Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical & Industrial Engineering

Transformer Failure Root Cause Analysis and Developing Mitigation Strategies: A Case of Addis Ababa City

A Thesis Submitted to the School of Graduate Studies of Addis Ababa Institute of Technology, Addis Ababa University in partial fulfillment for the Degree of Master of Science in Industrial Engineering

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Declaration

I hereby declare that the work which is being presented in this thesis entitled "Transformer Failure Root Cause Analysis and Developing Mitigation Strategies: A Case of Addis Ababa City" is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

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ABSTRACT

The distribution transformer is a critical component of the distribution system that must be very reliable in order to provide consumers with uninterrupted power supply. The failure of a distribution transformer has an impact on the supply system's reliability and power quality. This study aimed at failure root cause analysis and mitigation strategy development for distribution transformer in Addis Ababa. The study addresses 3,825 number of distribution transformers from the year 2020/21 to 2022/23 and the failure rate obtained is 13.4%. The collected data were recorded failure documents, interview and group discussion from Kotebi maintenance centers, Addis Ababa City Administration Electric Utility (AACAEU) and four electric utility districts in Addis Ababa. In the first part, the results of failure analysis are statistically summarized. In second part, the failure modes, effect analysis (FMEA) is used to analyze distribution transformer failure modes, causes, local and end effects of failure. To identify the most critical parts of the transformer, a risk priority number (RPN) is calculated based on the severity labelling, probability of occurrence, and probability of detection. Thus, from FMEA analysis, the most vulnerable parts of distribution transformers that have highest RPN value of 576 is insulation failure due to human related errors as a primary cause and with electrical mode of failure. Other component failure due to operational error and with thermal mode of failure is 512 RPN followed by winding failure, bushing failure and tap changer failure. FMEA leads to the identification of future preventative measures to be implemented to decrease the risk of the transformer by eliminating the causes of failure, thus minimizing the severity and probability of occurrence. The direct and indirect relationship between failure causes and effects of FMEA components are analyzed using causal loop diagram(CLD) and could clearly recognize unseen failure factors and their consequences. The root cause of transformer failure that covers 75% is human related factors, which is the primary source of operational failure causes like overloading, short circuit, internal problem and others. Solving failure of distribution transformers in Addis Ababa, the developed failure mitigation strategy is an asset management system of especially focused on predictive type supervisory control and data acquisition (SCADA) system. This study could fill the identified gaps, which means it has its own contribution to the body of knowledge of failure analysis. Finally, the outcome of this study has been thesis document, strategic solutions to minimize transformer failure and input source for further research.

Key words: Distribution Transformers, Failure Analysis, Failure Modes and Effects Analysis, causal loop diagram, asset management, reliability centered maintenance

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Abbreviations

AACAEU	Addis Ababa City Administration
CLD	Causal Loop
DGA	Dissolved Gas Analysis
EEU	Ethiopian Electric Utility
FMEA	Failure Mode and Effect Analysis
FTA	Failure Tree Analysis
HRC	High Rupturing Capacity
HV	High Voltage
IA	Immediate Attention
IEEE	Institute of Electrical and Electronics Engineers
LV	Low Voltage
METEC	Metals and Engineering Corporation
MIDI	Metal Industry Development Institute
OLTC	On-Load Tap-Changers
ONAN	Oil Natural Air Natural
RCA	Root Cause Analysis
RCM	Reliability Centered Maintenance
RPN	Risk Priority Number
SCADA	Supervisory Control And Data Acquisition

Chapter One

1. Introduction

1.1. Introduction and Problem Approach

The process of gathering and evaluating data to ascertain the root cause of a failure is known as failure analysis. Typically, this is done with the intention of ascertaining who is responsible or what the corrective measures should be(Mo & Cai, 2017). If done correctly and implemented, failure analysis can conserve resources, lives, and money. Failure analysis is a vital tool in the development of reliable products and the enhancement of existing ones(Kimita et al., 2018). Failure of a material component is the loss of ability to function normally and the causes for failure include: improper materials selection, improper processing, inadequate design, misuse of a component, and improper maintenance(Atiyah, 2019).

Root cause analysis (RCA) is a method of problem solving used for identifying the root causes of faults or problems(Abubakar et al., 2016). It is a form of deductive inference since it requires an understanding of the underlying causal mechanisms of the potential root causes and the problem. Its application area is in manufacturing, telecommunications, industrial process control, accident analysis, healthcare industry and others. According to Brandón et al., (2020), RCA can be decomposed into three steps:

- Identify and describe the problem clearly
- Distinguish between the root cause and other causal factors (e.g., using event correlation)
- Establish a causal graph between the root cause and the problem

According to ISO/IEC 31010, RCA may include the techniques Five whys, Failure mode and effects analysis (FMEA), Fault tree analysis(FTA), Ishikawa diagram, and Pareto analysis.

According to Naim et al., (2022), transformers can malfunction as a result of human error, natural disasters, malfunctioning components, overloads, aging, and vandalism. Electricity will be cut off when distribution transformers malfunction in any of the aforementioned scenarios, at least until they are replaced or until a nearby transformer takes over power sharing duties. Transformers typically die from unique stresses that weaken their brittle insulation and shorten their lifespan(Sako et al., 2017). A significant contributing factor to transformer failure is bushing failure, poor operational procedures, which lead to a poor culture of asset maintenance, are a common issue in public utilities(Smith, 2009). Utility companies frequently have workmanship issues when making electrical connections (Amadi & Izuegbunam, 2016). Hence, a single transformer suffers a similar failure reason after getting maintenance from utility personals and similarly failure of distribution transformers can also result from mistakes in manufacturing procedures (Ramachandran, 2021).

This study will be carried out based on 3,825 failed distribution transformers from the year 2019 to 2023 in Addis Ababa. This recent three years' data was collected from AACAEU four districts and Kotebe maintenance center.

The aim of this study was to analyze the root cause of failures of distribution transformers and to overcome those failures by developing appropriate mitigation strategies. The methods that employed in this study for failures analysis were statistical analysis, root cause analysis (RCA) using failure mood and effect analysis (FMEA) and causal loop diagram to analyze the indirect relationship among the causes and effects. By applying asset management techniques, the transformer failure mitigation strategy and model was developed. To be very effective in the implementation phase of asset management, the available transformers have to be changed to smart ones.

