to facilitate analysis of the failures. There are a number of published international standards and guidelines to conduct FMEA, The MIL_STD_1629A, Military Standard-Procedures for Performing a Failure Mode Effects and Criticality Analysis standard, AIAG’s, Potential Failure Mode and Effects Analysis, IEC 60812, SAE J1739, Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA), CIGRE.

First employed in the United States Department of Defense to perform FMEA in different military systems, MIL-STD-1629A [24] is the most widely used standard.

Since then it has been used in different industries to perform FMEA and it has evolved through the last 30 years.

The MIL-STD-1629A has a standard to scale for the Severity and Occurrence of failures whereas the Detection of the root causes is not included in this standard.

Table 2.2: Severity of Failure Effect Classification for Power Transformers. *MIL-STD-1629A*

Value	Description	Criteria
1	Category IV (Minor)	primary function can be done but Urgent repair is required.
2	Category III (Marginal)	reduction in ability to perform primary function
3	Category II (Critical)	causes a loss of primary function
4	Category I (Catastrophic)	product becomes inoperative

Table 2.3: Probability of Occurrence of Failures Classification. *MIL-STD-1629A*

Value	Description	Criteria
1	Level E (Extremely unlikely)	a single failure mode probability of occurrence O is less than 0.001, O<0.001
2	Level D (Remote)	a single failure mode probability of occurrence is 0.001 <O<0.01
3	Level C (Occasional)	a single failure mode probability of occurrence is more than 0.01 but less than0.10 (0.01<O<0.1)
4	Level B (Reasonably Probable)	a single failure mode probability of occurrence is more than 0.10 but less than 0.20 (0.1<O<0.2)
5	Level A (Frequent)	a single failure mode probability of occurrence is greater than 0.20 (O>0.2)

Table 2.4: Degree of Detectability for the Failure Causes of Transformers *MIL-STD-1629A*

Evaluation	Interpretation
1	(Almost certain that the problem will be detected)
2	(High probability that the problem will be detected)
3	(Moderate probability that the problem will be detected)
4	(Low probability that the problem will be detected)
5	None/minimal probability that the problem will be detected

Most of the standards have an assigned numerical value for Severity, Occurrence and Detection of failures. While the values of assigned numerical values might differ from one standard to the other, the procedures engaged into doing an FMEA remain the same.

2.8.5. FMEA for power transformers different components

A failure of power transformers in the electric distribution not only reduce reliability of power system but also affects power quality since reliability is one aspect of system quality [25].

FMEA, therefore, is worth considering in power transformers as a single failure in transformers' elements may cause multiple problems in the whole system and blackout that cover wide range of areas. This outage effect coupled with their chance of explosion due to high voltage in contact with oil and their expensiveness make transformers a very important asset in the distribution network [26].

Failure Modes and Effects analysis has been proven to be an effective technique of improving reliability and thus quality, widely used in power grids. FMEA was in particular proposed for power transformers for the significance and economic value that they have within the power grids [17].

Although FMEA analysis can be performed at system, sub system or component level, in any of the case it requires understanding the system model, components and their functions [27].

2.8.6. Failure Analysis of Power Transformers

Power transformers failure modes, failure causes and effects have been classified and defined by previous researchers. This failure information from individual experiences and hypotheses has been developed into general knowledge. Power transformers components failure modes can be classified based on the nature of the failure and the location of the failure. Based on the nature of failure the different failure modes for transformers can be categorized into thermal, dielectric and mechanical types [28].

A research conducted by Bartley and PE concludes that insulation failure was the major cause of transformers failures, however other causes (design, workmanship, materials and unknown) combined account for 65 % of transformer failures. Other causes include oil contamination, overloads, explosion, surge, inadequate O&M,

natural disastors.While this study has not considered age as a primary cause of failure, the faults that follow aging such as reduced dielectric and mechanical strengths and weakened conductor insulation were considered as causes of failure. As the result of these causes the turn to turn-to-turn insulation suffers a dielectric failure or a loose winding clamping pressure that is not able to withstand short circuits. According to the study in the average age of the transformers at failure was 18 [29].

In another research by Uzair, Dissolved Gas Analysis (DGA), has been engaged to estimate the proportion of dissolved gases in the oil sample of power transformers that indicates the condition of the transformers under study. This technique enables to identify various fault conditions and can also suggest preventative measures based on the volume and composition of gases generated from the transformers oil. The oil samples were checked for their colors, density, viscosity, resistivity and the results have been checked against IEC 60599 standards. According to the result, extensive oil deterioration in transformers increases with age, that eventually leading the transformers to failure [30].

In a research carried out to identify transformers components for condition based maintenance in [31] Weibull distribution technique has been used for failure analysis, failure forecasts and aging of 144 failure events in 71 power transformers. The result shows that the critical components leading the transformer to failure being On Load Tap Changer (OLTC) and tank with leakage causes in both of them.

The aforementioned study reflects the importance of knowing the conditions of power transformer components for condition-based maintenance and their statuses have been tracked using electrical tests, insulating oil tests and visual inspection.

Dissolved gas analysis combined with fuzzy expert system has also been proposed in [1] with inputs of thermal failure, C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 and fault definition as the output data. The following figure shows the general structure of the model used in [1].

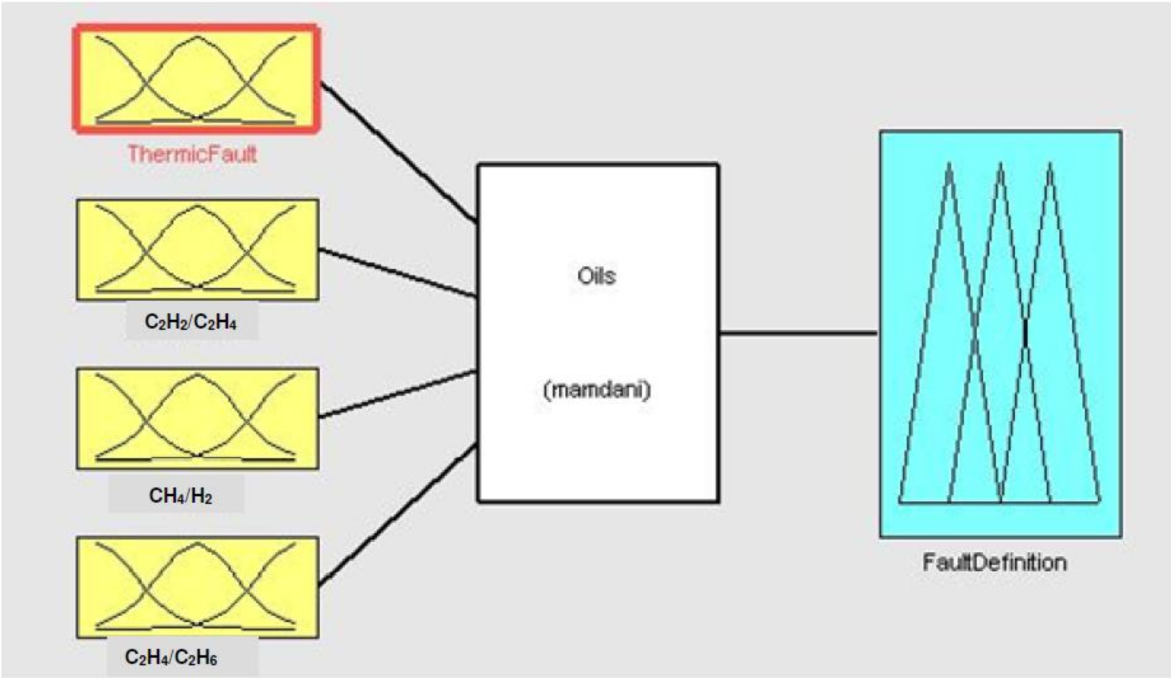

Figure 2.2 Fault Definition in Power Transformers. *Source:N.Pamuk et.al. (2010)*

Table 2.5: Possible Types of Failures against the Volume of Gases Generated

Source: N.Pamuk et.al. (2010)

Failure mode	Definition of failure	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	Partial discharges	<0.01	<0.1	<0.2
D1	Discharges of low energy	>1	0.1 - 0,5	>1
D2	Discharges of high energy	0.6 - 2.5	0.1 - 1	>2
T1	Thermic faults T<300℃	<0.01	>1	<1
T2	Thermic faults 3000℃<T<7000℃	<0.1	>1	1 - 4
T3	Thermic faults T>700℃	<0.2	>1	>4

e

Different gases found during the dissolved gases in oil analysis were used to detect the type of failures in power transformers.

2.9. Common Faults in Medium Voltage Distribution Transformers

2.9.1. Open phase/ phase loss

Open phase is the most recurring fault in medium voltage distribution network transformers. The main causes of open phase faults include loose connection, blown fuse, broken conductors and less integrated circuit breakers. Transformers perform their normal operation in the lower voltage side when an open phase occurs in the primary side until the threshold limit is crossed, it is only when the transformer is overloaded that the protection relay pick up a fault. Open phase condition is relatively hard to detect based on the complexity of core and winding construction and the loading of the transformer [32].

2.9.2. Ground faults

In medium voltage transformers, the reactance decreases for faults heading towards the neutral. The magnitude of the ground fault current therefore increases for those faults close to the neutral compared to faults in the middle of the winding [33].

The following figures adapted from [33] for star and delta connections show how ground fault current increases when the distance of the fault is closer to the neutral.

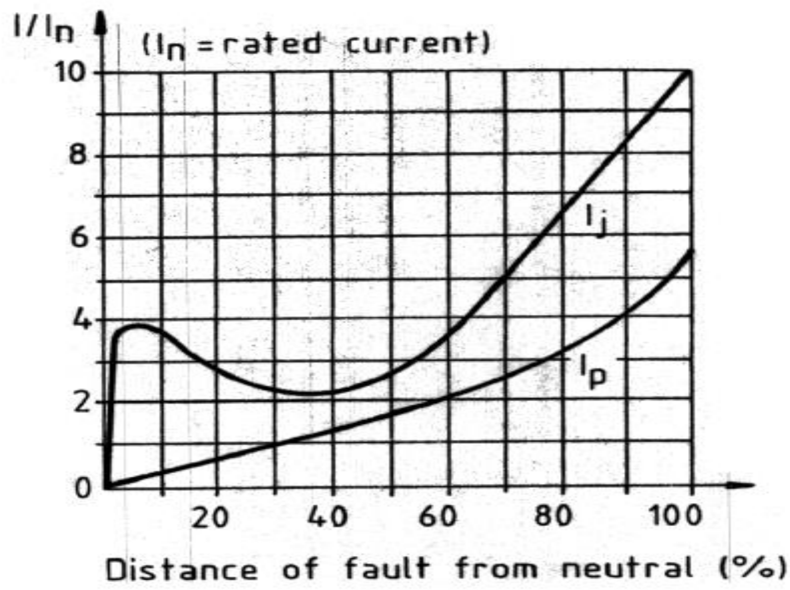

Figure 2.3: Ground Fault Current in a Solidly Grounded Star-connected Winding.

Source: Nylon R. (2006)

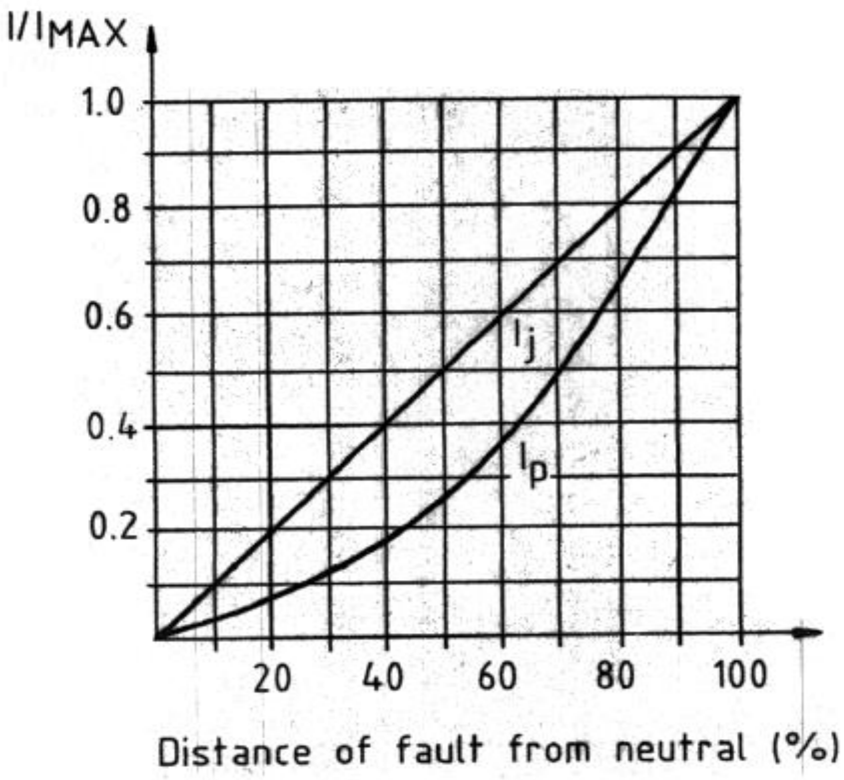

Figure 2.4: Ground fault current in high impedance grounded star-connected winding

Source: Nylon R. (2006)

Ground fault currents short circuits normally arise depending on the transformers grounding level. Low impedance grounded transformers have high ground fault currents. Ground fault currents can be protected by ground over current relays and directional over current relays [34].

2.9.3. Turn to turn faults

Turn to turn faults are very common types of transformer faults that start from mechanical vibration or insulation deterioration from overvoltage. An abnormal distribution of current occurs in the coil during the existence of turn to turn faults. A progressive coil deterioration arises from turn to turn faults that leads to complete transformer failure. Differential protection is recommended for such type of faults [35].

2.10. Causes of Failures in Distribution Transformers

Operation problem related with fuse sequential operation has been referred to contribute 40% of distribution transformers failures in a research followed by lightning, 25%.In the later, even if lightning occurs only 7% of the time, it remained the most common failure cause due to the wide range eventful impact. In addition, lightings occur during the night, when most of the technicians are off duty that limits the visibility to react as soon as possible [7].Though underlying causes may be lightning or fuse operations, the study concludes that most of the failure causes to be current related. The high current from lightning or any source may cause oil arcing, voltage surge and the decomposition of the oil under fault conditions.

Root cause analysis has been engaged to identify Overload and overvoltage have as major causes of distribution transformers failures [36].

Improper Operation and Maintenance can be one of the contributing causes for the failure of transformers. Damage to the insulation happens when transformers operate at high temperature, high voltage or overloaded to the point that they draw high current leading to complete failure of the transformers. Improper operation of the OLTC is also one of the contributing causes for the failure of trasformers.OLTCs should be operated according to the manufacturer's instruction and incase of faults the transformers should be equipped with protective relays and monitors that vary according to the size, rating and voltage level of the transformers [33].

2.11. Power Transformers Protective Devices

Pole mounted transformers are equipped with fuses connected at the primary supply side that serves to limit the number of customers affected by the fault via disconnecting the fault that happens at the high side from transmitting to the lower side. Additionally, fuses interrupt the flow of power to the failed part of the transformer to limit the complete failure of the transformer and injury to people around. The excessive current, that fuses react towards, is usually arise from internal faults in the transformer or less integrity in the insulation system.

While fuses have been used as long standing tools to detect faults happening to transformers, they cannot differentiate high current due internal transformer faults and high current flowing into the transformer due to overload or other reasons [7].

Damage of transformers is directly proportional to the time they become exposed to the fault. Transformers should therefore be equipped with protective relays that limit the damage once faults occur and monitors to detect faults and abnormal conditions as fast as possible. Though the extent of transformers protection varies from manufacturer to manufacturer, the following protective devices are recommended [33].

Long duration outages are mainly associated with failure of bushings, winding insulation systems and On Load Tap Changers. The installation of a monitoring system to warn the condition of these components is quiet essential for the reliability of transformers. A Gas Detector Relay can be used to reduce the risk of failure by monitoring the presence of failure gases in a chamber normally filled with the transformer oil. When failure occurs, undissolved failure gases enter into the chamber and replace the normal transformer oil. If the volume of the gas exceeds the norm, an alarm is activated and also can be used in combination with dissolved gas analysis to diagnose failures [37].

Transformers also require overvoltage and thermal overload protections to protect them from insulating problems caused by high voltage levels and damages caused by thermal overheating [38].