1.2. Background and Justification of the study

A power distribution system is a large, complex network that is highly integrated and its effectiveness is measured in terms of efficiency, reliability, and service quality(Kifle et al., 2018). Inaccurate design and operation practices, old infrastructure, a radial network, and excessive exposure to the external environment are the primary causes of failures in electric power distribution systems. Based on AACAEU planning head Mr. Awol, transformers are essential, pricey, and risky components of the transmission and distribution network for energy compared with other components like transmission cable, mounted poles, switchgears and so on but frequently failed component. Hence, this thesis focus on transformers rather than cable, pole, or other elements in a network.

Distribution transformer failure rate in developed nations like the United States of America is 0.8%, 3% in Canada, and 1% in Australia. For distribution transformers, IEEE standards 100/1980 and 500/1984 stipulate a maximum annual failure rate of 3% (Pandit et al, 2017) . This is a concern for all power distribution utilities. Transformers are highly reliable under ideal continuous working conditions up to 30–40 years of design life(Murugan & Ramasamy, 2019). However, few transformers in Addis Ababa City are operating for considerably not longer than 3 years(Tariku & Bekele, 2020).

In different reported studies, the major causes of transformer failures are bushing failure, lifespan of transformers, insulation problem at the high voltage and moisture effects(Aj et al., 2017). They are source of power fluctuations that can bring fire, oil spills, electric system outages, and complete equipment damage, all of which raise unanticipated maintenance or replacement expenses. When a distribution transformer fails, the power supply to all low voltage tension line (LT) consumers fails(Singh, 2020). That means power supply reliability is primarily dependent on the healthy operation of distribution transformers. Most vital transformer components are continuously subjected to various operational stresses during their long-term operation, causing degradation and can lead to catastrophic failures(Tran et al., 2020). These failures resulting in significant financial losses to both consumers and the distribution power utility (AACAEU), as well as power interruption to customers.

In order to prevent transformer failure from happening again as well as to consistently guarantee the quality and reliability of the supplied electric power, the service provider must also be aware of the allowable failure rate(Ramachandran, 2021). However, the failure rate of repaired transformers is approximately twice that of new transformers because of incorrect repairs. Relevant monitoring and diagnostic techniques produce vital information for managing the transformer network effectively and raising the effectiveness, performance, and reliability of the transformers(Ramesh et al., 2022). It is therefore highly desirable to continue making efforts to improve the current traditional maintenance practices in Addis Ababa.

In eastern Addis Ababa, the failure rate of distribution transformers are approximately 6.5% per annum, which is higher compared to the failure rate of 1-2% in the developed countries per annum (Tariku & Bekele, 2020). So, transformer failure mitigation study in the case of Addis Ababa gives direction for Ethiopian Electric Utility (EEU) to provide a reliable service and to satisfy the inquires of customers throughout the whole region of Ethiopia. Healthy transformers can deliver reliable power, that can maximize income for the government by collecting more taxes(Sarajcev et al., 2020). And hence, it maximizes the number of new attracted investments, expansion of established businesses and for the growth of other economic activities. The AACAEU, Ministry of Industry and Manufacturing Industry Development Institute (MIDI) have strong concern in transformer reliability analysis study with failure mitigation strategies.

1.3. Problem statement

Transformer failure is the cause of power interruption and a common serious problem in Ethiopia. Within a day, in the capital city Addis Ababa and the rest of the regions there are several interruptions occurred and it brings early equipment failure, bulb blackening, and lower efficiency of home appliances (Kifle et al., 2018). Similarly, frequent power interruption and fluctuation in Addis Ababa can suffer the community's household electrical equipment burnout, decrease in capacity utilization of different industries and production of defective products. The main causes of frequent electric power outages are transformer failures. According to AACAEU semiannual report of 2020, the opportunity cost lost was around 19,000,000 birr. The frequent failure of distribution transformers, resulting in fire, oil spillage, electric system outage and complete damage of equipment thereby increasing the unforeseen repair or replacement costs. Moreover, transformer failures also result in serious injury to people's lives as well as damage to property because of the high voltage working in contact with oil.

According to Ethiopian electric utility (EEU) 2022 annual report, the maintenance costs of failure of transformers is above two hundred million birr per annum. A single transformer outage can affect directly 50-150 customers connected to it. The major transformer failure can bring fire and oil spillage and which affects people's lives and environment safety. The number of distribution transformers currently available in Addis Ababa is around 9,500 and the average total annual minor and major failure is 1,275 per annum. From 2020/21- 2022/23, three years burned and replaced transformers data, the annual rate of 5% burned and replaced is presenting in Table1.

Table 1.1: Burnout and replaced distribution transformers

No.	Years	Burnout /Replaced	Quantity
1	2020/21	Burnout	274
		Replaced	261
2	2021/22	Burnout	224
		Replaced	216
3	2022/23	Burnout	183
		Replaced	137
Total		Burnout plus Replaced	1,295 = (681 +614)

Source: - Addis Ababa City Administration Electric Utility (AACAEU)

In general, transformer failure leads to loss of revenue to electric utilities, customers, manufacturing industries, micro and small enterprises and commercial and service institutions which are being affected by the power fluctuation.

1.4. Research Question

This research study will be expected to answer the following questions:

1. What are the major causes of transformer failure and their impact?
2. what mitigation strategies will be developed?

1.5. Objectives

1.5.1. General Objective

The main objective of this study is analyzing the root causes of transformer failures and to minimizing those failures by developing appropriate mitigation strategic.

1.5.2. Specific Objectives

- To identify sources and causes of transformer failures
- To analyze the impact of failed transformers and
- To identify current maintenance procedure used
- To develop mitigation strategies to minimize failures, risks of failures and improve the reliability of transformers.