2.12. Power Transformers Diagnosis Tools

2.12.1. Dissolved gas analysis (DGA)

Dissolved Gas Analysis (DGA) is performed by taking samples of oil from a working transformers to receive warning information about existing or developing faults. The DGA results are compared with acceptance limit to decide whether a preventative action is needed or not.

DGA is the most efficient tool to recognize the existence of thermal and electrical modes of failures in transformers. Each failure generates its own unique gas that are dissolved in the oil of transformers. Typical failures that can be recognized with DGA includes partial discharge, oil breakdown and overheating. These failures generally generate methane, ethane, carbon monoxide and carbon dioxide [39, 40].

2.12.2. Sweep frequency analysis (SFA)

SFRA method is a time consuming method to detect the consequences of short-circuit currents, over currents and anything that is possible to damage the winding or magnetic flux of a transformer. The test can be performed without removing the subsystems of a transformer. This method is effective when used immediately after the manufacturing of the transformer to record the initial test values and continuously compare these values in the service life of the transformer. The SFRA method employs vibration sensors to indicate the conditions of the equipment with what the vibration used to be in normal circumstances. The following can be derived from the comparison of vibrations sensors in SFRA: [41]

- Winding movement and deformation
- Short circuit or open winding
- Loose or damaged switching system
- Core movement, wrong grounding
- Core connection problems
- Winding partial breakdown

2.13. Life Time Management of Power Transformers

Life Time Management aims at keeping an asset at fittest level all the times to get the required service from it by performing all the required actions such as: maintenance, rehabilitation, refurbishment, specification and procurement [28].High proportion of costs in electric utilities are mostly associated with maintenance and asset deterioration. The main purpose of life time management in the electric grids is therefore to ensure a reasonable return on investment based on optimal usage of the remaining useful life of asset and having a constant distribution of costs for maintenance throughout its life time. This requires an enormous effort to track the records of individual components in the grid using statistical approach and condition based monitoring. The current health of power transformers and their remaining life can be accurately assessed and tracked using a blend of statistical approach and condition monitoring [4, 42].

2.13.1. Application of Asset management techniques for Power Transformers

Transformers asset management is the most important consideration to take in distribution network management. Transformers are the determining factors for the total reliability of the distribution network. Though there are numerous asset management techniques, maintenance plans and conditions monitoring are the most common asset management activities to consider for power transformers.

A holistic asset management technique including the following activities has been in traduced in [43]

1. Condition monitoring and condition assessment techniques
2. Performing maintenance plans
3. Aging, health and end of life assessments

In a comprehensive asset management technique introduced in [44] stresses on the importance of considering both life cycle costs and quality of the system with in the given requirements and regulation. The research suggests a blend of Condition Based Maintenance, Reliability Centered Maintenance, Corrective Maintenance and Time Based Maintenance as possible asset management strategies.

2.13.2. Power transformers failure prediction and remaining life time models

As discussed in [29] in their previous researches power transformer failures prediction considered age of transformers as the major factor and used models similar with human mortality.

Prediction has been evolved over the years and included variables other than ages such as random events as it is in lightning and collisions

Power transformers, being critical assets in the distribution network, their Failure modes of their components have been well dealt and documented. There are a number of models for modeling failures modes and failure prediction in transformers. An Extreme value theory used to model history of transformer life shown in [45]to predict the probability of failure of one of power transformer components, insulation paper. Using sensor the researchers the researchers studied the degree of polymerization for the whole life of the transformer assuming that the deviation from

the norm or the standard would follow an extreme value distribution. Comparing the model value for DP with a general extreme value distribution generated and subtracts the deviation until DP reaches a point of failure of the transformer. The researcher of the .the work is more of demonstrating the method than applying to real problem as the former DP history of the transformer was not documented and only one factor, insulation paper degradation was taken as possible causes of failure of transformer.
Distribution fitting, probability density function, FMEA have been used by previous researchers.

There is a growing demand for criteria or tools to model remaining useful life (RUL) of power transformers in order to prioritize refurbishment, repair and replacement [4].Though RUL prediction is full of uncertainty, introduced Bayesian particle filtering to model the inherent uncertainty in predicting future asset health. The study introduced probabilistic model to study the aging rate of paper for varying loading and temperature of 180MVA, 275/132KV exampled transmission transformer. The study considered the initial DP of the paper, the exact temperature and load through a probabilistic modeling approach as shown in the following equation which otherwise overlooked in deterministic approach.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Research Design

The method engaged in this work applies Failure Modes and Effects Analysis (FMEA) combined with Analytical Hierarchy Process (AHP) for 1322 power transformers prominent failures under the study. The FMEA presented in this work begins with identifying modes of failures, revealing underlying causes of the failure modes and proposing appropriate remedial measures. In this respect, the FMEA study forms the background to focus on recurring failures or components that have most significance for the reliability of transformers. The FMEA also creates the background for future studies to select transformers to consider for their remaining useful life (RUL) prediction.

The work presented in this study is unique as EEU maintenance staff feedback has been included as subject matter expert feedback into the Analytical Hierarchy Process (AHP). The FMEA serves to identify the most severe, recurring and hard to detect failures according to EEU maintenance staff opinion. In this case the staff opinion serves to emphasize in finding remedial measures and keep the focus of the work on failures that have strong link with the reliability of power transformers instead of acting upon each and every failures regardless of their relevance. In this work, the FMEA will also serve as a basis to determine the Remaining Useful Life (RUL) of transformers by identifying normal age related failures, should age related data be recorded in the future.

The FMEA presented in this work adapts the procedure described in [24].

- Identify modes of failures
- Identify consequences and related systems for each mode
- Rate the severity (S) of each effect
- Identify potential root causes for each failure modes
- Rate the probability of occurrence (O) of each root causes

- Identify process controls and indicators as a way of mitigating the risks and inform the operators what need to be done
- Rate Detectability (D) of each mode/root cause
- Calculate the Risk Priority Number (S*O*D)
- Use design to mitigate high-risk or highly critical failure, and re-assess to ensure goals have been achieved.

3.2. Data Collection

Primary and secondary data have been collected from Ethiopian Electric Utility. Failure histories of 1322 prominent distribution transformers failures have been gathered from years 2013 to 2016 from EEU monthly and annual reports, traditional failure registers and the history of repaired power transformers from EEU maintenance department.

3.3. Questionnaire

Questionnaire distributed to EEU maintenance staff has been used to have a baseline for the development of FMEA worksheet and Risk Priority Numbers (RPNs) setting. The questionnaire in particular assesses the consequences of failures in terms of electric power interruption, loss of component (damage of the affected component or its contribution to the further damage of subsequent sub systems).

The questionnaire also assesses the frequency of failures and degree of detection of the root causes once failures occur. (Annex-01 Questionnaire)

Failures have been also evaluated against suppliers, region, age, component and reasons of failure.

3.4. Interviews

Unstructured interviews have been used to assess the existing working procedures and workmanship in EEU in relation with distribution transformers. Field Engineers, Foremen and Unit Heads have participated in interviewing issues directly linked with distribution transformers procurement, handling, maintenance and power sharing operations. After the conclusion of the conventional FMEA analysis further interviews have been conducted to selected subject matter experts to assist in doing Analytical Hierarchy Process (AHP) for failure causes with similar Risk Priority Numbers (RPNs).

3.5. FMEA Worksheet

One of the outputs of the study, FMEA worksheet, has been used to summarize all the failures under study with the following data included:

- Component
- Failure mode
- Failure Category
- Failure Cause
- Failure Effect /consequence
- Controls
- Severity of effect/consequence
- Probability of occurrence
- Detection of the root cause
- RPN
- Remedies
- New RPN assigned after remedial measures

3.6. Risk Priority Number (RPN)

The result of the questionnaire distributed to EEU maintenance staff has been used as input to base Risk Priority Numbers (RPNs) calculation .Therefore the RPNs for each failure modes have been calculated by incorporating questionnaire inputs and conventional FMEA steps.

RPNs have been calculated as a product of Severity of consequence (S), probability of occurrence (O) and Detection (D). While the RPN for most of the identified failure modes have been calculated, the failures chosen for further analysis were those failure modes with the highest value of severity, highest probability of occurrence and lowest detection values.

The selection of component or failure for further analysis also depends on the feedback of EEU maintenance staff.

3.7. Failure Categories

The research work combines MIL-STD-1629A [24] standard and maintenance staff opinion as traced from the questionnaire to rate the severity and probability of occurrence of failures.

For the ease of identifying the weak links in power transformers, the research employs further classifications of failures by location, by age, by cause, by modes of failure and by manufacturers.

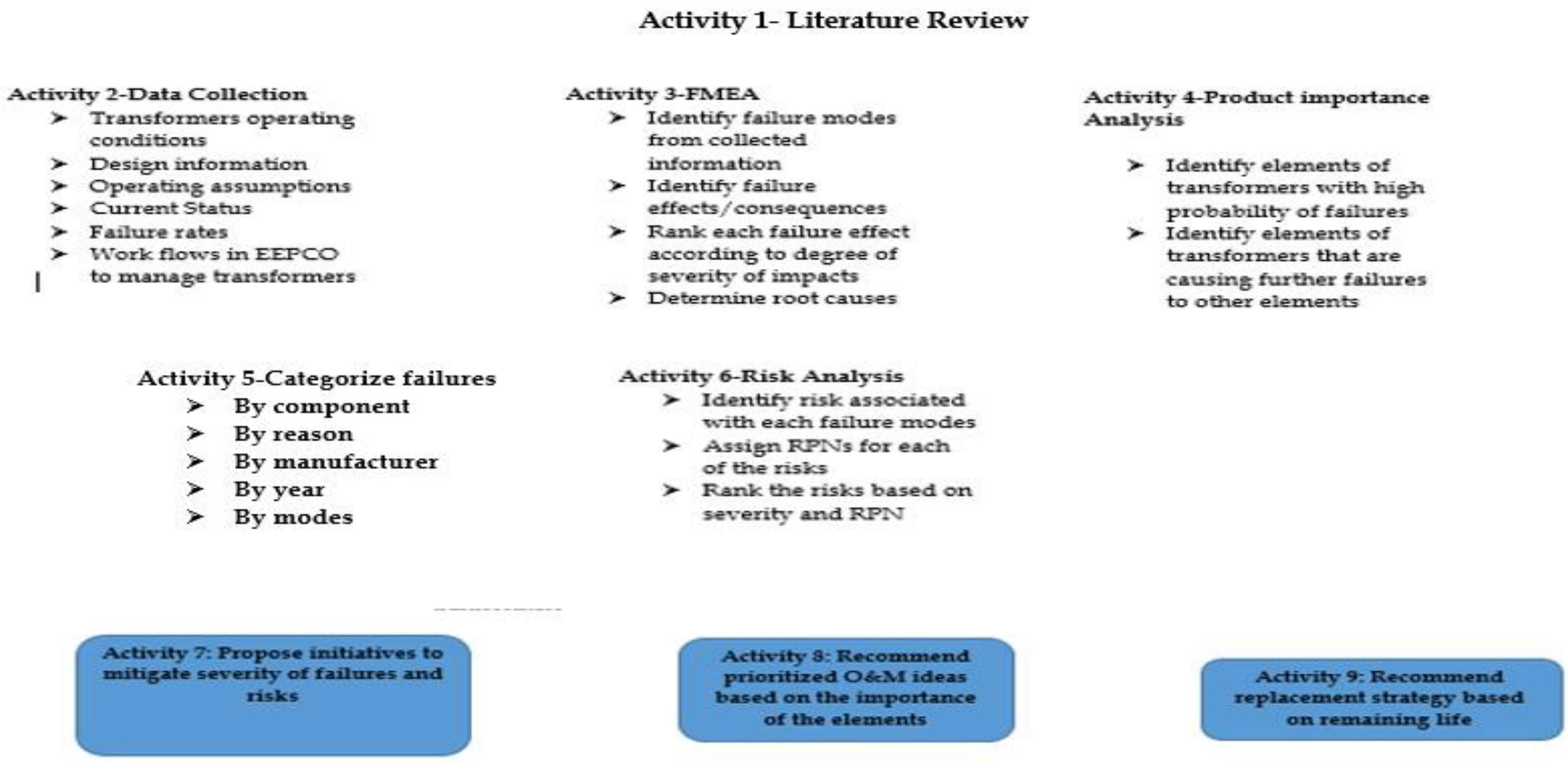

Figure 3.1: Research Methodology

CHAPTER FOUR

DATA COLLECTION AND ANALYSIS

4.1. Introduction

Electric power generation and supply in Ethiopia is solely governed by two integrated state owned organizations. These two institutions have been operating as a unique entity for the generation, transmission and distribution of electricity for many years. From recent years, however, the operation has been segregated as Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU) for improved quality, service delivery and uninterrupted supply of electricity.

Ethiopian Electric Power (EEP) is responsible for the generation of electricity as well as the management of transformers with more than 132KV voltage levels. The Ethiopian Electric Utility (EEU) is responsible for the power construction for the supply of electricity to customers based on their requests and the management of distribution networks including step-down transformers with less than 132KV.

While the independent operation of the institutions was expected to address the outstanding power issues in the country, frequent power interruption remained a concern afterwards. Following the segregation of the institutions, a foreign company had been hired to manage EEU to share internationally acceptable experiences, to implement automated system, to address the issue of power interruption in a better strategy based on researches.

4.2. Geographical Location

EEU manages the operation of distribution transformers through its 15 regions in Ethiopia. Four of the regions are located in the capital city Addis Ababa and the rest 11 are dispersed in towns in Ethiopia. The figure below shows the location and the name of the regions according to EEU naming style. Each region has its own service center for the mounting of power transformers, rehabilitation and preventive maintenance works. A central workshop in Addis Ababa supports the regions in the capital city and the other regions in the supply and procurement of the necessary materials.

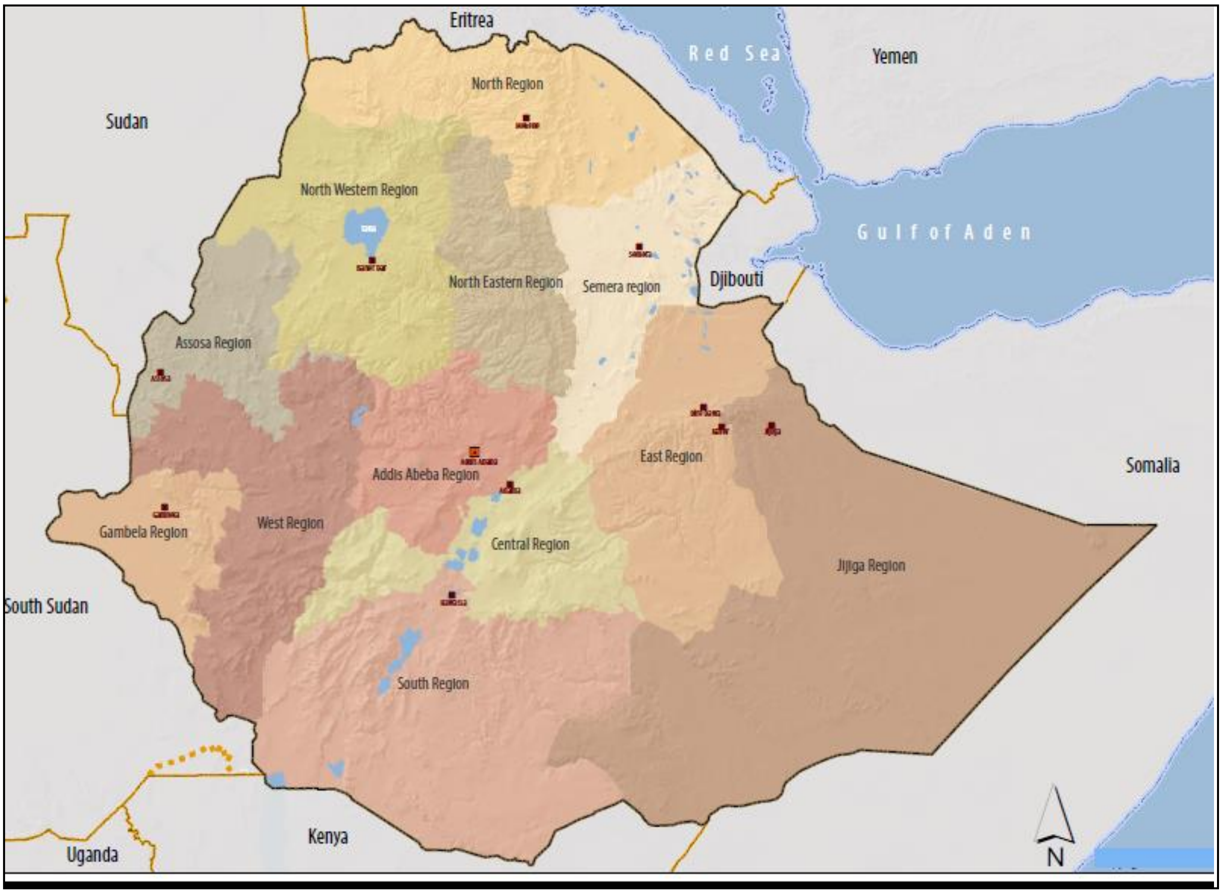

Figure 4.1: Geographical location of Regions under EEU Management. *Source: Tesfay Gebrehiwot (2017)*

4.3. Manpower

Ethiopian Electric Utility (EEU) maintenance staff receive trainings on the procedures of distribution network repair and replacement in a centralized training center located in Addis Ababa, Kotebe. When new hires join the organization, trainings are organized on the basics of distribution network construction, phase balancing and load checking in transformers.

The maintenance department is composed of Engineering Unit, Emergency Unit, Switch Gear Case Team and Workshop Unit .The Emergency Unit takes the lead to respond to customer calls related with transformer problems and unacceptable load check results. When the problems become more complex to get solved in the level of the Emergency Unit, they will be sent out to the Switch Gear unit or Workshop Unit for further analysis. The Engineering Team is responsible for the feasibility study and implementation of new power rehabilitation programs.

4.4. Supplier

The existing distribution transformers are supplied from different manufacturers. The relatively aged transformers belong to Stromberg, ABB, NEC and Pauwels and the recently installed include METEC transformers (a national state owned manufacturer) and the rest from India and China.

Recently, METEC has become the sole supplier of transformers following the government strategy to encourage local manufacturers and issues related with foreign exchanges.

4.5. Distribution Network Maintenance in EEU

Maintenance work pertaining to distribution network generally consists of Preventive or Scheduled maintenance and Emergency Maintenance in case of sudden faults and consumers compliant.

4.5.1. Distribution network preventive maintenance (DNPM)

DNPM signifies the periodical work including operational and any other testing on a piece of network equipment for its suitability in service and to maintain it in proper working condition. It is scheduled on the basis of data obtained through inspection and maintenance checks by giving priority to the troubles threatening normal operation of the line/equipment.

It also signifies maintenance of the distribution network involving major disassembly of the network equipment. It is scheduled on the basis of normal life expectancy of the equipment or when the need arises on the basis of data obtained through inspection and maintenance checks.

Following “Inspection”, there are two important actions, namely “Reporting” & “Rectification”. Any defects observed during the inspection are rectified within the shortest possible time in order to avoid its development into a major fault. In any case, the observations of inspection are recorded and reported in a suitable form for follow-up action.

For this purpose, formats of “Inspection Reports” for medium voltage network, Distribution transformers and Low voltage networks of the distribution system have been developed. The formats are easy to fill up and to get interpreted by the workers in the team that undertake the inspection & preventive maintenance works.

These formats have been used by the distribution teams since the implementation of Business Process Reengineering (BPR) in the utility. (Annex-04. Distribution Transformers Inspection Sheet)

While inspecting the distribution network, the inspection team technicians put a remark that states whether immediate attention (IA) is required or it can await the periodic preventive maintenance. For those network parts which need immediate attention (IA), the problems would be rectified or the network part would be repaired immediately.

Such inspection reports are prepared by the workers participating in the network inspection task and submitted to the Team Chief Officer/Manager. The Team Chief Officer keeps a continuous check to ensure that rectifications are being carried according to the Inspection Reports submitted to him.

For those defects observed during inspection which could wait till periodic preventive maintenance based on the inspection findings the following tasks would be performed:

- ✓ Identify the network parts to be maintained
- ✓ Prepare detail sketches of the network with pole numbers and references (Local areas)
- ✓ Prepare work Authorizations and get approval from Team Chief Officers/Managers
- ✓ Plan/scope the work and prepare interruption programs
- ✓ Move materials to site
- ✓ Perform the preventive maintenance work

4.5.2. Check inspection

These include the inspections carried out by the engineers-in charge of distribution network preventive maintenance as a check on the conditions of line and the efficiency of the involved staff and to point out the defects which could not be noticed by the staff in the first instance.

Check Inspection is one of the preventive maintenance activities in the distribution network. The minor defects noticed during inspection would be rectified at the time of inspection itself wherever possible, and the other defects at the earliest possible time after scheduling a program in advance. However Manufacturer's instruction is always given less due consideration while carrying out the particular maintenance on particular equipment.

Distribution network inspection is carried out by the district inspection group assigned by the Technical Section Head or by the District Foreman when applicable.

The need of inspection of Distribution Network Equipment (DNE) is determined by the increase of complaints or the failure rate of the feeders based on the reports from the operation personnel or the latest inspection result of the distribution network.

Distribution Network Component	Inspection Activity
Distribution Transformers and Accessories	• Oil levels are at normal value • Temperature rise of oil is beyond permitted value • Thermometer glass is broken • Unusual noise are heard • Bushing arc horn gaps are misaligned • Silica jel changes its normal color • Silica jel glass is broken • Lightning arrestor is cracked or damaged • Ground connections of arrestor ,neutral and transformer bodies are in normal condition • The insulation resistance is below the permitted value • The earth resistance at the grounding point of transformer is

at acceptable value

- Fuse rating (HT & LT sides) are as per standard The position (height) of distribution box is as per the standard
- Oil leakage is observed
- Bolts, nuts & cable lugs are damaged or burnt
- H.T side terminals are burnt or damaged
- Supports (poles, cross-arms and stays) are in good condition
- Tap changer position is appropriate
- Radiator damage is observed

Poles	Inspect for: ▪ support needed ▪ damaged ▪ pole cap condition ▪ tilted
Insulators	Inspect for: ▪ accumulation of dust ▪ Unscrewed ▪ Cracked

- Chipped or broken

Cross Arm

Inspect for:

- Tiled
- Rusted
- Loose, broken or missing braces

Wires

Inspect for:

- Broken strands
- Twisted wires
- Side trimming
- Sag & tension adjustment
- Loose connection
- Burned wires
- Burned jumpers

Clamps

Inspect for:

- Corrosion
- Damage
- Loose connection

Anchor and Guys

- Loose connections
- Condition of guy anchoring
- Broken or chipped guy insulators

Hooks	• Tilted • Loose • Corrosion
Disconnections	• Defective switch • Cracked/broken insulators • Burned blades • Damaged arcing contacts
Underground terminals	• Bolt & nuts are loose • Oil levels are at normal value • Cracking of load • Burnt terminals Damaged gaskets
circuit breakers & accessories	• The need of general cleaning • Oil condition • Loose or damaged or burnt relay terminals • Inappropriate load setting • Burnt or overheated contacts

- The need mechanism adjustment
- Normal conditions of CT's & PT's connections

4.5.3. Preventive maintenance plan

The inspection group leader prepares a sketch of the area of the place that is due for PM based on the result of the inspection. The sketch includes the sub city, kebele, industries, buildings or other important signposts, material requirements and labor cost. The inspection team leader submits the report to the District Manager for approval and the District Manager sends the work to District Technical Section or to the foreman for execution.

4.5.4. Preventive Maintenance Schedule

The work unit prepares maintenance schedule and get approval of the District Foreman. The approved maintenance schedule is submitted to Regional Director, Regional Distribution Office and Regional Operation Division. An interruption schedule, an exchange of information and notification is prepared and is sent out to Regional Director, Regional Distribution Office and Regional Operation Division for approving. The interruption schedule includes

- Reason for interruption
- Feeder (s) code to be interrupted
- Areas affected due to interruption
- Employee (s) responsible during maintenance
- Additional remarks (if necessary)
- Duration of interruption

- The estimated unsold electrical energy cost

PM Tasks on Distribution Transformer

- Check oil level and top up if required
- Based on the inspection result (if the temperature value of oil is Unacceptable) and load check record upgrade the transformer or share the load to the nearest existing transformer or erect new transformer.
- Avoid unusual noise
- Align bushing arc horn gaps
- Dry the silica jell breather of the transformer until its color changes from pink to blue.
- Replace the silica jell container glass if it is found broken
- Replace damaged lightning arresters
- If the insulation resistance of a transformer is unacceptable it is dehydrated. i.e. put through a drying out process .after the drying out process is complete the transformer will be allowed to cool to ambient temperature. Then the insulation resistance is measured again.

PM Tasks on Poles

- Erect supporting poles
- Replace decayed poles
- Set right tilted poles
- Replaced damaged poles

PM Tasks on Insulators

- Replace damaged insulators
- Set right tilted insulators
- Clean dirty insulators

- Checked and replace broken insulators

PM Tasks on Cross arms

- Set right tilted cross arms
- Brush or rusted cross arms
- Tight or replace loose, broken or missing braces

PM Tasks on Wires

- Repair broken strands by providing repair sleeves.
- Adjust span sag in accordance with the norm of EEPCO.
- Trees or branches coming close to the wires (lines) should be trimmed according to the norm of EEPCO.
- Replace burnt wires and jumpers
- Tight loose connections.

PM Tasks on Clamps

- Replace or brush corrosive clamps
- Replace damaged clamps

PM Tasks on Anchor & guys

- Tight loose guys
- Replace broken guy insulators
- Guy anchoring should be filled with earth and improved

PM Tasks on Hooks

- Tight loose hooks
- Brush or replace corroded hooks

PM Tasks on Disconnections

- Repair or replace defective switches
- Replace burned blades
- Brush or replace damaged arcing contacts.

PM Tasks on Underground cable terminals

- Tight loose bolt and nuts
- Check oil level and top up if required
- Solder cracked leads
- Repair or replace burnt terminals
- Replaced damaged gaskets

4.5.5. Commissioning of Distribution Network and Power Restoration

After the completion of the maintenance work commissioning of lines is conducted before power restoration. The network is checked whether all planned maintenance has been done according to the sketches prepared. Visual inspection is also conducted to check that the line is free of human and other contacts before disconnecting the ground set. At the completion of the work, power is restored on the medium voltage side followed by on LV side.

4.5.6. Job Completion Report

Job completion report is prepared by the work group engaged in the maintenance activity and is approved by the Technical Section Head. The job completion report is submitted to regional accountant office, Regional Distribution Office and to the District Manager.

The job completion report includes the following:-

- General information about the preventive maintenance job activity starting from inspection to commissioning of lines
- New material received
- New material returned
- Old material returned
- Date of work started
- Estimation date of work completion

- Date of work completed
- Cost of unsold electrical energy during interruption
- Maintenance cost

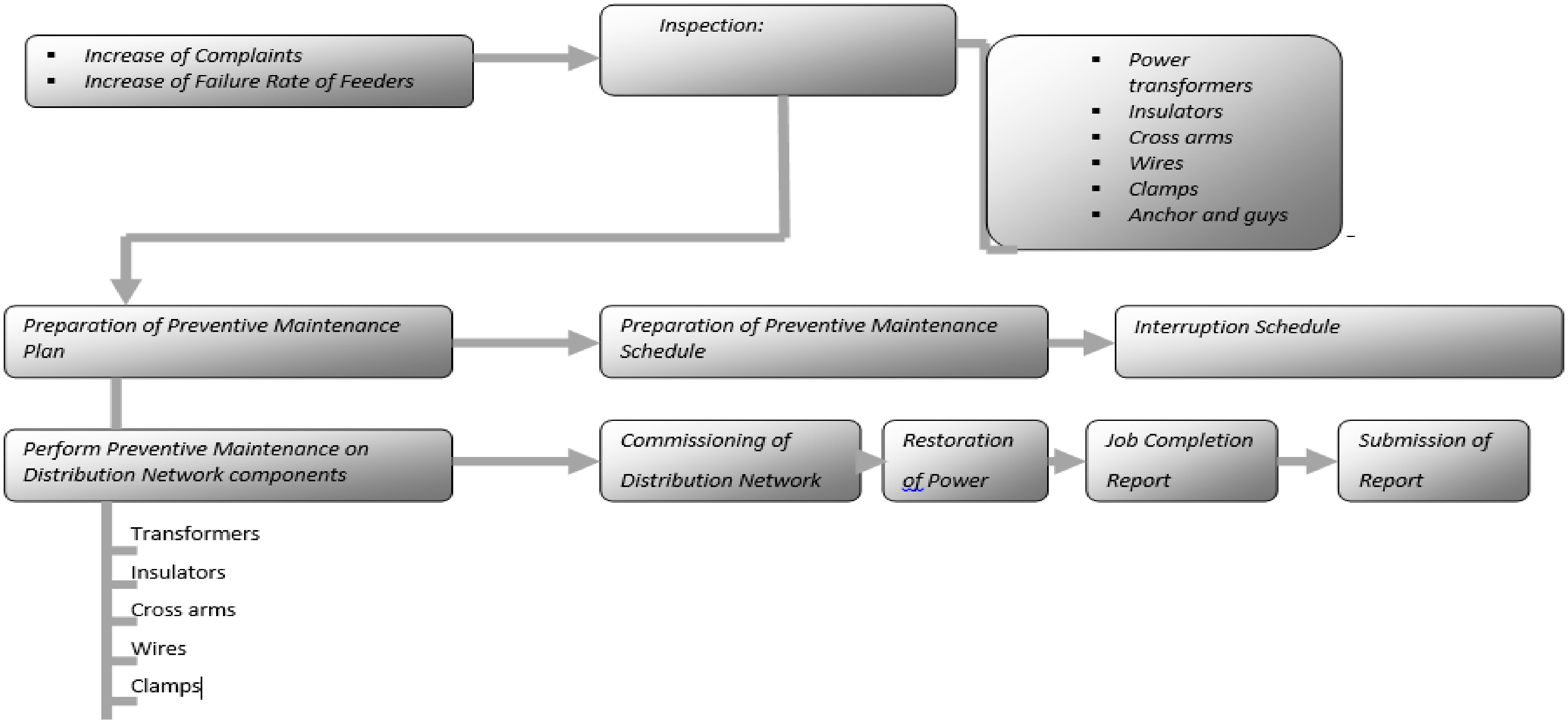

Figure 4.2: EEU Distribution Network Preventive Maintenance (DNPM) Work Flow: *Source: EEU*

4.5.7. Fault clearing activities on distribution transformers in EEU

Fault Reports are submitted to Emergency Unit or to the Section Service Crew or the Technical Section by radio communication, telephone or direct contact .The faults could be reported by the primary substation operators, other staff or the customer.

The supervisor or the crew leader sends the fault finding and clearing crew to the location of the faulty distribution transformer to commence the fault finding process. The fault finding process starts with opening the low voltage fuse and then the medium voltage 15 or 33 KV links respectively.

The next step is to check if liquid fuses or fuse links are blown to identify the faulty Phases. The Search continues for possible faults on the transformer and its accessories. The technicians use visual inspection to low voltage fuse boxes, low voltage cables followed by various tests on the transformer.

After the fault is identified the next step is to continue the work to clear the fault on the faulty components and perform the necessary repairs.

On the completion of the repair work, the crew leader or the supervisor checks, if the transformer and its accessories are free from human and other contact to close the 15 or 33 KV drop out fuse & low voltage fuse boxes respectively.

A report with the following data is prepared by the crew leader and get approved by the supervisor and submitted to district or service center heads and to the emergency service unit.