1.6. Scope and limitation of the study

1.6.1 Scope of the study

The scope of this research study is limited to the failure of any one of the power distribution transformers in the electric grid contributes for electric power interruptions found in Addis Ababa city. For the purpose of managing electric power, transformers failure data has been collected from the AACAEU office or from the four electric utility districts and zonal maintenance centers of Addis Ababa. This study mainly focusses on failure causes related with distribution transformers failures. To forecast future occurrences of transformer failures, to design which proper strategic solution is suitable for mitigating this serious issue and to know the maintenance trends found in AACAEU maintenance centers. Finally, this study included all varieties of failure of distribution transformers with different sizes, variety of transformer component failures and geographically covers the whole Addis Ababa

1.6.2. Limitation of the study

The main data provider. AACAEU is a government owed organization The bureaucratic nature of service delivery in AACAEU has been some impact to get the required amount and type of quality data on time. Other constraints were the unavailability of some respondents in their office during working hours affect the study to get more respondents data through interview. However, the study was performed within these limitations.

1.7. Significance of the study

The availability of electricity boosts a nation's economic development. On the other hand, power outages and shortages have a detrimental effect on economic growth and the productive contributions of society to the expansion of the economy. Electric power outages are currently having a detrimental impact on people's daily lives in Ethiopia. The problem becomes much worse when there is a power outage that lasts for days or even weeks. Therefore, by examining one of the potential causes of power interruptions, power transformer failures, this study helps to improve the country's reliable supply of electric power. The study provides practical significance for electric utilities on how to manage power transformer failures, keep critical assets safe, and monitor failure risks. These contributions will result in theoretical concepts development to improve transformer reliability, resulting in a reliable supply of electric power. Improved and dependable electricity supply fosters a safe, happy, and productive society, as well as profitable industries. This will almost certainly contribute to the country's overall economic growth.

1.8. Organization of the paper

This paper is organized in six chapters. The first chapter is an introductory part, which contains the problem statement, research questions, objectives, scope and significance of the study. The second Chapter which is the related literature review part on how to analyze Transformer Failure Root causes and its effects, and review of studies on failure mitigation systems and identifying gaps. The third chapter states the methodology approach, data source, tools, methods of data collection and analysis was discussed. The fourth chapter deals with the data collection and analysis, model development, result and discussion. The fifth chapter shows the developed failure mitigation strategy, implementation procedure and validation. Finally, the six chapter states the conclusion, recommendation and future study area.

Chapter Two

2. Literature Review

2.1. Introduction

This literature reviewed covers various related articles and other supplementary materials on transformer failure root cause analysis, diagnostic test, maintenance systems and proposed solutions. The literatures relevant to this thesis focusing on emerging fault conditions and failures are gathered and discussed in this paper. And hence the literature gaps were identified in order to fill the body of knowledge

2.2. Reliability Challenges in Power Distribution Network

The term "reliability" refers to the system's capacity to supply an adequate supply of electricity and energy. As a result, the topic of distribution network reliability analysis is not new in the electric power industry; numerous studies and research have been conducted in response to the rising cost of blackouts and fault outages (Anthony et al., 2014). However, because its effects are more localized, a distribution network is slightly less expensive than generation and distribution. According to Anteneh (2020), an examination of the customer failure statistics of the majority of utilities demonstrates that the distribution system makes the greatest individual contribution to the inability of customers to obtain electrical power.

Reliability of a power system is influenced by a few major factors. There are four categories of factors that affect the reliability of power systems. Reliability of components, conditions of the environment, loading, and system configuration (Escalera et al., 2018). Similarly, to ensuring the distribution networks reliability to reach in an adequate level the following traditional approaches are required: meshed grids (parallel components, alternative supply-restoring feeders, etc.), improved asset upkeep, the use of more dependable parts, and the addition of more protection devices. And also, new set of opportunities exist for further enhancing supply reliability as distribution networks shift toward Smart Grids and more environmentally friendly energy systems (Brown et al., 2018).

The purpose of the power distribution system was primarily to provide customers with a sufficient supply of electricity at a reasonable cost and with reasonable assurance of reliability(Mohamad et al., 2018). In Addis Ababa, power distribution networks size and technology have increased exponentially over the past few years. As a result, the utility company needs to make every effort to meet the reliability needs of its customers at the reasonable possible cost.

Power availability in distribution system depends on the state of operation of system equipment. Any equipment failure results in power interruption. Failure rate modeling and repair time prediction is a very difficult task. Failure and repair rates of different equipment have different wear out curves and life time curves(Kuno et al., 2022). Hence, it's a challenge in estimating reliability of a system. Only general equipment operation assumption of failure rates, normal operation and wear out time can be modeled like that of bath- tub component life time curve. This puts the composite system reliability have no uniform model and representation for all system components.

Generally**, c**ompared to generation and transmission systems, reliability studies of distribution network systems have received less attention. The inadequacy of reliability operation of distribution network can have widespread effects on society and the environment due to their capital-intensive and safety issues.

2.3. Distribution Transformer Operations

A distribution transformer(DT), also known as a service transformer, is a transformer that performs the final voltage transformation in an electric power distribution system, stepping down the voltage used in distribution lines to the level used by the customer (Howlader et al., 2018). AC power distribution became feasible with the invention of a practical efficient transformer; a system using distribution transformers was demonstrated as early as 1882(Brusso et al., 2021). Distribution transformers mounted on a utility pole are known as pole-mount transformers. And if they are mounted on concrete pads and locked in steel cases if the distribution lines are above ground or underground, and are thus known as distribution tap pad-mount transformers(Harcourt, 2014).

Distribution transformers (DT) are energized 24 hours a day (even when they are not carrying any load), reducing iron losses is critical in their design. They are designed for maximum efficiency at lower loads because they are rarely used at full load. Voltage regulation in these transformers should be kept to a minimum to improve efficiency(Jarrahi et al., 2019). As a result, they are designed to have a low leakage reactance. Under normal conditions, distribution transformers operate with a load factor of 40 to 60 percent. In addition, only 25% of a network's distribution transformers are capable of accommodating peak load demand, and even then, only for a brief period of time (Arumugam, 2021). Due to their low load factor, distribution transformers are assumed to be invulnerable to all failure scenarios. Consequently, corrective maintenance procedures are frequently applied to existing distribution transformers.

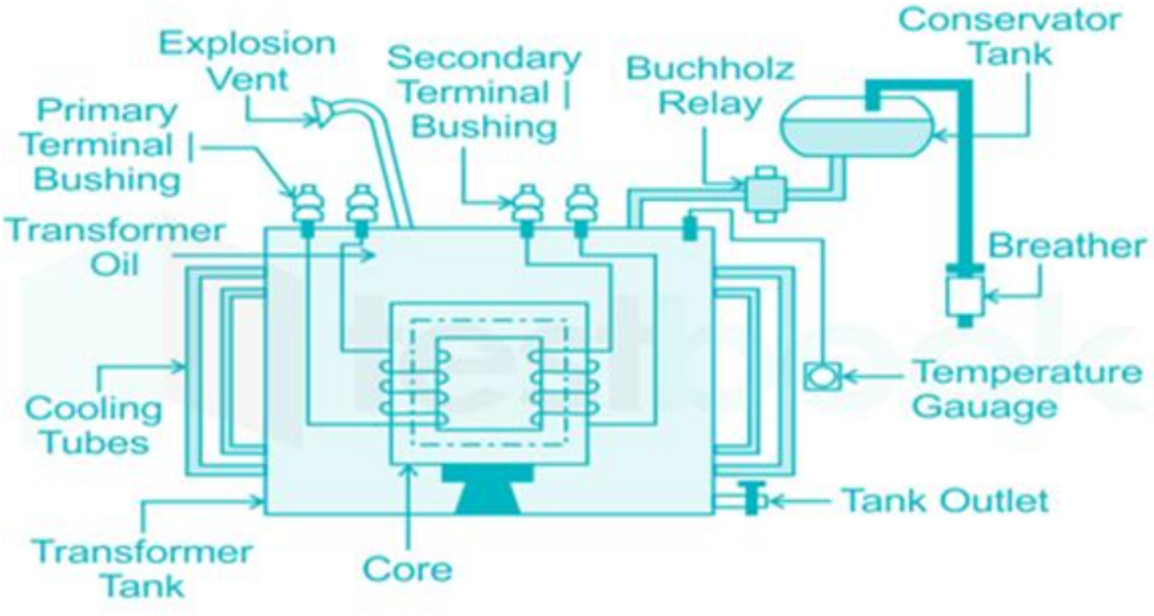

Figure 2.1: Transformer main components (SSC JE EE,2022)

The main components of distribution transformers shown in Figure 2.1 that directly affected by failure causes are core, primary and secondary winding, transformer body tank, insulation oil, cooling tubes (radiating tubes), breather, oil conservator tank, buchholz relay, bushings, tap changer, explosion vent and temperature gauge.

Overloading, transient conditions, internal winding issues, and a variety of other factors can cause internal failures in some distribution transformers (Ndungu et al., 2017). The majority of these internal failures may go unnoticed during the initial phase and only become apparent when the situation becomes terrible (Arumugam, 2021). As a result, diagnostic tests are essential for monitoring distribution transformers.

Generally, very limited research is done on prediction distribution transformers operations which step up or down the voltage levels, mounted in pol or pad and working for 24 hours a day with maximum efficiency at lower loads. Continuous operation of distribution transformers at full loads can lead to failure of insulation due to overheating generated in the transformer. There is transformer overload for an extended period of time, transformer operation with nonlinear loads, a malfunctioning cooling system, obstruction of oil ducts, transformer operation under excessive stress and transformer operation in temperatures above ambient have not had attention by many researchers.

2.4. Significance of early diagnostic Measurements

The AC power system is a complicated network, and failures in power transformers result in significant financial loss due to power outages and the expense of replacement or repair for a variety of causes(Isaac et al., 2019). In order to determine the state of the transformer, inspections use data collection and information on cases of transformer failure (Guo et al., 2020). Tests of chemical, electrical, thermal, optical, and mechanical properties are frequently utilized in the diagnosis of problems with transformers (Aj et al., 2017). A chemical diagnostic approach that incorporates furfural analysis provides the most significant results, widely used, and is the most significant diagnostic method when compared to the other methods (breakdown voltage and dissolved gas analysis, or DGA). Data collection and information on transformer failure cases are used in inspections to determine the state of the transformer(Guo et al., 2020). Chemical, electrical, thermal, optical, and mechanical tests are frequently used to diagnose transformer problems(Aj et al., 2017). From these tests, the most impactful results are produced by a chemical diagnostic approach that includes furfural analysis delivers the most significant results, most popular and important diagnostic methods compared to the other methods (breakdown voltage and dissolved gas analysis (DGA)).

A lot of attention has been paid to power transformers mechanical durability of the windings, the effect of temperature and moisture on the power transformer's insulation, the effect of terminal connections on improving the sensitivity of relevant diagnostic methods, and the use of non-conventional methods to determine the power transformer's inter winding capacitance (Arumugam, 2021). However, distribution transformer diagnosis is neglected in every transformer failure mitigation literature and hence, research needs to be conducted on this issue. Five failure analyses of transformers, including: 1) periodic testing, 2) services, 3) protective operation, 4) insulation issues, and 5) others (bushing faults, development, lightning, etc.), which need to be looked into in order to advance production technology and maintenance schedules(Arumugam, 2021). However, the testing procedures now used on distribution transformers are not diagnostic, but rather uses corrective actions after a malfunction has already happened which is outdated and only provide information of the case.

In general, few research studies investigate diagnostic methods in power transformers which is very essential to overcome the possibility of occurrence of failures at the source point. But, early diagnosing method of distribution transformer is not studied because of high demanding cost.

2.5. Failure Cause and Identification in Transformers

Failure cause of transformers can be defined as Physical or chemical processes, design problem, quality defects, misapplication of parts, or other processes that cause the failure or can initiate a physical process that leads to the failure (Chawda, 2015). High rates of current rise, multiple flashes, and positive lightning flashes are the lightning parameters most closely associated with transformer failures. Low impedance faults are frequently the result of transformer saturation during the prolonged lightning return stroke and continuing currents(Hoole et al., 2017). Despite the possibility of underlying causes like lightning or fuse operations, the investigation concludes that the majority of failure causes are related to electric current. Voltage spikes, oil arcing, and oil decomposition and discharge are all possible outcomes of excessive electric current in fault situations, whether it comes from lightning or another source.