- Type of fault
- Remedy taken to clear the fault
- Total time taken to clear the fault
- Material used to clear the fault
- Cost incurred to clear the fault

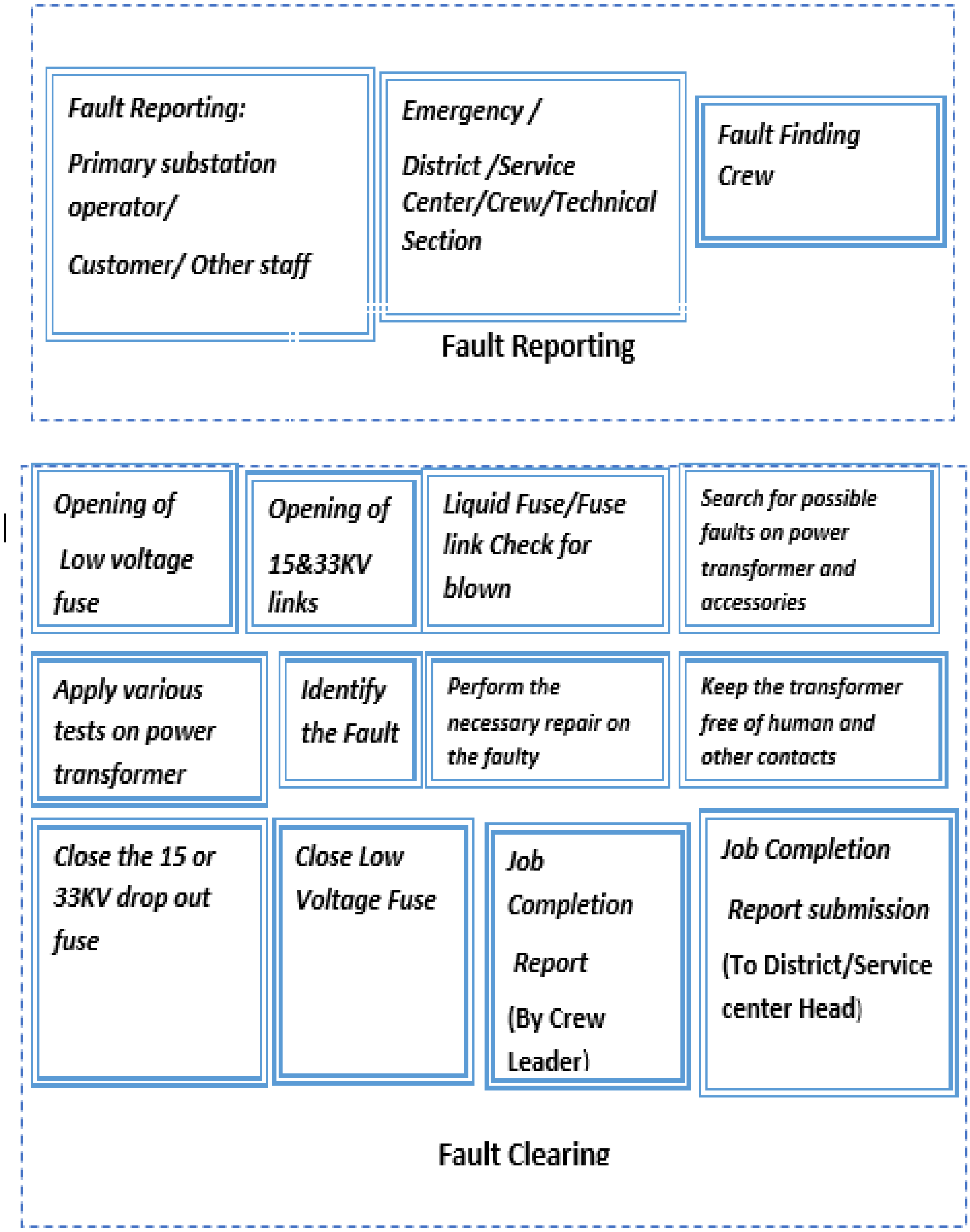

Figure 4.3: Fault Finding and Clearing Activities in Distribution Network in EEU. *Source: EEU*

4.5.8. Load Transferring/Sharing Operation Activities of Distribution Network

Load transferring/Sharing is considered in EEU when there is mechanical damage of wires, poles, accessories and transformers, overload of transformers, short circuit or earth faults and PM schedules.

4.5.9. Load Transferring/Sharing Operation Activities of Medium Voltage network (33 & 15 KV)

The supervisor or crew leader prepares a map or sketch that shows clearly the load transfer/sharing operations and gets the approval of the Technical Head of the District Manager when applicable. The sketch indicates the configuration of the network before and after load transferring /sharing operations.

The supervisor or crew leader checks the load condition of feeder lines and primary substations which are supposed to supply additional load, whether they are capable to handle the new additional load.

During load transfer & interruption there will be status change of switching devises from open position to close position or vice versa. Switching devices include links, load breaker switches, circuit breakers or disconnectors. Therefore the supervisor prepares operation sequence of those switching devices. (The load transferring operation is communicated by concerned work unit through radio or telephone to the different work units in load transferring/sharing operations.

After disconnecting power supply from primary substation through opening circuit breakers by the substation operator, the supervisor or crew leader supervises the closing and opening of disconnections as per the operation sequence that has been prepared for the load transferring/sharing purpose. Once the desired status of the disconnections is achieved for the load transferring/sharing purpose, circuit breakers which were opened only for the purpose of closing & opening operations of disconnections will be closed. (Annex-03 EEU Load Transferring /Sharing Operations)

After the completion of preventive maintenance or clearing faults or replacement of defective components of the line, the network configuration will be brought back to the original status.

Here closing & opening of section switches is performed after opening of circuit breakers at primary substation and a reliable communication among concerned work units.

Load transferring/sharing operations report is prepared by three crew leaders to be approved by the supervisor. The report is to be submitted to the regional operation division, to the regional distribution office, to district technical section, the emergency unit and other concerned work units. The following data is included in the job completion report.

Reasons of load transferring

- The load before and after load transferring/sharing of the feeders and substations which take part in load transferring/sharing operations.
- The duration of load transferring/sharing

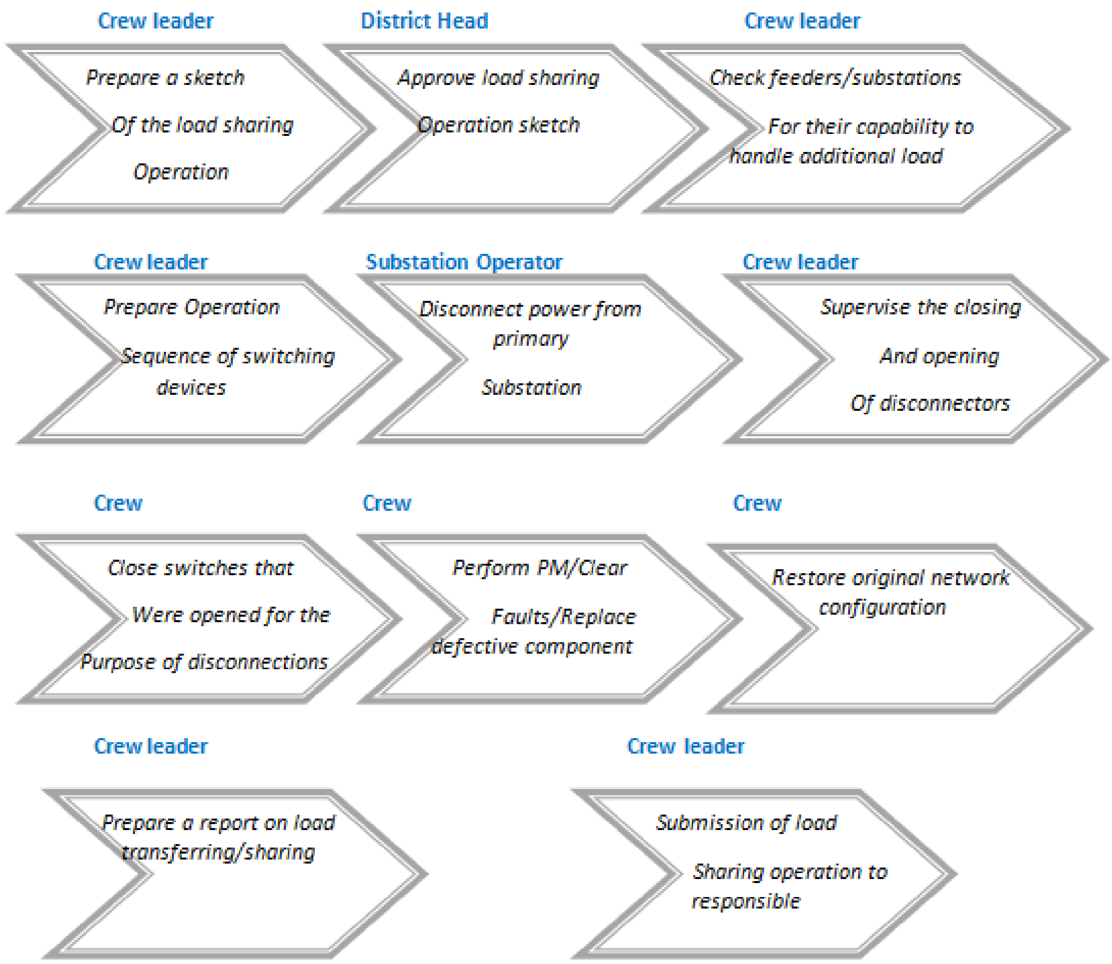

Figure 4.4: EEU Load Transferring/Sharing Operation Activities of Medium Voltage Network. *Source: EEU*

4.5.10. Load Transferring/Sharing Operation of Low Voltage Network (380/220V)

As it is with the medium voltage network, the supervisor prepares a map that indicates the configuration of the network before and after load transferring/sharing operations. The supervisor or crew leader shall get approval for the load transferring/sharing from the technical head of the district.

The sketch includes distribution transformer, section switches with their status and other network components.

The supervisor or crew leader checks the load condition of those low voltage feeders and distribution transformers which are supposed to supply additional load, whether they are capable to handle the additional load.

During load transfer & interruption there will be status change of switching devices from open Position to close position or vice versa. The switching devices could be section switches and/or HRC fuse boxes. Therefore, supervisor prepares an operation sequence for the switching devices that include Operation sequence, Status of switching and Reason of status change.

Closing and opening of section switches is performed after disconnecting power supply from distribution transformers by opening HRC fuses boxes. If the section switches are on-load section switches it may not be necessary to open HRC fuses from the distribution transformer during closing and opening of section switches. After the appropriate status of the section switches is achieved for the load transferring/sharing purpose, those HRC fuses which were opened only for the purpose of closing & opening operation of section switches get closed. (Annex-02-EEU Operation Sequence Form)

Upon completion of preventive maintenance or clearing faults or replacement of defective component of the line, the network configuration would be brought back to the former status. Closing & opening of section switches is performed after opening of HRC fuses at the low voltage side of distribution transformers.

A report on load transferring/sharing operations, prepared by three crew leaders and approved by the supervisor would be submitted to the technical section, the emergency unit and other concerned work units. The report includes the following data.

- Reasons of load transferring/sharing
- The loads before and after load transferring/sharing of the feeders and transformer which take part in load transferring/sharing operations.
- The duration of load transferring/sharing

4.6. Prominent Failures

For the purpose of this research only 1322 prominent failures have been considered out of 4525 total failures from the year 2013 to 2016 recorded in step down distribution transformers in Ethiopia. The population covers all prominent failure in the mentioned period for all the 15 regions in Ethiopia under the supervision of EEU.

Prominent failures in this research apply for all failures that required the transformer to be removed from its normal operation and have repair lead times of more than 18 days and also transformers that could not be able to serve their normal duty once they failed. Though the other 3203 transformers had also failed in their life time, they are not considered as prominent failures as they had not required the transformers to get removed from their normal operation or if removed, the transformers were mounted back within few days of repair lead times.

Transformers are brought to normal operation through maintenance, repair, upgrade or replacement of their components unless they have inherent problems related with design, assembly or factory defects.

All the transformers covered in this research have voltage levels of 15&33KV and their capacity ranges from 10-315KVA. The transformers are mainly used in public, residential areas, schools and health facilities. (Annex: 05 Sample Failure Database)

The following table shows the total population of failed transformers considered in this research work.

Table 4.1: Total Population of Failed Transformers

Transformer Rating (KVA)	No of Prominent Failures
10-30	61
50-75	439
100-150	439
200-315	383
Total	1322

4.7. EEU Staff Understanding about Failure of Transformers

Data have been collected through questionnaire that has been designed to include EEU maintenance staff opinion in addition to the MIL standard employed in this study to perform FMEA analysis.(Annex:01-Questionnaire)

The questionnaire had the objective to assess EEU maintenance staff opinion on the severity of consequences, probability of occurrence of failures and the detectability of failure of major subsystems of distribution transformers and to rate their opinions from scales 1 to 5 .Though these parameters are clearly stated in MIL standard engaged the questionnaire has been used only as an adjunct.

According to EEU failed distribution transformers repair procedures, a customer would call through 905 free customer service call or the problem would be recognized during technician checks.

Then according to the severity of the problem it may be send from any one of the regions to emergency case team or maintenance case team or switch gear case team or transformers workshop.

While the sampling avoids the rest of the maintenance staff, the questionnaire was distributed to either the maintenance personnel in the switch gear unit or in the transformers workshop. Switch gear case team and transformer workshop employees are chosen for the researcher believes that their judgment represents all the maintenance staff in all the regions since any severe problem in relation to distribution transformers is addressed by these technician or else remain unaddressed should it come beyond their capacity.

Therefore, this study engages Non-probabilistic judgmental sampling method for selecting respondents based on the nature of the population and the purpose of the questionnaire.

From 40 questionnaires distributed to switch gear unit and transformers workshop staff 34 of them have been returned.

Accordingly 72% of respondents strongly agree that winding failure causes entire failure of distribution transformers, 68% strongly agree that failure of the core has severe consequences and also causes further failure of other components of the transformer.

From the questionnaire OLTC and Tank failure are responded with the lowest severity rating and not causing further damage to other sub-systems.

CHAPTER FIVE

SUMMARY OF FINDINGS AND DISCUSSION

5.1 Failure Rate

The failure rate for 4525 total number of transformers is 6% on average. The following table shows the failure rate for 15 regions all over Ethiopia for the period under consideration.

Table 5.1: Failure Rate of Distribution Transformers from year 2013 to 2016

Region	2013			2014			2015			2016		
	Transformers in service	Failures	Failure rate %	Transformers in service	Failures	Failure rate %	Transformers in service	Failures	Failure rate %	Transformers in service	Failures	Failure rate %
A.A	5252	348	6.6	5777	337	5.8	5200	391	7.5	5600	331	5.9
Central	1942	127	6.5	2130	256	12.0	2100	226	10.8	1920	227	11.8
North	1670	153	9.2	1838	58	3.2	2100	26	1.2	2018	47	2.3
Semera	268	49	18.3	295	48	16.3	324	6	1.9	348	20	5.7
South	2067	265	12.8	2273	45	2.0	2274	247	10.9	2262	22	1.0
Western	898	159	17.7	988	129	13.1	980	139	14.2	1002	11	1.1
Eastern	994	110	11.1	1094	115	10.5	1094	38	3.5	1090	30	2.8
Asosa	344	98	28.5	378	35	9.3	373	33	8.8	412	42	10.2
Gambela	262	54	20.6	290	21	7.2	290	15	5.2	312	6	1.9
Jijiga	189	49	25.9	566	208	36.7	560	22	3.9	560	20	3.6
North Eastern	1129	125	11.1	1242	136	11.0	1248	130	10.4	1290	98	7.6
North Western	2275	248	10.9	2502	183	7.3	2528	129	5.1	2590	124	4.8
Total	17290	574	3.3	19373	1571	8.1	19071	1402	7.4	19404	978	5.0

5.2 Failure by Rating

50KVA & 100KVA with 33% and 200KVA with 19% contribute for the highest share of failures from the failed transformers under consideration. At present EEU is continuously replacing the 10, 63, 75 KVA rating transformers with 50,100 and 315KVA transformers when they fail, thus the few percentage by rating. These failures from 10,63,75 KVA transformers also contribute for the number of population for prominent failures in this study as they were unlikely to get repaired and restored to serve their normal functions.