Root cause analysis has been used to pinpoint insulation problem due to switching surges, over voltage and line faults and fuse burnouts due to overvoltage and vandalism of earthing system are the two main contributors to the failure of distribution transformers (Ndungu et al., 2017). However ,transformers can fail for a variety of reasons, including improper operation and maintenance(Jan et al., 2021). When transformers run at high temperatures, high voltages, or are overloaded to the point that they draw a lot of electric current, the insulation can become damaged, ultimately causing the transformers to fail completely. Transformer failure can also be attributed to improper on load tap changer (OLTC) operation, which is one of the contributing factors(Hoole et al., 2017). The manufacturer's instructions should be followed while using OLTCs, and in the event of a malfunction, the transformers should be fitted with protective relays and monitors that differ depending on their size, rating, and voltage level.

Diverse study and test analyses have been carried out in an effort to determine the root causes of the transformer's failure in the power system and the measures that can be taken to prevent future breakdowns(Martin et al., 2019). However, the study mainly focuses on bushing failure and ignoring the other man-made and natural causes of failure.

A distribution transformer's failure rate throughout the course of its service life follows a curve with a "bath-tub"-like shape(AJ et al., 2018). This "bath-tub" curve shows that distribution transformer failures are at their maximum during the initial (installation and commissioning) and final stages (typical end of service life), while they are at their lowest during the intermediate stage.

Under high electrical fields, transformer oils provide electrical insulation; It's possible that the oil is no longer capable of carrying out this essential function if there is a significant decrease in the dielectric capacity. Even a minor fault, such as damage to the insulation of the core bolt or local overheating, creates an arc that slows down the oil's gas production. The localized heating and decomposition of oil is caused by every fault in the transformer core and windings (Esteban et al., 2020). However, the safety issue related with failed transformer oil have not seen. According to the literature, distribution transformer failures are attributable to insulation, overloading and winding-core failures.

Distribution Transformer Failure in India Root Causes and Remedies (Pandi,2017) and Causes of Failure of Distribution Transformer and its Remedial Measures (Chawda, 2015) summarized under Table 2.1 shows the causes of failure, factors behind the cause and also recommends some solution.

Table 2.1: Major causes of failure and their remedies summary(authors)

No.	Causes of failure	Remedies
1	Overloading due to no record of the transformer's loading, loading without authorization and Power theft or misuse	✚ Keeping accurate records of the total number of customers and connected loads ✚ Keeping accurate records of the transformer's loading ✚ Metering of the distribution transformer
2	Imbalance loading Factors such as absence of record on the phase, Improper service connection without taking considering the phase load	✚ Keeping track of the phase-by-phase loading and regular load balance in a timely manner. ✚ Providing service only from the appropriate phase(s) after carrying out the proper shutdown ✚ Phase conversion.
3	Low transformer oil level factors like oil leakage and oil thefts	✚ Proper tightening of terminals and joints and replacement of loose/burnt out gaskets ✚ B) Proper sealing of valves
4	Low break Down Value (BDV) of the transformer oil and poor insulation resistance (IR) value factors like overheating, contamination and moisture, dissolution of varnish and cellulose leads to formation of acid, sludge formation	✚ Augmentation of transformer or construction of a new substation. ✚ Proper tightening of terminals and joints. ✚ Replacement of deteriorated gaskets. ✚ Replacement of cracked bushings. ✚ E) Prompt replacement of deteriorated silica gel & dirty oil in the breather.
5	Poor earthing or absence of earthing due to undersized loop from the conductor to the lighting arresters, high soil resistivity, earth	✚ Periodical checking of the soil resistivity. Renovation of earth pit or making a new earth pit. ✚ Usage of the appropriate size of earthing loop.

	wire rested or disconnected and no lightning arrestors	✚ Periodical checking of earth wire and earth connection. ✚ Tightening of the terminal connections. ✚ Earthing loop of lighting arrester's is to be separate.
6	Improper or poor cable terminal factors, such as loose connection and poor lugging	✚ Proper tightening of terminal connections. ✚ Proper lugging and usage of appropriate size of lugs.
7	Vandalism factors like unsecured substation and public ignorance	✚ Proper fencing and the gate (with lock if needed). ✚ Danger plate in the substation. ✚ Public awareness through media and meetings

In general, different researchers investigate various factors that contribute to transformer failure, such as improper cable terminals, overloading, imbalance loading, low transformer oil level, external short circuit, overrated fuse, flash over, and vandalism. However, the factors that contribute to transformer failure are not broken down into fundamental(primary) and derived causes. Failures that occur as a result of mechanical, electrical, or thermal stress failure modes leads to fundamental causes of failure are not discussed.

2.6. Transformer Failure Modes

Failure Mode can be defined as the way in which a failure is observed, describes the means the failure occurs, and its impact on transformer operation. It is always challenging to identify a specific mode of failure for a transformer, which can fail as a result of a combination of electrical, mechanical, or thermal factors. The majority of transformers fail due to insulation failure. Therefore, insulation failure caused by electrical, mechanical, or thermal stress may cause the transformer to fail electrically(Singh & Singh, 2016). Hence, most of the failure factors are 1) Electrical Factors: - Transformer failures can be caused by a variety of electrical factors that can be broadly categorized into the following three groups: Transient or overvoltage conditions; surges of lightning and switching; Discharging in part. 2) Mechanical Factors: - Damage to the transformer's solid insulation and break is because of mechanical cause. The transformer may go out of power electrically if there is severe damage. The transformer's winding may break due to electromechanical forces or shipping damage. 3) Thermal Factors: - Heat generated during normal transformer loading degrades the cellulose insulation over time. It reduces the insulation's dielectric strength and makes it more likely to rupture under normal voltage conditions.

Generally**, i**nsulation failure is caused by either one failure mode factor or more than one failure mode factor which is the major source of transformer failure. Electrical, mechanical, or thermal stress failure mode of transformers have not given enough attention by many researchers who studied transformer failure.