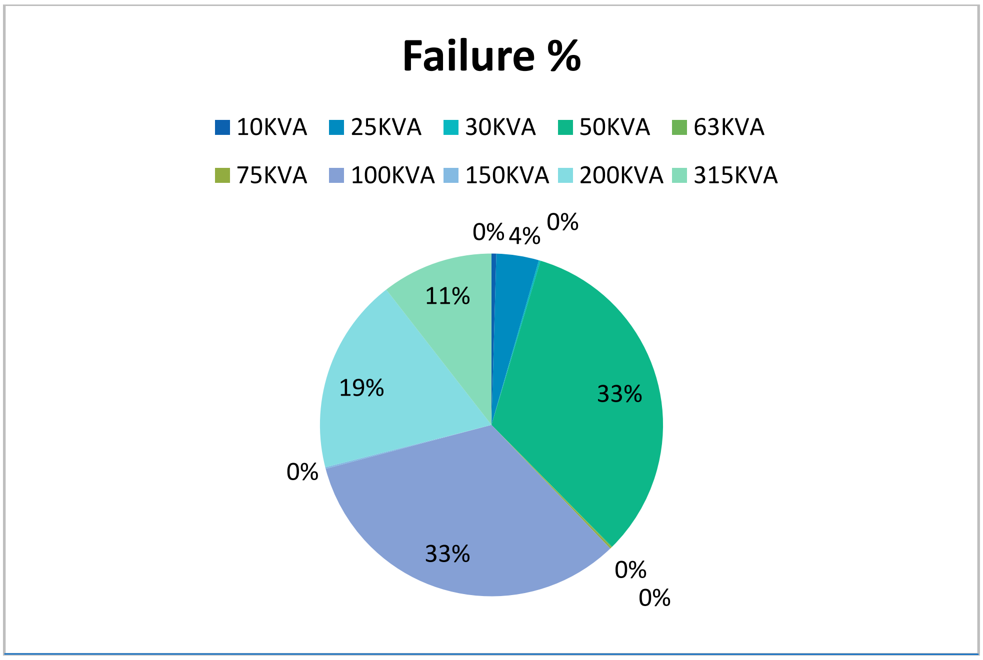

Figure 5.1: Failure Percentage by the failed transformers rating

5.3 Failure by Reason of Failure

Distribution transformers failure database has been further analyzed based on failure reasons. Fig 4.6 shows the failure reasons for all prominent failures. Lightning constitutes the most frequent failure reason with 202 number of

Failures followed by overload and heavy wind with 146 and 108 registered failures respectively.

Comparison of the reasons of failures against the date the failure happened shows that, one of the top three registered failure reasons, lightning, has been mentioned many times in Ethiopian winter season as well as dry season. This undermines the reliability of the data to draw such conclusion as lightning was the main reason of distribution transformers failures in Ethiopia. These types of cases should be analyzed with care by incorporating reasonable assumptions. Lightning mentioned in the failure data base might have been confused with other failure reasons such as external short circuit or winding failures for those failure dates that fall in Ethiopian dry season. Therefore, the failure data base has been further analyzed assuming that all failure reasons that were registered as lightning in Ethiopian dry season have been replaced with external short circuit or winding failures. And failure reasons registered as lightning in Ethiopian winter season have been taken as they were.

Likewise failure reasons associated with heavy wind have been checked against the regions in Ethiopia under considerations. Accordingly, 93% of the registered failure reasons as heavy wind lie in the northern region of Ethiopia that proves the credibility of the failure database.

Figure 5.2: Distribution Transformers Failure Reasons

5.4 Failure by Year

The number of prominent failures in distribution transformers increased from 298 in the year 2013 to 513 in the year 2014. This figure seems quiet proportional compared to the 17,290 number of transformers in service in the year 2013 compared to what it was in 2014, 19,373.While the number of distribution transformers in the beginning of year 2015 was almost the same as it was in 2014, the prominent failures for the year have been reduced. The possible reason for this could be most of the registered failures in the year 2015 were replaced or upgraded and restored to their normal conditions within few days repair lead time. From the collected information, the number of failed transformers with 10,63 and 75KVA were few and this limited their contribution for the overall number of prominent failures in the year 2015.The year 2016 number of prominent failures is few compared to the previous years covered in the study. The possible reason could be the research work was conducted in the middle of the year 2016, before the conclusion of the year and the failure database did not cover all of the failures in the year. The other reason could be the stabilized population of distribution transformers in service in the year following the government strategy that blocked imported transformers from India and china and totally relied on METEC, Ethiopian based power transformers manufacturer. The number of prominent failures would have increased if not for the high shortage created out of the sole reliance on local manufacturer.

The above evidences show that there exists a continuous increase in the number of prominent failures for the same number of distribution transformers in service in a given period of time.

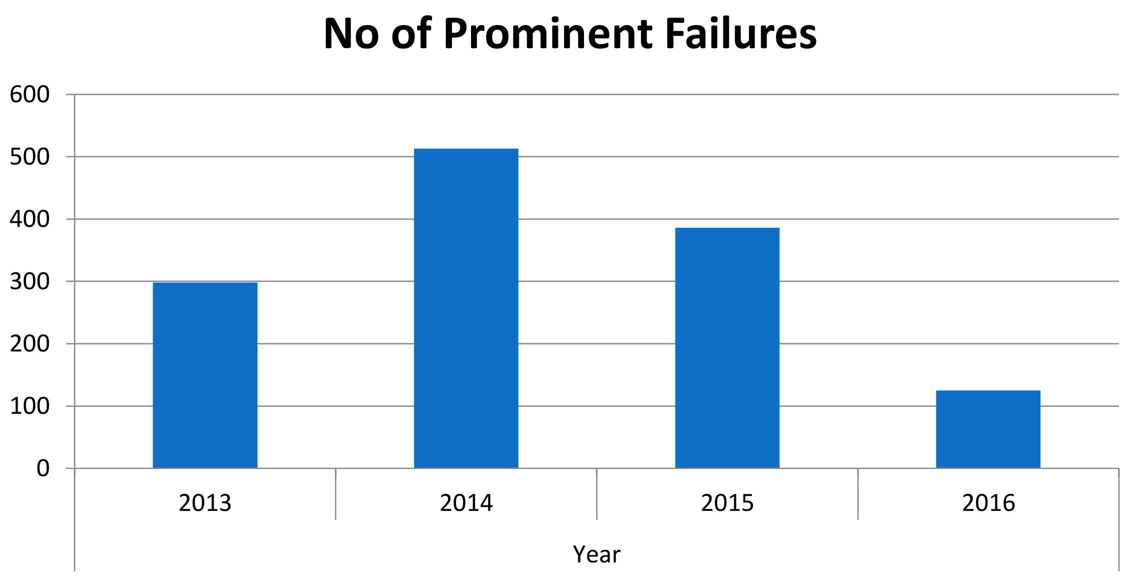

Figure 5.3: Number of Prominent Failures in Distribution Transformers from year 2013 to 2016

5.5 Failure by Manufacturer

Fig 4.8 shows the share of contribution of prominent failures with the origin of the power transformers. 26% of the transformers registered as prominent failures were manufactured by a local manufacturer named METEC, 20% from India, 18% from China, 9% from ZENNARO and 7% from Iran. Minor contributions from other manufacturers include ABB, Italy, Koncar, NEC Pauwels, Poland, Tanzania, Stromberg and Yugoslavia.

Even if the highest share of failure contribution for the prominent failures goes to METEC, it has also the highest contribution into the total population in service. This makes the failure analysis by manufacturer quiet difficult to arrive into to a conclusion to assign prominent failures to the manufacturers directly. Thus other factors such as age at failure and reasons of failure have been incorporated whenever analyzing the failures that emanate from manufacturers of distribution transformers with prominent failures.

The failure database has been analyzed against age at failure for regions that have fully recorded age of the transformers at the time of failure. The result shows that transformers manufactured from METEC, India, China and ZENNARO showed premature failure. The rest minor percentage failure shares from Italy, ABB, NEC, Stromberg, Yugoslavia and Pauwels show normal age related failures. The other failures from Poland, Tanzania and Iran show moderate failures that are neither premature failures nor age related.

Reasons of failure have also been analyzed against failures by manufacturers. Accordingly, the failure database has proven that Overload has been associated with most of the transformers with prominent failures and manufactured by METEC.

Further analysis on the above recorded failure reason for power transformer manufactured by METEC shows that the transformers could not carry loads that was declared in the name plates of the equipment. High voltage equipment should carry loads not exceeding 10% of the capacity indicated in their name plates. This was denied in the case of METEC manufactured transformers with the frequent failure occurred when the transformers were loaded with exactly the same amount indicated in their name plates. This would question the reliability of power transformers produced by METEC, despite the international certifications that METEC acquired for its consistent and internationally accepted standards of high voltage equipment production.

Internal short and winding failures have been recorded frequently for transformers that were supplied from China, India, Iran and ZENNARO.

Winding failure associated with failed transformers imported from Italy, ABB, NEC, Yugoslavia and Stromberg might be caused by the insulation deterioration that could occur with age leading to winding short circuits.

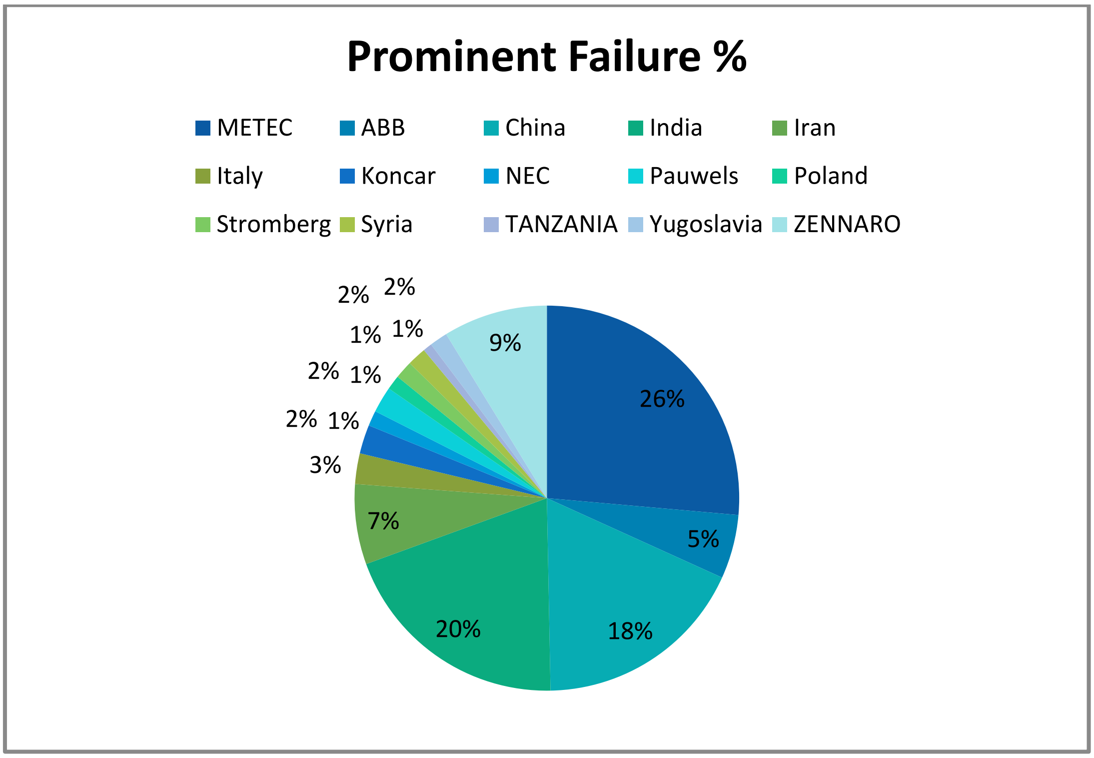

Figure 5.4: Failed Distribution Transformers with Origin of Manufacture

5.6 Failure by Component

Prominent failures are further classified by the specific transformer component that was affected and lead to the failure of the transformer.

Winding failure contributes the leading 52.4% of the total prominent failures. The effects of heavy wind, lightning and overload recorded in the failure database might have probably caused short circuits and melting of the copper wire from which the winding of power transformers made.15.5% were recorded as unknown locations, 9.6% bushing damage, 8.4% cooling system, 5.3 tank and 3% tap changer problems.

From the above mentioned components, cooling system failure is associated with failure records related with oil leakage and oil theft. The oil leakage arises from tank mechanical damage or corrosion. Oil theft is becoming significant cause of transformer failures from recent years that the transformers oil is being stolen and later will be used for illegal production of edible oil. Oil theft contributes more damage to the cooling system than the oil leakage as it does not allow the maintenance responsible to buy time to correct the problem before the complete failure of the transformer.

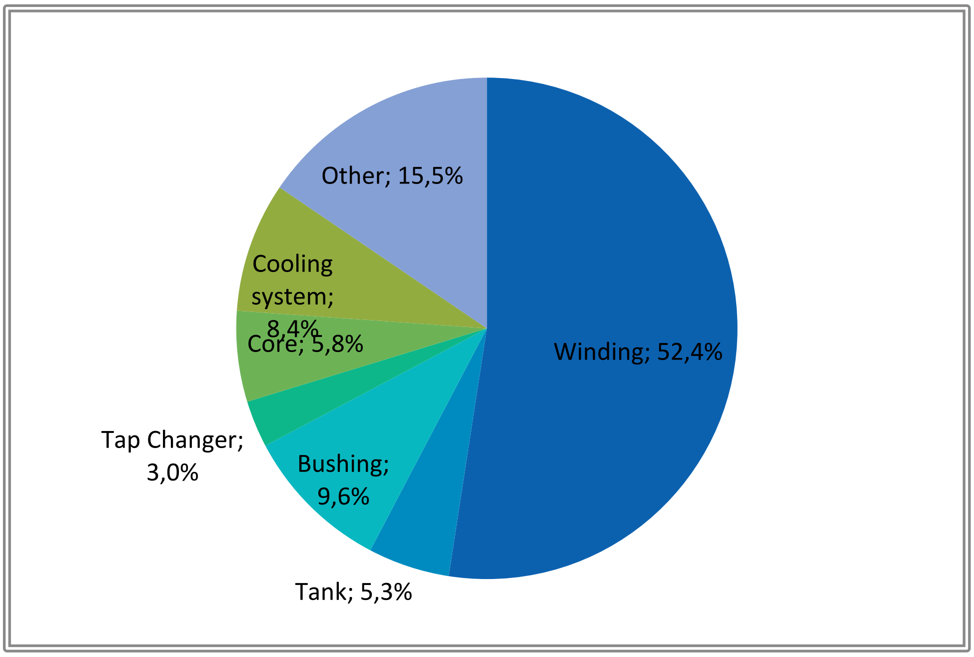

Figure 5.5: Distribution Transformers Failure Locations

5.7 Failure by region

Fig 4.10 shows the recorded failures by region. Addis Ababa region registered the highest number of failures with 1407 failures followed by central region with 836 failures and north western region with 684 failures.

Further analysis of the case shows that the high failure rate in Addis Ababa region might be the overload that occurred with the expansion of residential and public facilities.

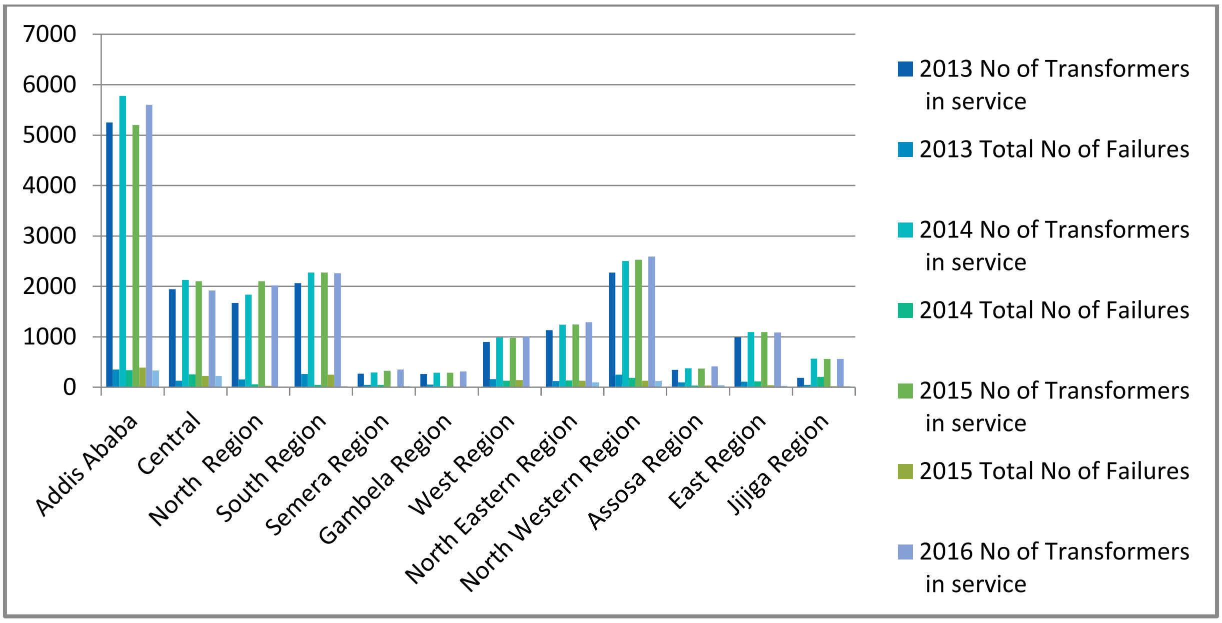

Figure 5.6: Distribution Transformers Failure by their Regions

5.8 Failure by Age

The failure database did not include age of the transformers population in service and their age when failure occurs. Table 4.3 shows the age of transformers against number failed for regions where the failure database includes the age of transformers.