2.7. Failure types and Transformer failure

Failure can be defined as the inability of a component/system to carry out its intended function at a particular time and under specific operating conditions (Tamssaouet et al., 2020). Similarly, an interruption in supply occurs when a functioning electrical power system fails and cannot supply electric power to all or any of its customers. A system's failure can be broken down into two categories: faults, both damaging and non-damaging (Afsharnia, 2017). So that, a failure of an item that results in the operation of the surrounding protection devices is referred to as an active failure. In this instance, protection devices include a fuse or breaker that, when activated, trip (open) and isolate the failure.

A passive failure is one in which an object fails without affecting the surrounding protection systems. Most of the time, a passive failure occurs when breakers are accidentally opened or circuits are open. The outages caused by the protection devices fall into the second category of failures, which are non-damaging faults (Mariprasath & Kirubakaran, 2018). Hence, depending on how the fault is fixed, these outages are categorized as temporary forced outages or transient outages. The outage is temporary forced if a protection device automatically restores, as the outage duration is negligible. Other kinds of safety devices must be manually restored, either mechanically or by replacing a fuse (Afsharnia, 2017). Because these kinds of things take time, the outage is called a temporary forced outage. Outages may occur at a number of these devices' load points if an active failure event occurs and the protection device around it opens. These occurrences are referred to as additional active failures because they are not directly triggered by a damaging fault. A failure mode known as additional active failure occurs when one system component's active failure interrupts other system components (Mariprasath & Kirubakaran, 2018).Not only does replacing or repairing the damaged transformer cost money, but the utility also loses money as a result of not being able to supply customers with power. The sum of the probability of failure and its consequences is known as the risk of failure. It is essential to lower the failure rates in order to decrease the risk of failure and enhance the system's reliability (Tamssaouet et al., 2020). The system's decreased reliability as a result of frequent power supply failures is another significant drawback of systematic investigation of a real-time field data collection for distribution transformer failures. The aforementioned concern about transformer failures has been incorporated into a number of international standards (Singh & Singh, 2016).

2.7.1. Transformer failure classification

Like many electronic devices, a power transformer experiences numerous failures. MIL-STD-1629A standard is utilized to group various shortcomings that happen (Ndungu et al., 2017). For the past 40 years, it has been the most widely used standard worldwide. Each fault is initially grouped into two classifications which are further subcategorized. The first category the faults are classified are on the basis of severity of the fault. The bigger the fault the more sever it is (Jan et al., 2021). Table-2.2 shows this classification.

Table 2.2: Severity classification for transformers

Value	Description	Criteria
1	Category IV (Minor)	Primary function can be done but immediate repair is required
2	Category III (Marginal)	Reduction in ability to primary function
3	Category II(Critical)	Causes a loss of primary function
4	Category I (Catastrophic)	Product becomes inappropriate

The second category in which faults are categorized is based on when the fault occurred. The severity of a fault increases with its frequency (Jan et al., 2021). This is shown in Table 2.3.

Table 2.3: Occurrence of failure classification for transformers

Value	Description	Criteria
1	Level E (Extremely unlikely)	Probability of occurrence less than 0.001
2	Level D (Remote)	Probability of occurrence more than 0.001and less than 0.01
3	Level C (occasional)	Probability of occurrence more than 0.01and less than 0.1
4	Level B (Reasonably Probable)	Probability of occurrence more than 0.1and less than 0.2
5	Level A (Frequent)	Probability of occurrence more than 0.2

2.7.2. Priority Number (PN)

Each fault has a numerical value called Priority Number (PN) that is determined by the fault value from the three tables above. When a fault occurs, equations is used to determines the priority number (PN) = Severity * Occurrence * Detection (Ndungu et al., 2017). The smallest possible number of PN for any fault is one, while the largest possible number is. Additionally, the probability of the fault occurring before it does is forecast using the PN, allowing necessary preventative measures to be taken.

The Risk Priority Numbers are then ranked in order of importance. Although FMEA has proven to be essential in various industries, there are some shortcomings with this method. Inherently, FMEA is a qualitative approach and the value of Risk Priority Number is not conclusive unless it is used in comparison with other Risk Priority Numbers from other parts of a system, for prioritization purposes (Arias Velásquez & Mejía Lara, 2020). This method also requires scaling of different affecting parameters and so far, there is no one-fits-all method for a proper scaling (Meekhof & Bailey, 2017).

Generally, **t**ransformer failure can be classified based on severity of failure (minor, marginal, critical and catastrophic), occurrence of failure (unlikely, remote, occasional, probable and frequent) and failure risk priority number (RPN = severity* occurrence* detection). These failure classifications have great role to solve transformer failure in sequential order manner but they have limited attention by previous researches.

2.8. Transformer failure impacts

A single distribution transformer is made up of many different parts that work together. Each of these various components has distinct flaws that result in distinct failures. Some are more severe than others, some happen more often, and others are hard to spot(Jan et al., 2015). However, a single fault affects many other parts of the transformer, so a small fault can cause a larger failure in the transformer. And hence, transformer experiences numerous failures, the severity, frequency, and method of detection of each of these failures determine the unique priority numbers (PN) assigned to them. As a result, failure modes, their failure causes, their failure effects, and a common index that is used to measure the severity of the failure are used, typically the risk priority number (RPN) (Arias Velásquez & Mejía Lara, 2020). It is determined how a failure mode affects a system's operation, function, or status. Whether the component will be replaced or whether the malfunction will result in transformer failure.

A step in determining how serious the identified effects would be if a given failure occurs is severity. From "no failure" to "severe," a severity number from 1 to 10 is assigned to each effect. These numbers make it easier to rank the failure modes and the effects they have(Singh et al., 2019). The necessary step for determining the number of times a failure occurs is Probability of Occurrence. It is based on the actual failure frequency data that was gathered. A failure mode typically receives a score between one and ten, with ten representing "no occurrence" and one representing "high occurrence." The numerical estimate of the failure modes that result from a specific cause is known as the probability of detecting, and it is used to prevent the effect of failure. From high detection likely to almost impossible, a scale of 1 to 10 is used. RPN is calculated by ranking for severity, detection probability, and occurrence probability. Particularly, transformers are experiencing accelerated aging and an increased risk of failure as a result of thermal stresses(Soleimani & Kezunovic, 2020). Due to the accelerated loss of life, a premature transformer failure may increase the frequency and length of service interruptions and place an unanticipated financial strain on the utilities' asset management budget.