The table represents failures from EEAR, WAAR, SAAR and Central regions.

Table 5.2: Failed Distribution Transformers against Age at Failure

Age at Failure (Year)	Number of Failures
0-1	91
1-3	182
3-9	179
9-12	12
12-19	71
19 and above	35

5.9 Failure Modes and Effects Analysis of ONAN Distribution Transformers

The Failure Modes and Effect Analysis further illustrate the underlying failure cause for what have been discussed in the statistical analysis into detailed failure categories.

To employ FMEA to a system, the system must be divided in to its subsystems and each component should be defined. In this work, Oil Natural Air Natural (ONAN) distribution transformers employed in Ethiopia have been divided into their sub systems and their major components have been defined as follows:

5.9.1 Function of ONAN components

Doing an FMEA starts with defining the functions of the system under study. In this study functions of the relevant components of ONAN transformers in Ethiopia have been defined according to [46]

Core: the core is used to concentrate magnetic flux

Winding: winding is used to conduct electric current

Insulation System: is used to isolate the windings from each other.

Bushings: are used to insulate a high voltage conductor that passes through the tank wall

Tap Changer: are used to alter the voltage level by increasing or decreasing the number of turns

Tank: The tank serves as the container of transformer oil to be used both for insulation and cooling. The tank also serves as a support structure for accessories.

5.9.2 Failure modes associated with components

Affected components/subsystems as a result of the occurrence of failure have been used to group failures into the following universally accepted modes of failure.

Dielectric Modes of Failures: involve the breakdown of dielectric materials that are originally serving as insulation materials. When the material no longer serves the function of insulation by means of polarization, the windings will have a direct contact resulting in short circuits

Thermal Modes of Failures: are caused by the heat created on windings as a result of shortage of the number of turns of the insulation material. The inadequate turns cannot withstand the mechanical vibration from the inside of the transformer and results in insulation paper degradation.

Electrical Modes of Failures: are loose connection and short circuits caused by poor joints and contacts on OLTC, bushings and windings resulting from factory defects, improper O&M and ground deteriorations.

Mechanical Modes of Failures: is caused as result of the displacement of windings during shipping, installation. Some factory defects also result in the displacement of electromagnetic force that pushes and tears the insulation paper.

Physical Chemistry Modes of Failures are the result of contamination of the insulation oil with debris, alloys, moisture and other particles. This leads to the dielectric polarization problem in the oil insulation and winding-ground insulation.

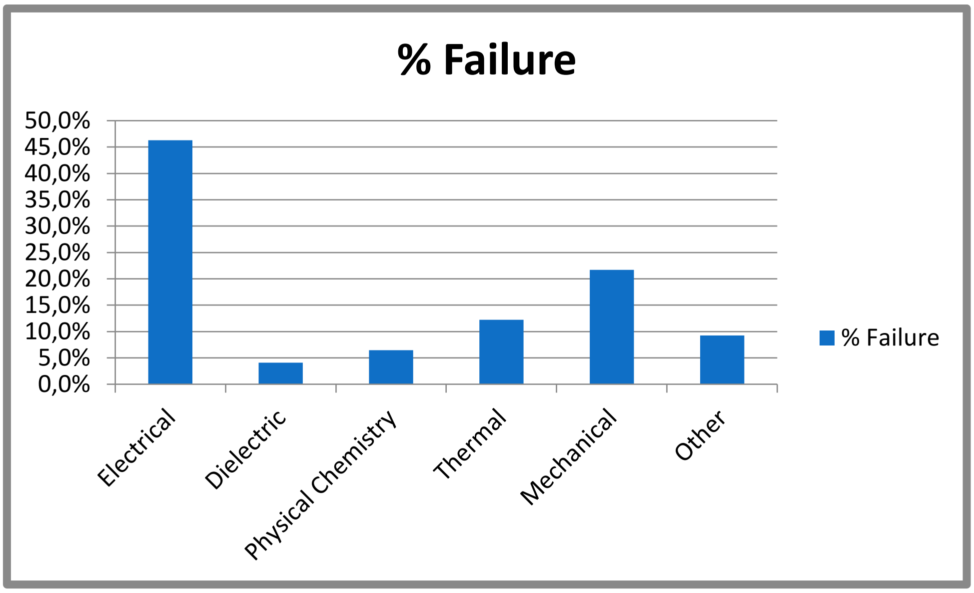

Figure 5.7: Distribution Transformers Failure Mode Distribution

5.9.3 Failure cause

The failure reasons recorded in EEU failure database can be further fall in any of the following universally accepted Failure Cause categories

External Event- Vandalism, Impact of foreign material

Environmental- Lightning, Heavy wind, Rain, flood

Design Defect- Design problem, specification problem, Material Defect, improper factory assembly

Deterioration- age of components, insulation deterioration

Internal Event- Overload unbalanced load

Improper Operation- improper installation, improper repair, improper Replacement, improper maintenance, improper adjustment

Typical Failure Modes for each of the components of power transformer is derived from [28]

5.9.4 FMEA Worksheet- Distribution ONAN Transformers in Ethiopia

Failure Mode	***Failure Cause***	***Probability of Occurrence (O) (1-5)***	***Failure Effect***	***Severity of Effect (S) (1-4)***	***Prevention/ Detection Control***	***Detectability (D) (1-5)***	***RPN 1***	***Recommended Action***	***Revised RPN***			
									O	***S***	***D***	***RPN 2***
Electrical	*Open phase/phase loss*	*5*	*Electromagnetic disturbance in the secondary winding resulting in winding failure*	*4*	*Frequency Response Analysis(FRA)/ Oil test, turns ratio*	*4*	*80*	*Tighten loose cable, replace a blown fuse, replace circuit breaker, replace broken*	*2*	*4*	*4*	*32*

								conductor				
Electrical	*Phase to Ground Failure*	*4*	*Winding Failure*	*4*	*Oil test/Insulation resistance FRA*	*4*	*64*	*Ground overcurrent and directional overcurrent relays*	*2*	*4*	*4*	*32*
Electrical	*Turn to Turn Failure*	*5*	*Winding Failure*	*5*	*Oil Test/Turns ratio/Insulation resistance*	*4*	*100*	*Turn-to-turn specific differential relay*	*2*	*3*	*4*	*24*
Dielectric	*Winding Insulation damage*	*4*	*Winding Failure*	*5*	*Sweep Frequency Response Analysis (SFRA)*	*5*	*100*	*Dry out the transformer/eliminate leaks and re-sealing*	*1*	*5*	*5*	*25*

Mechanical	*Loose Turns*	*4*	*Winding Failure due to deflection of electromagnetic force*	*4*	*Frequency Response Analysis(FRA)*	*5*	*80*	*Winding resistance test/replace*	*1*	*4*	*5*	*20*
Electrical	*Twisted turns*	*4*	*Winding Failure*	*3*	*winding capacitance Leakage Impedance (LI) Leakage Reactance (LR) Low Voltage Impulse (LVI) Sweep Frequency Response Analysis (FRA)*	*4*	*48*	*Replace deformed winding*	*1*	*3*	*4*	*12*
Thermal	*Overload*	*5*	*Exceeded nominal operating temperature,curre*	*4*	*IEC 726 to set the temperature of the winding during normal operating conditions*	*3*	*60*	*Regular load checking to avoid the transformer*	*1*	*4*	*3*	*12*

			nt,voltage Transformer overheat Transformer Failure		*IEC 905 to set the temperature of the winding during overloads*			*from overloading beyond its design capabilities*				
Mechanical	*Loose clamping*	*5*	*when the transformer gets overload, the clamps of the coil will get apart from the high current passing through the coils resulting in Immediate Electrical Failure*	*4*	*Use of higher density insulation and higher clamping pressures during manufacturing*	*5*	*100*	*Re-clamping*	*1*	*4*	*5*	*20*

Failure Mode	***Failure Cause***	***Probability of Occurrence (O) (1-5)***	***Failure Effect***	***Severity of Effect (S) (1-4)***	***Prevention/ Detection Control***	***Detectability (D) (1-5)***	***RPN 1***	***Recommended Action***	***Revised RPN***			
									O	***S***	***D***	***RPN 2***
Thermal	Core Overheated	*4*	*Core Failure/ Loss of efficiency*	*4*	*Oil test, Insulation resistance/Core grounding test*	*4*	*64*		*2*	*4*	*4*	*32*
Electrical	*Wrong Grounding of Core*	*4*	*Core Failure*	*4*	*Core ground insulation resistance test*	*4*	*64*		*1*	*4*	*4*	*16*

Thermal	*Iron Loss*	*4*	*Increased Transformer Temperature/ Cracking of components/Reduction in the dielectric strength of the insulation material*	*4*	*Core Iron loss tests*	*5*	*80*	*Core and transformers iron loss estimation during production*	*1*	*4*	*5*	*20*

Thermal	*Overload*	*3*	*Increased Temperature/ Transformer failure*	*4*	*IEC 726 and IEC 905 to set the temperature of the winding. The core will get adjust itself automatically*	*4*	*48*	*Thermal Protection Devices to the LV side*	*1*	*4*	*4*	*16*
Electrical	*Overexcited Core*	*3*	*Transformer Failure*	*4*	*Furfuraldehyde Analysis (FFA)*	*4*	*48*		*1*	*4*	*4*	*16*

Failure Mode	***Failure Cause***	***Probability of Occurrence (O)***	***Failure Effect***	***Severity of Effect (S)***	***Prevention/ Detection Control***	***Detectability (D)***	***RPN 1***	***Recommended Action***	***Revised RPN***			
									O	***S***	***D***	***RPN 2***
Physical Chemistry	*Water in Oil*	*3*	*Deterioration of both the insulation oil and the insulation paper*	*4*	*IEC 156 test the dielectric strength of an insulating oil. (A measure of the oils ability to withstand electrical stress without failure)*	*3*	*36*	*Regular sampling and testing of the transformer oil. Avoid bad gasketing*	*1*	*4*	*3*	*12*

Physical Chemistry	*Acids in Oil*	*3*	*Partial discharge/Corona Carbonization of the oil Insulation breakdown*	*4*	*Regular test of the dielectric strength of the oil Test for acidity*	*3*	*36*	*Avoid atmospheric openings oil contamination tests to avoid decomposition*	*1*	*4*	*3*	*12*
Mechanical	*Broken Insulation Paper*	*4*	*Excessive current*	*4*	*measure the impedance of the transformer from the high voltage side and check the integrity of the insulation by applying a test voltage from a*	*4*	*64*	*Protection fuses at the high voltage side*	*1*	*4*	*4*	*16*

					suitable source							
Dielectric	*Aged Insulation*	*5*	*Transformer Failure*	*4*		*4*	*80*	*Avoid overloads to slow accelerated aging of the insulation*	*2*	*4*	*4*	*32*
Dielectric	*Oil level too low*	*4*	*Exposed top of core & Coil assembly*	*4*	*Regular monitor of oil level and the silica gel breather*	*3*	*48*	*Top up*	*1*	*4*	*3*	*12*

Table 5.3: Summary of Risk Priority Numbers for Final Ranking

Failure Mode	Failure Cause	Occurrence	Severity	Detectability	RPN
Electrical	Turn to turn failure	5	5	4	100
Dielectric	Winding insulation damage	4	5	5	100
Mechanical	Loose clamping	5	4	5	100

Analytical Hierarchy Process (AHP)

Based on the conventional FMEA analysis, three failure causes had the same RPN values, Table 5.3. Therefore to prioritize these failures, an Analytical Hierarchy Process (AHP) subject to expert judgment was established to aid in decision making for risk mitigation considerations. AHP pairwise comparison matrix was established by applying the procedures entailed in [22]

Further to the MIL standard applied in this study to rank failures for the conventional FMEA analysis, seven EEU maintenance staff have been empirically interviewed to make pairwise comparison among equal RPNs for the AHP inputs.

Subject matter experts were asked to compare failure causes with similar RPN values each other relative to predefined criteria in the Analytical Hierarchy Process (AHP) tree as follows.

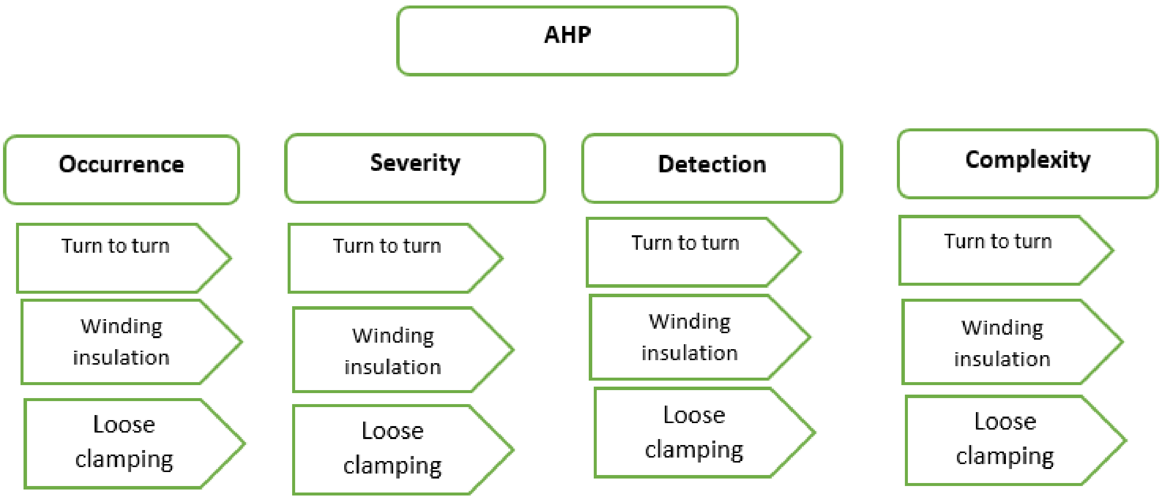

Figure 5.8: AHP Tree for Similar RPN Failure Causes with Predefined Criteria

In the above AHP tree the subjective decision problem starts to become multi-dimensional with multiple criteria and multiple judges, seven subject matter experts to come up with a weighted ranking score.

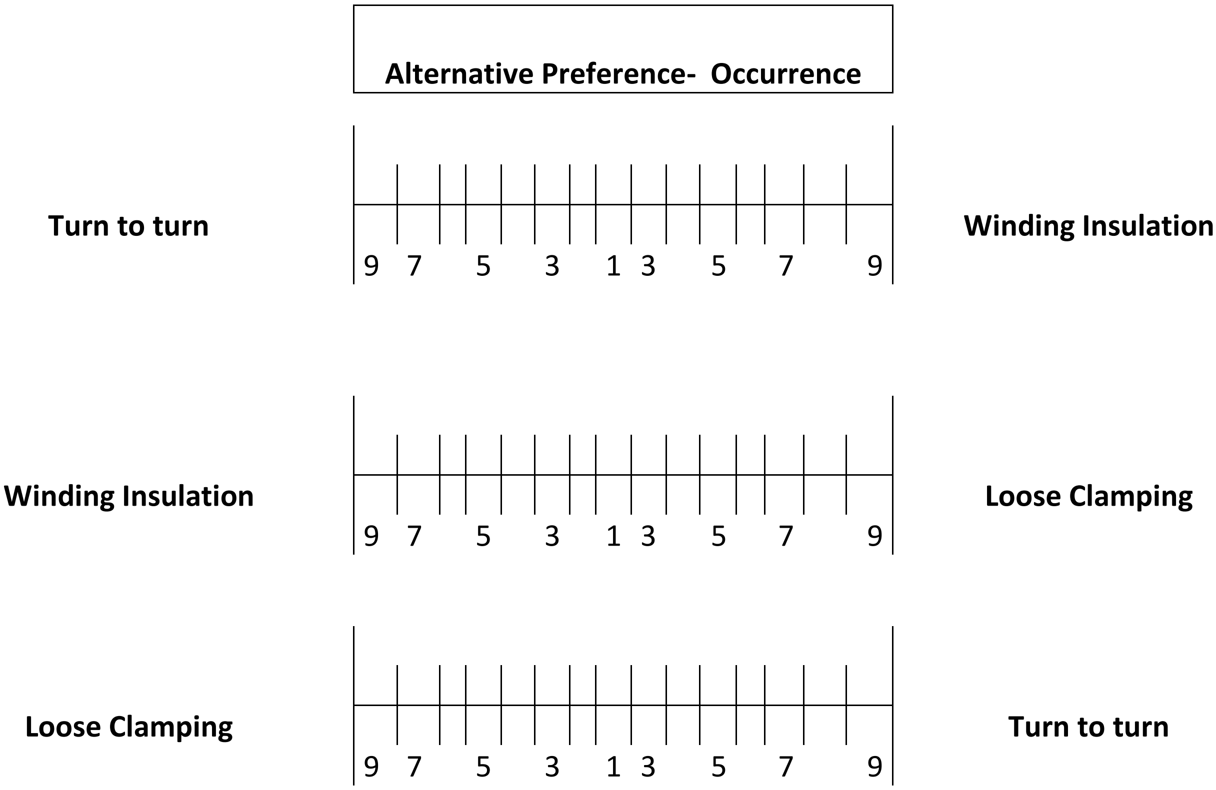

Figure 5.9: Alternative Preference Scale for each Failure Cause-Given Occurrence

A rank scoring scale from 9 to 9 was established from one cause of failure to the other with all possible combinations. In this case, three causes of failures will have three possible comparisons, n (n-1)/2. Where n stands for the number of causes of failures under comparison. The subject matter experts were expected to compare each causes of failure with one another relative to a given criterion. In the above alternative preference scale, if the subject matter expert is indifferent between “turn to turn” and “winding insulation” in relation to the probability of occurrence, they put 1.Similarly,if they believe that “winding insulation” is a little bit better than “loose clamping”, they may choose 3 or 5 to the scale towards “winding insulation damage”. If the judge prefers 9 between “loose clamping” and “turn to turn” towards the scale closer to “loose clamping”, that means, “Loose clamping” is in absolute preference over “Turn to turn”, the subject matter expert decides both the direction of preference and the strength.