Its actual impact on the transformer's health during operation by evaluating the oil parameter following each fault(Paul et al., 2020). This study tries to find out how voltage sag actually affects power transformers, how it affects insulating oil, and how long they last in service. Natural ester dielectric insulating fluids have been shown to have less of an impact on the environment as well as improved safety and performance for older transformers when driven by appropriate handling and specialized engineering evaluation(Asano & Page, 2014). However, the transformer oil used in Addis Ababa is mineral hydrocarbon oil which is risky for environment health and safety.

In general, **t**he impact of a transformer failure is numerous, ranging from financial loss to the loss of customer reliability. As a result, utility companies must make every effort to lessen the impact of transformer failure. In the past, little research has been done on the predictive methods for transformer failures caused by a variety of internal and external factors. This is due to the fact that failure is difficult to predict precisely and that makes it difficult to prevent. As a result, advanced mitigation strategies like timely field crew positioning, early health assessment techniques, and timely transformer replacement or repair could lessen the impact of transformer failure.

2.9. Transformer Failure analysis

2.9.1. FMEA

The root cause analysis, diagnosis and classification of faults in power transformers with high accuracy and efficiency is the fundamental key to ensure reliability and power quality with least interruptions (Arias Velásquez & Mejía Lara, 2020). The distribution system's reliability is affected when a transformer fails. In order to save the transformers in the future and improve the system's reliability, it is necessary to determine the causes of transformer failure. Failure Modes Effect and Criticality Analysis (FMECA) is utilized for this purpose (Singh et al., 2019). The most crucial approach to failure analysis is this one. An important step in failure analysis is the FMECA, which determines failure modes, causes of failure, effects of failure, their severity, and preventative measures. FMECA is put into action in two parts. In the first section, the failure modes and effect analysis (FMEA) are carried out, and in the second section, the severity and likelihood of occurrence of failure modes are used to classify them for the criticality analysis.

FMEA is considered as a process of ranking the most critical parts of a system; and it can be used for efficient resource allocation and maintenance scheduling based on higher priorities (Meekhof & Bailey, 2017). FMEA is a proactive process to determine several key potential failures in the system through the comparison of some predefined factors, and as a result, it helps increase the reliability and availability of that system. This process has been used on almost any equipment from cars to space shuttles. In FMEA study, after determination of the failure modes, the main calculation procedure comprises of three steps (Peeters et al., 2018): 1) The probabilities of the failure modes occurrences need to be determined. These may be obtained from the previous data for the failed parts. These probabilities are then categorized and assigned a scaling number; with the lowest number for the least probable category. 2) The rate of severity of each failure mode is assigned and scaled due to the consequences of the failure and the amount of damage to the equipment. 3) Another scale number is assigned to the fault detection possibility; with the lowest number to the most likely detection of the failure.

FMEA is a method for systematically evaluating potential failure modes, their effects, and their causes. The ways in which something could fail are known as failure modes. Effects analysis refers to studying the consequences of those failures. The FMEA's goal is to take steps to reduce or eliminate failures, starting with the highest priority ones. The method of the analysis can be qualitative or quantitative. A FMEA's fundamental steps could be (Franzén & Karlsson, 2007). These are 1. Define the system that will be analyzed. System boundaries, internal and interface functions, expected performance, and failure definitions are all part of a complete system definition. 2. Determine the failure modes that are connected to system failures and make a list of all the possible causes of failure for each function. 3. Determine the possible effects of failure modes and identify the system's consequences for each failure mode. 4. Determine the severity of each effect and rank them. It is necessary to identify and determine the equipment that had the greatest impact on the system's overall operation. 5. Find all of the possible root causes for each failure mode, 6. Identify the available methods of detection for each cause and determine RPN and 7. Determine the recommended actions that can lessen the severity of each failure for each cause.

The FMEA process consists of the following: FMEA Prerequisites, Functional Block Diagram, Failure mode analysis and preparation of work sheets, Team Review' Corrective action (Villacourt,1992). Similarly, the FMEA analysis which consists of the items listed in the figure2.2 are procedures to be followed strictly.

2.9.2. Fault tree analysis (FTA) and Fish bon diagram

Fault tree analysis (FTA) is the most commonly used technique for causal analysis in risk and reliability studies. Fault tree analysis is a failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events. FTA is basically composed of logic diagrams that display the state of the system and is constructed using graphical design techniques. Originally; engineers were responsible for the development of Fault Tree Analysis, as a deep knowledge of the system under analysis is required (Peeters et al., 2018): Fault trees are built using gates and events. Most commonly, fault trees are composed of "AND" and "OR" gates, connecting the events toward the root failure. If either of a group of events causes the top failure to occur, then those events are connected using an "OR" gate. On the other hand, if all events need to occur to cause the top failure, they are connected by an "AND" gate. The kinds of gates used determine whether a fault tree is static or dynamic. A static fault tree is one in which only static gates like AND, OR, and k-out-of-n are used in the fault tree (Ruijters & Stoelinga, 2015). A fault tree is considered to be dynamic if it includes both static and sequence-dependent gates. Each of the failure causes may also be further explored to determine the failure modes associated with them. However, the expansion of the tree is dependent on how much detailed data are available from operation history of the equipment.