The subjective opinion captured from subject matter experts have been consolidated and converted to objective matrix below through simple mathematical model.

Table 5.4: Subject Matter Expert_ Objective Matrix

Occurrence			
	Turn to turn failure	Winding insulation damage	Loose clamping
Turn to turn failure	1	7	5
Winding insulation damage	0,1	1	5
Loose clamping	0,2	0,2	1

Severity			
	Turn to turn failure	Winding insulation damage	Loose clamping
Turn to turn failure	1	5	3
Winding insulation damage	0,2	1	7
Loose clamping	0,3	0,1	1

Detection			
	Turn to turn failure	Winding insulation damage	Loose clamping
Turn to turn failure	1	9	5
Winding insulation damage	0,1	1	5
Loose clamping	0,2	0,2	1

Complexity			
	Turn to turn failure	Winding insulation damage	Loose clamping
Turn to turn failure	1	5	3
Winding insulation damage	0,2	1	5
Loose clamping	0,3	0,2	1

Next, the geometric mean for each alternative criterion has been calculated and tabulated below.

Table 5.5: Weighted Preferences of Failure Causes

Occurrence-Weighted Preference		
3,27106631	72,6	Turn to turn
0,893903535	19,8	Winding insulation
0,341995189	7,6	Loose clamping

Severity_Weighted Preference		
2,466212074	62,5	Turn to turn
1,118688942	28,3	Winding insulation
0,362460124	9,2	Loose clamping

Detection_Weighted Preference		
3,556893304	75,3	Turn to turn
0,822070691	17,4	Winding insulation
0,341995189	7,2	Loose clamping

Complexity_Weighted Preference		
2,466212074	63,7	Turn to turn
1	25,8	Winding insulation
0,405480133	10,5	Loose clamping

Next, an alternative matrix developed from each weighted preference and also having the assumption that each criterion has the same weight, through matrix multiplication, "Turn to turn failure" has got 68% of ranking score followed by "Winding insulation damage" (22.8%) and "Loose Clamping" (8.6%).

Table5.6: Alternative Matrix, Criteria Matrix and Weighted Preference

Alternative Matrix				
	Occurrence	Severity	Detection	Complexity
Turn to turn failure	72.6	62,48	75,34	63,70
Winding insulation damage	19,8	28,34	17,41	25,83
Loose clamping	7,59	9,18	7,24	10,47

Criteria Matrix	
Occurrence	.25
Severity	.25
Detection	.25
Complexity	.25

Weighted Preference	
Turn to turn failure	68.5 %
Winding insulation damage	22.8 %
Loose clamping	8.6%

Interpretation of Results

The modes of failure summarized in the FMEA worksheet constitute the most frequent modes of failure in the failure database. The MIL standard and maintenance staff opinion from the questionnaire have been used to rate the scaling of probability of occurrence of failures, severity of quensequences and detectability of the root causes.

Accordingly the high failure rate associated with winding failures in Ethiopian distribution transformers is caused by short circuits either with the turn-to-turn or phase to ground or open phase or twisted turns.

All the failure causes associated with short circuits belong to electrical modes of failure and contribute to either failure of the winding or electromagnetic disturbances in the secondary windings of transformers.

These faults are very common in Ethiopian ONAN distribution transformers because of the lack of appropriate testing and diagnosis procedures. The high RPNs associated with these short circuits can be greatly reduced by regularly performing Sweep Frequency Analysis, oil tests, turns ratio tests and insulation resistance tests.

Mechanical failure modes associated with windings include loose turns and loose clamping. Both of these failure causes result in winding failure due to deflection of electromagnetic force. Loose turns and loose clamping are very common in Ethiopian ONAN distribution transformers for operation problems related with overloads, the clamps of the coil will get apart from the high current passing through the coils. The high RPN values associated with these failures can be reduced with avoiding overloads and high clamping pressures during manufacturing.

Common Core failure causes associated with thermal failure modes include overheated core, overload and iron loss. These failure causes have a local effect of increased transformers temperature and an end effect of failure of the core or failure of the transformer. The high RPN values associated with these failure modes can be reduced with regular oil tests, insulation resistance tests and core iron loss tests. In addition to this, the installing of thermal protection devices to the LV side protects transformers from the severe damage of overloads.

Iron loss in cores can generally be improved with continuous follow up and estimation of the losses both in transformer and its core during the production process.

Electrical failure modes associated with core include wrong grounding of core and overexcited core.RPNs associated with these failure modes can be improved with having core ground insulation resistance test and Furfuraldehyde Analysis (FFA) with the later.

On the other hand deformed magnetic flux associated with the core of the transformers is the result of mechanical deformation from shipment, relocation and mounting. Therefore, transformers should be checked out before and after any shipment, transportation from warehouses and mounting.

Insulation systems of ONAN transformers are the most vulnerable for physical chemistry and dielectric modes of failure. Failure causes include water in oil, acids in oil and too low oil level. These failure causes are mainly associated with aged transformers as the insulation paper deteriorates with time and chances are there to accumulate water in the insulation system. The significant RPN values for these failure causes can be reduced with regular test of the dielectric strength of the oil, test for acidity and regular monitor of the oil level and silica gel breather. Physical chemistry modes of failure can also be prevented by regular sampling and testing of the transformer oil, using appropriate gasketing and use of contamination tests to avoid decomposition.

High RPN values are also observed in broken insulation paper as a result of mechanical failure modes. Instantaneous failures associated with mechanical breakdown of the insulation paper can be protected by having protection fuses at the high voltage side of transformers.

The FMEA worksheet generally shows that, most of the modes of failure observed in Ethiopian ONAN distribution transformers can be greatly reduced with having appropriate tests, diagnosis and protection devices.

Recommended action based on the FMEA analysis can be prioritized based on the RPN values associated with each failure cause. The Analytical Hierarchy Process (AHP) employed further to the conventional FMEA can be also used to prioritize failure causes with similar RPNs.

CHAPTER SIX

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

With the current increasing demand of electric power in the country, the Ethiopian government has continued working on sustaining the supply through the construction of mega electric power generation projects. The recent completion of Gibe 3 hydroelectric power project with 1870MW electric power generation capacity has increased the overall electric power generation capacity of the country to 4200MW.The construction of power generation plants not only contributes for the improvement of the supply of electric power in the country but also serves as technology and knowledge transfer as well as improved social networks.

Though the effort being carried out in the provision of adequate supply of electricity sounds promising in ensuring the electric demand of the country, power distribution is still a serious problem in the country with frequent power outages and fluctuations. Problems related with electric distribution are mainly associated with aged power carrying, transmission lines and failure of power transformers. Shortage of power transformers with very long production lead times has also made the replacement and maintenance procedures very complicated, even if power is available from the source.

So the main objective of this research was to identify causes of distribution transformers related failures by using Failure Modes and Effects Analysis.

From the literature review, FMEA has been used as a long standing technique to identify modes of failures, consequences of failures and the probability of occurrence of root causes and detectability of the same into prioritizing action to be done in order to protect critical assets. The method can be used either in the design phase to improve features of assets or during the useful life of assets to learn more on the usage and handling of assets and to identify what needs to be done to keep them in working order all the times.

The result of the research generally shows that the existing problems in Ethiopia related with failure of distribution transformers are caused by improper operation and maintenance, inadequate testing and diagnosis and lack of skilled workmanship to carry out repair and maintenance as it is demanded from the current technological advancement of these critical assets.

Besides the above mentioned causes, lack of protective devices, improper handling and shipment also have significant contribution to failure of transformers either at the date of installation or shortly after. Transformers that are left unattended are also vulnerable for oil theft and vandalism.

From the analysis of the research, operation related failures of distribution transformers are mainly associated with overloads. Studies reveal that transformers work efficiently and without the risk of failure when they are working at half of the full load. The research revealed that power transformers were overloaded during expansion of the existing consumers and during power sharing operation when a nearby transformer fails.

Winding related failures are normally arise during lightning and heavy wind. From the literature, distribution transformers must be protected with lightning arrester in the high voltage side and HRC fuses in the low voltage side. In the case of the transformers under study and the result of in-house research by EEU, there is no enough follow up either to inspect the proper installation of these protective devices or to inspect if they are in good working order.

Longer repair lead times associated with prominent failures were the result of improper operation and maintenance practices. Less due concern for manufacturer's manuals and transformer specific operation procedures make very difficult to deal with specific problems and to get updated information in relation with recent technological advancement.

From the findings of the research, tests are often ignored, when there are no outages and everything appears normal. Inadequate testing and diagnosis are also the result of lack of appropriate diagnosis and testing tools and expertise. Though EEU new maintenance staff receive training on how to perform testing and diagnosis, the training is not adequate to take the responsibility to perform the required maintenance over the entire life of the transformers. This lack of expertise is normally observed in re-fusing faulted transformers that causes further failure.

6.2 Recommendations

Based on literature review and research findings, the study recommends the following:

- Windings of distribution transformers should be designed to withstand various mechanical or thermal stresses caused by short-circuit currents occurring during operation to avoid instantaneous and progressive failures
- To avoid lightning and heavy wind related failures, distribution transformers should be equipped with lightning arrester in the high voltage side and HRC fuses in the low voltage side all the times. Protective devices should be inspected regularly for proper functioning, minor defects noticed during inspection must be attended. In additions transformers should be inspected immediately after
- Manufacturers' instructions should always be given due consideration while carrying out maintenance of distribution transformers and accessories.
- EEU distribution transformers maintenance staff and operators should receive continuous training and couching on testing and diagnosis of distribution transformers as applicable to the specific technology.
- EEU maintenance program should include periodic tests and diagnosis of distribution transformers as per the requirement of IEC or other appropriate norms, a continuous record of all tests and diagnoses should be maintained to keep a complete and up-to-date record of all the inspections, periodic maintenance, overhauls & repair works.
- During power sharing operations, distribution transformers should not be overloaded more than their designed capacity.
- To avoid vandalism and oil theft, distribution transformers should not be left unattended.
- Replacement strategy should be in place for aged transformers, transmission and power carrying lines to avoid age related failures of distribution transformers
- Iron losses in core should be estimated during the manufacturing process to avoid cracking of components and deformation of magnetic flux

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ANNEXES

ANNEX: 01 - Questionnaire

Rate your agreement with respect to the following scale					
	1 I don't agree	2 Moderately agree	3 Agree	4 Strongly agree	
I	**Winding Failure**				
		1	2	3	4
Winding failure causes failure to other components of the transformer					
Winding Failure occurs very often					
Winding failure has very severe quensequences					
Winding failure is very hard to detect					
Winding Failure cause entire failure for the transformer					
Winding failure cause power outage					
II	**Core Failure**				
Core failure causes failure to other components of the transformer					
Core Failure occurs very often					
Core failure has very severe quensequences					

Core failure is very hard to detect				
Core Failure cause entire failure for the transformer				
Core failure cause power outage				
III **Tank Failure**				
Tank failure causes failure to other components of the transformer				
Tank Failure occurs very often				
Tank failure has very severe quensequences				
Tank failure is very hard to detect				
Tank Failure cause entire failure for the transformer				
Tank failure cause power outage				
IV **OLTC Failure**				
OLTC failure causes failure to other components of the transformer				
OLTC Failure occurs very often				
OLTC failure has very severe quensequences				
OLTC failure is very hard to detect				
OLTC Failure cause entire failure for the transformer				
OLTC failure cause power outage				

ANNEX: 02 – EEU Operation Sequence Form

ETHIOPIAN ELECTRIC UTILITY

operation sequence Form

Regions ___________________________ District/service Center ____________________________

Date _________________

Status change of switching devices				Reason for status change
Operation sequences		Open/interrupt	Close/connect	

ANNEX: 03 – EEU Load transferring/Sharing operations

ETHIOPIAN ELECTRIC UTILITY

Load transferring/Sharing operations

Region ______________________________ District/Service center ____________Date ______________

1) Reason for load transferring/sharing

____

____

____

2) The load transferring/sharing covers the period

Time : from _________________________ To ______________________

Date _________________________ ______________________

3) Load to be transferred:-

From To

S/S Name ___________________ _____________________

___________________ _____________________

___________________ _____________________

Feeder code ___________________ _____________________

___________________ _____________________

___________________ _____________________

_______________________ _________________________

Prepared by ____

Approved by ____

ANNEX: 04- Distribution Transformers Inspection Sheet

ETHIOPIAN ELECTRIC UTILITY

MEDIUM VOLTAGE (15 OR 33 KV) NETWORK INSPECTION SHEET

Last inspection Date ____________________

Last maintained Date ____________________

Current Inspection Date ____________________

District ____________________

Region ____________________

Kiffle Ketema ____________________

Kebele ____________________

Area ____________________

Substation Name ____________________

Feeder Code ____________________

Map No. ____________________

No.	**Components**	**Inspection for**	**Quantity of Defective network components**								**Total**	
	Distribution transformers	Earth resistance below the acceptable value	Trafo code									

		Insulation resistance below the acceptable value	Trafo code									
		Oil level is below the normal value	Trafo code									
		Temperature of oil is above acceptable value	Trafo code									
		Unusual noise	Trafo code									
		Misaligned bushing arc horn gap	Trafo code									
			Qty									
		Changed silica jel color	Trafo code									
		Cracked or damaged lightning arrester	Trafo code									
			Qty									

		Ground connection of arrester ,neutral of transformer and transformer body	Trafo code									
			Good									
			Poor									
		Oil level indicator glass is broken	Trafo code									
		Thermometer glass is broken	Trafo code									
		Silica jel glass is broken	Trafo code									
		If fuse rating as standard	Trafo code									
			No									
			Yes									
		Distribution boxes are at appropriate height from the ground level	Trafo code									
			No									
			Yes									

		Oil leakage	Trafo code									
		Bolts & nuts and cable lugs	Trafo code									
			Qty									
		Defective terminals	Trafo code									
			Qty									
		Tap changer position	Trafo code									
			Position									
		Radiator condition	Trafo code									
			Good									
			Poor									
	Circuit breaker & accessories	General clearing	Trafo code									
		Oil condition	Trafo code									
			Good									
			Poor									
		Relay terminals	Trafo code									
			-need repair -To be replaced									
		Need of load setting contact	Trafo code									
			Qty									

		adjustment										
		Mechanism work	Trafo code									
			-No									
			- Yes									
		CT's as per design	Trafo code									
			-No									
			- Yes									

Annex: 05 Sample- Distribution Transformers Failure Database

Voltage (KV)	Date of failure	Manufacturer	Reason for Failure	Damaged System	Detail of Failure	Age at Failure (Year)
15	2015	METEC	Overload	Winding	Unbalanced phase	2
15	2015	METEC	Overload	Winding	Open winding	0.5
15	2015	METEC	Overload	Winding	Open winding	0.4
15	2015	METEC	Overload	Winding	Open winding	0.5
15	2015	METEC	Overload	Winding	Open winding	1
15	2015	METEC	Overload	Winding	Phase to Ground Failure	0.9
15	2015	METEC	Overload	Winding	Open winding	2
15	2015	METEC	Overload	Winding	Open winding	3
15	2015	METEC	Overload	Winding	Open winding	3
15	2015	METEC	Overload	Winding	Open winding	3
15	2016	METEC	Overload	Winding	Turn to Turn Failure	3
15	2015	METEC	Overload	Winding	Phase to Ground Failure	3
15	2015	METEC	Overload	Winding	Phase to Ground Failure	3
15	2015	METEC	Overload	Winding	Phase to Ground Failure	3
15	2015	METEC	Overload	Winding	Phase to Ground	3

					Failure	
33	2015	METEC	Lightning	OLTC		3
33	2016	METEC	Overload	Winding	Phase to Ground Failure	2
33	2016	METEC	Overload	Winding	Phase to Ground Failure	2
33	2016	METEC	Overload	Winding	Phase to Ground Failure	2
33	2016	METEC	Overload	Winding	Phase to Ground Failure	2
33	2016	METEC	Overload	Winding	Phase to Ground Failure	2
33	2015	METEC	Overload	Winding	Unbalanced phase	2
15	2015	METEC	Overload	Winding	Unbalanced phase	2
15	2015	METEC	Overload	Winding	Unbalanced phase	2
15	2015	METEC	Overload	Winding	Unbalanced phase	2
15	2015	METEC	Overload	Winding	Unbalanced phase	1.5
33	2015	METEC	Oil leakage	Tank		1.2
15	2015	METEC	Internal short	Winding	Phase to Ground Failure	1.3
15	2015	METEC	Bushing damage	Bushing		2
15	2015	ZENNARO	Internal short	Winding	Unbalanced phase	2.3

15	2015	China	Internal short	Winding	Unbalanced phase	0.6
15	2015	METEC	Internal short	Winding	Unbalanced phase	0.4
15	2015	India	Internal short	Winding	Unbalanced phase	0.9
15	2015	India	Internal short	Winding	Unbalanced phase	0.5
15	2015	India	Internal short	Winding	Unbalanced phase	4
15	2015	India	Internal short	Winding	Unbalanced phase	2
33	2015	India	Internal short	Winding	Unbalanced phase	6
15	2016	India	Internal short	Winding	Unbalanced phase	0.5
33	2016	ZENNARO	Internal short	Winding	Unbalanced phase	5
15	2016	ZENNARO	Internal short	Winding	Unbalanced phase	5
15	2016	ZENNARO	Internal short	Winding	Unbalanced phase	5
33	2016	METEC	Internal short	Winding	Unbalanced phase	0.4
15	2015	China	Internal short	Winding	Unbalanced phase	5
15	2015	China	Internal short	Winding	Unbalanced phase	5
15	2015	China	Internal short	Winding	Phase to Ground Failure	0.5
15	2015	China	Internal short	Winding	Phase to Ground Failure	5
15	2015	China	Internal short	Winding	Phase to Ground Failure	5
15	2015	China	Internal short	Winding	Phase to Ground Failure	5

15	2015	China	Internal short	Winding	Phase to Ground Failure	5
15	2015	China	Internal short	Winding	Phase to Ground Failure	0.5
15	2015	China	Internal short	Winding	Phase to Ground Failure	5
15	2015	China	Internal short	Winding	Phase to Ground Failure	5
15	2015	China	Internal short	Winding	Phase to Ground Failure	0.5
15	2015	China	Lightning	Winding	Loose clamping	5
15	2015	China	Lightning	Winding	Unbalanced phase	5
15	2015	Iran	Internal short	Winding	Unbalanced phase	4
15	2015	China	Internal short	Winding	Unbalanced phase	4
15	2015	China	Internal short	Winding	Unbalanced phase	4
15	2015	China	Internal short	Winding		5
15	2015	China	Unknown	OLTC		6
15	2015	ZENNARO	Unknown	Insulation		1
33	2015	ZENNARO	Oil leakage	Insulation		1
33	2015	ZENNARO	Oil leakage	Insulation		1
33	2015	ZENNARO	Oil leakage	Insulation		1
33	2015	ZENNARO	Lightning	Insulation		0.5

33	2015	ZENNARO	Oil leakage	Tank		0.9
15	2016	ZENNARO	Internal short	Winding	Unbalanced phase	1
15	2016	ZENNARO	Internal short	Winding	Unbalanced phase	1
15	2016	ZENNARO	Internal short	Winding	Unbalanced phase	1
15	2016	ZENNARO	Internal short	Winding	Unbalanced phase	0.4
15	2016	ZENNARO	Internal short	Winding	Unbalanced phase	1
33	2016	ZENNARO	Internal short	Winding	Unbalanced phase	1
33	2015	ZENNARO	Internal short	Winding	Unbalanced phase	0.3
15	2015	ZENNARO	Internal short	Winding	Unbalanced phase	1
15	2015	ZENNARO	Overload	Winding	Unbalanced phase	1
15	2015	ZENNARO	Overload	Winding	Unbalanced phase	5
15	2015	ZENNARO	Overload	Winding	Unbalanced phase	7
15	2015	ZENNARO	Overload	Winding	Unbalanced phase	4
15	2015	ZENNARO	Overload	Winding	Unbalanced phase	7
15	2015	ZENNARO	Overload	Winding	Unbalanced phase	3
15	2015	ZENNARO	Overload	Winding	Unbalanced phase	3
15	2015	Iran	Overload	Winding	Open winding	5
15	2015	Iran	Overload	Winding	Open winding	5
15	2015	Iran	Overload	Winding	Open winding	5
33	2015	Iran	Overload	Winding	Open winding	0.5

33	2015	Iran	Overload	Winding	Open winding	5
15	2015	Iran	Overload	Winding	Open winding	5
15	2015	Iran	Overload	Winding	Open winding	5
15	2015	Iran	Overload	Winding	Open winding	5
15	2015	Iran	Overload	Winding	Open winding	0.5
15	2015	ZENNARO	Overload	Winding	Open winding	5
15	2015	ZENNARO	Overload	Winding	Open winding	5
15	2015	ZENNARO	Overload	Winding	Open winding	0.5
15	2015	ZENNARO	Overload	Winding	Open winding	5
15	2015	Iran	Overload	Winding	Open winding	5
15	2015	Iran	Overload	Winding	Open winding	4
33	2015	Iran	Overload	Winding	Open winding	4
33	2015	Iran	Overload	Winding	Open winding	4
33	2015	Iran	Overload	Winding	Open winding	5
33	2015	Iran	Overload	Winding	Open winding	6
33	2015	India	Internal short	Winding	Open winding	0.3
15	2015	METEC	Internal short	Winding	Open winding	0.5
15	2015	METEC	Internal short	Winding	Open winding	3
15	2015	METEC	Internal short	Winding	Open winding	0.8
15	2015	METEC	Internal short	Winding	Phase to Ground Failure	0.3

15	2015	METEC	Internal short	Winding	Phase to Ground Failure	0.4
15	2015	METEC	Internal short	Winding	Phase to Ground Failure	1
15	2015	METEC	Internal short	Winding	Open winding	1.2
15	2015	METEC	Internal short	Winding	Open winding	5
33	2015	METEC	Unknown	Unknown		5
15	2015	METEC	Unknown	Unknown		5
33	2015	METEC	Unknown	Unknown		5
15	2015	METEC	Unknown	Unknown		0.5
33	2015	METEC	Unknown	Unknown		5
33	2015	METEC	Unknown	Unknown		5
15	2015	METEC	Unknown	Unknown		0.5
15	2015	METEC	Unknown	Unknown		5
15	2016	METEC	Unknown	Unknown		5
15	2016	METEC	Unknown	Unknown		4
15	2016	METEC	Unknown	Unknown		5
15	2016	METEC	Core Problem	Core		5
15	2016	METEC	Core Problem	Core		5
15	2015	METEC	Core Problem	Core		5
15	2015	METEC	Core Problem	Core		0.5

15	2015	METEC	Core Problem	Core		5
15	2015	METEC	Core Problem	Core		5
15	2015	METEC	Core Problem	Core		0.5
15	2015	METEC	Core Problem	Core		5
15	2015	METEC	Core Problem	Core		5
15	2015	METEC	Core Problem	Core		4
15	2015	METEC	Core Problem	Core		1
15	2015	METEC	Core Problem	Core		2.5
15	2015	METEC	Core Problem	Core		2.3
15	2015	METEC	Core Problem	Core		2
15	2015	METEC	Core Problem	Core		3
15	2015	METEC	Core Problem	Core		2
15	2015	METEC	Core Problem	Core		2
15	2015	METEC	Core Problem	Core		2
15	2015	METEC	Core Problem	Core		2
15	2015	METEC	Core Problem	Core		2
15	2015	METEC	Core Problem	Core		2
33	2013	India	Oil theft	Insulation		5
15	2013	China	Vandalism	Bushing		4
15	2013	China	Core Problem	Core		4

15	2013	India	Core Problem	Core		4
15	2013	Pauwels	Core Problem	Core		13
15	2013	Pauwels	Core Problem	Core		12
15	2013	ZENNARO	Core Problem	Core		13
15	2014	ZENNARO	Core Problem	Core		12
33	2013	India	Core Problem	Core		4
15	2013	Yugoslavia	Core Problem	Core		12
15	2013	Yugoslavia	Core Problem	Core		5
33	2013	Syria	Core Problem	Core		6
33	2014	India	Core Problem	Core		7
15	2014	India	Core Problem	Core		7
15	2013	India	Core Problem	Core		0.8
15	2013	India	Heavy wind	OLTC		0.5
15	2013	Yugoslavia	Heavy wind	OLTC		0.4
33	2014	India	Lightning	OLTC		9
15	2014	India	Lightning	OLTC		4
33	2014	Syria	Lightning	OLTC		5
33	2014	Syria	Lightning	OLTC		12
33	2014	Iran	Lightning	OLTC		11
33	2013	India	Core Problem	Core		6

15	2014	METEC	Internal short	Winding	Loose clamping	1
33	2014	Iran	Internal short	Winding	Loose clamping	4
15	2013	ZENNARO	Internal short	Winding	Loose clamping	4
15	2014	NEC	Old age	Insulation		20
15	2013	NEC	Old age	Insulation		21
33	2013	India	Bushing damage	Bushing		4
15	2013	Italy	Old age	Insulation		17
33	2013	India	Bushing damage	Bushing		4
33	2013	Italy	Old age	Insulation		17
33	2015	Stromberg	Old age	Insulation		17
15	2015	Stromberg	Old age	Insulation		16
33	2015	Stromberg	Old age	Insulation		18
33	2015	Stromberg	Old age	Insulation		17
33	2014	India	Core Problem	Core		6
15	2014	METEC	Overload	Winding	Open winding	3
33	2014	ZENNARO	Overload	Winding	Open winding	5
33	2014	ZENNARO	Overload	Winding	Open winding	2
33	2014	China	Overload	Winding	Open winding	3
15	2014	ZENNARO	Overload	Winding	Phase to Ground	1

					Failure	
33	2014	India	Overload	Winding	Phase to Ground Failure	4
33	2014	India	Overload	Winding	Phase to Ground Failure	5
33	2014	China	Overload	Winding	Open winding	6
15	2014	Stromberg	Internal short	Winding	Open winding	7
33	2014	ZENNARO	Lightning	Core		5
33	2014	ZENNARO	Lightning	Core		4
33	2014	Stromberg	Lightning	Core		7
15	2014	India	Lightning	Core		5
33	2014	Stromberg	Oil theft	Insulation		8
33	2014	METEC	Oil leakage	Insulation		3
33	2014	Koncar	Heavy wind	Core		7
15	2014	METEC	Overload	Winding	Open winding	1
33	2014	India	Overload	Winding	Open winding	1
33	2014	METEC	Internal short	Winding	Open winding	0.8
33	2014	METEC	Internal short	Winding	Open winding	0.8
15	2014	METEC	Internal short	Winding	Open winding	0.8
33	2014	METEC	Vandalism	OLTC		0.8
33	2014	Koncar	Vandalism	OLTC		8

33	2014	India	Lightning	Tank		3
15	2016	India	Core Problem	Core		3
33	2016	China	Core Problem	Core		2
33	2016	ZENNARO	Core Problem	Core		1
33	2016	India	Unknown	Unknown		2
15	2014	ZENNARO	Vandalism	Bushing		2
33	2014	ZENNARO	Unknown	Unknown		1.3
33	2014	ZENNARO	Unknown	Unknown		1.2
33	2014	Pauwels	Unknown	Unknown		7
15	2014	ZENNARO	Vandalism	Tank		1
33	2013	METEC	Core Problem	Core		1
33	2014	ZENNARO	Vandalism	Tank		2.3
33	2014	ABB	Core Problem	Core		7
15	2014	Pauwels	Core Problem	Core		11
33	2014	ZENNARO	Core Problem	Core		4
33	2014	METEC	Overload	Winding	Open winding	2
33	2014	China	Overload	Core		3
15	2014	METEC	Core Problem	Core		2
33	2014	China	Core Problem	Core		2
33	2014	China	Core Problem	Core		2

33	2014	ZENNARO	Core Problem	Core		2
15	2014	India	Core Problem	Core		3
33	2014	ZENNARO	Core Problem	Core		3
33	2014	ZENNARO	Core Problem	Core		3
33	2014	Pauwels	Core Problem	Core		8
15	2014	METEC	Core Problem	Core		1
33	2014	Stromberg	Old age	Insulation		18
33	2014	METEC	Bushing damage	Bushing		1
33	2014	Stromberg	Old age	Insulation		18
15	2014	METEC	Bushing damage	Bushing		0.3
33	2014	India	Bushing damage	Bushing		4
33	2014	ZENNARO	Bushing damage	Bushing		3
33	2014	METEC	Bushing damage	Bushing		0.5
33	2014	ZENNARO	Core Problem	Core		1
15	2014	ZENNARO	Bushing damage	Bushing		1
33	2014	ZENNARO	Core Problem	Core		1

33	2014	India	Oil theft	Insulation		1
33	2014	India	Bushing damage	Bushing		1
33	2014	METEC	Internal short	Winding	Open winding	0.6
15	2015	Pauwels	Internal short	Winding	Open winding	11
33	2015	ZENNARO	Internal short	Winding	Open winding	3
33	2015	METEC	Internal short	Winding	Open winding	1
33	2015	China	Lightning	OLTC		1
33	2015	METEC	Internal short	Winding	Open winding	1
15	2015	China	Internal short	Winding	Open winding	1
33	2015	METEC	Internal short	Winding	Open winding	1
33	2015	India	Internal short	Winding	Open winding	1
33	2015	India	Vandalism	Insulation		1
33	2015	India	Vandalism	Insulation		1
15	2015	India	Internal short	Winding	Open winding	0.5
33	2015	India	Internal short	Winding	Open winding	0.5
33	2015	India	Oil leakage	Tank		0.5
33	2015	India	Internal short	Winding	Open winding	0.5
33	2015	India	Heavy wind	Bushing		0.5
15	2015	METEC	Heavy wind	Bushing		0.5
33	2014	India	Lightning	OLTC		0.5

33	2014	METEC	Lightning	OLTC		0.5
33	2014	METEC	Internal short	Winding	Open winding	0.5
33	2014	METEC	Oil leakage	Tank		0.5
15	2014	ZENNARO	Oil leakage	Tank		0.5
33	2014	ZENNARO	Oil leakage	Tank		3
33	2014	METEC	Oil leakage	Tank		2.5
33	2014	China	Vandalism	Tank		2
33	2014	India	Oil leakage	Tank		3
15	2014	India	Oil leakage	Tank		4
33	2014	India	Oil leakage	Tank		2
33	2014	India	Oil leakage	Tank		3
33	2014	India	Oil leakage	Tank		4
33	2014	India	Oil leakage	Tank		5
33	2015	India	Internal short	Winding	Open winding	6
15	2015	India	Internal short	Winding	Open winding	1
15	2015	India	Internal short	Winding	Open winding	2
33	2015	India	Internal short	Winding	Open winding	0.5
33	2015	India	Internal short	Winding	Open winding	1
15	2016	India	Internal short	Winding	Open winding	1
33		2016		India		Internal short