In the context of system operation and environment, the fault tree analysis is a tool for identifying and evaluating the combinations of undesirable events that can result in an undesirable system state. It is widely acknowledged as an important tool for system design, development, and operation's safety and dependability. A top event represents the undesirable state of the system (Brier & lia dwi jayanti, 2020). The system's weakness can be found and potential upgrades can be evaluated using fault tree analysis. Additionally, fault tree analysis can be used to determine the causes of a system failure that has been observed and offer potential solutions. This method has been used and improved over the years. It is appealing because it does not require a lot of theoretical work and is a practical tool that any engineer can easily learn to use. A fault tree analysis is a logic diagram that shows the relationship between potential events and how they could affect system performance (Brier & lia dwi jayanti, 2020). Using fault tree analysis, protection engineers can easily compare the reliability of the proposed transformer protection. Probability theory, Boolean algebra, and reliability theory are the foundations of fault tree analysis. The mechanism for analyzing extremely complex systems and the intricate connections between hardware, software, and humans is a very straightforward set of rules and symbols (Ruijters & Stoelinga, 2015).

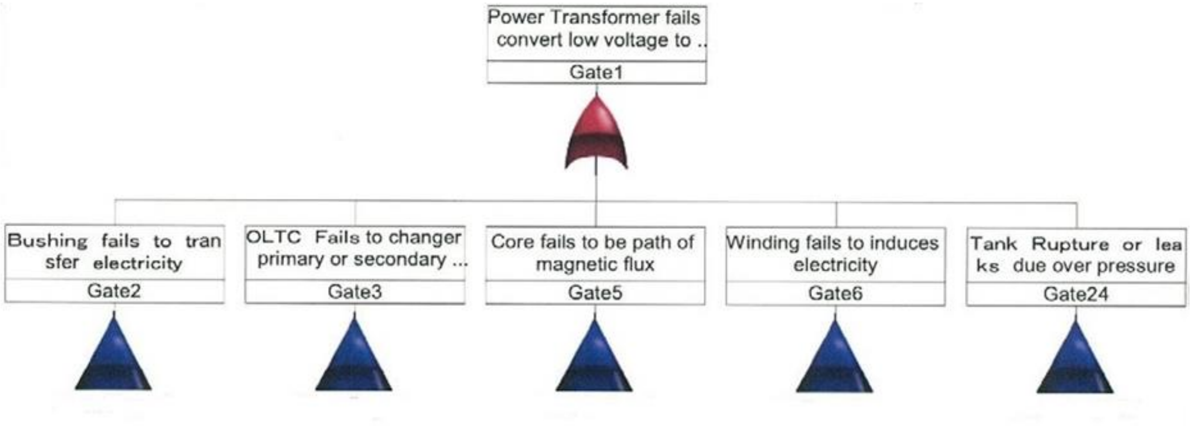

Figure 2.2: Top event of power transformer fault tree (Brier & lia dwi jayanti, 2020).

Modeling the system and creating a transformer fault tree based on its function and main component structure are the first steps. After that, a top event was identified, and the subsequent events in the fault tree were deduced step by step (Brier & lia dwi jayanti, 2020). The transformer fails to convert low voltage of electricity to high voltage of electricity is the primary occurrence in this study. The failure of the five primary devices, which are referred to as the sub-top events, constitutes the top event failure. The minimal cut sets and qualitative importance are then determined in qualitative fault-tree analysis.

The cause and effect (fish bone diagram) analysis of the failures were identified; allowing the identification and selection of the variables that affect the operation of transformers. The cause can be divided into external and internal (Marriaga-Márquez et al., 2020). External short circuits are faults that are related to the environment in which the transformer is located. These faults can be caused by vandalism, failures in the circuits of the end users, contact between distribution lines caused by wind gusts, or the short circuit being caused by contact with a tree, animal, or other object. Internal issues include failures caused by moisture and a lack of tightness, broken output terminals, low oil levels, factory defects, and damage caused by improper transport and assembly handling.

According to Murugan & Ramasamy, (2019), transformer components that are most susceptible to damage from mechanical, electrical, and thermal stress include the active part (winding and core), on load tap changer, bushing, insulation (Oil & Paper), and tank.

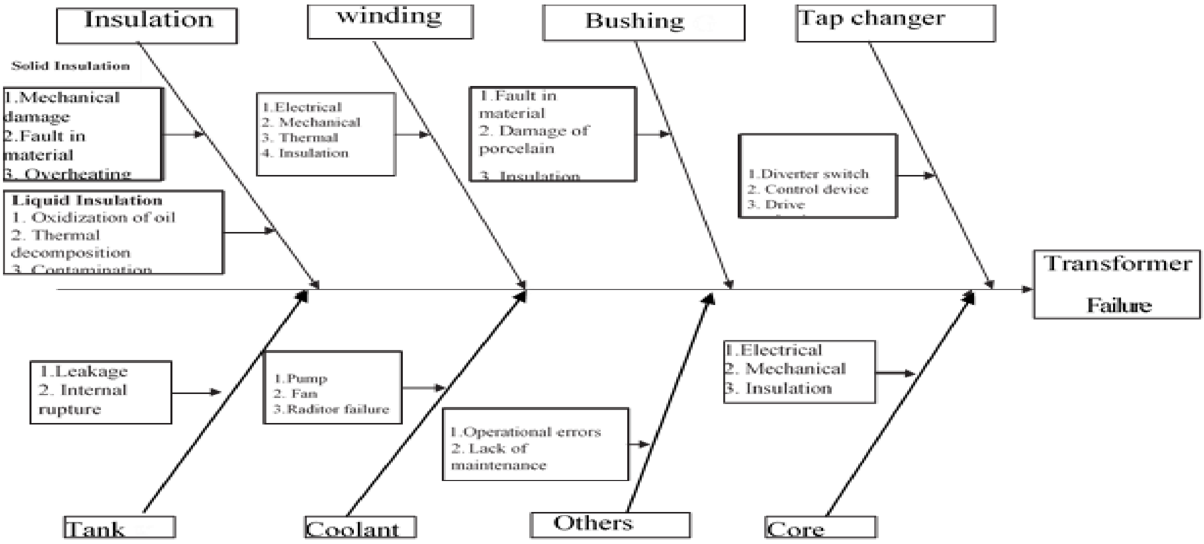

Figure 2.3: Fishbone diagram of transformer failure (Murugan & Ramasamy, 2019).

Generally, previous researches on transformer failure analysis were done by using either of FMEA, FTA, RCA cause and effect methodological failure analysis tools. But almost no research study uses the mixed tools to analyze transformer failure. A single defined adverse effect of component failures can be analysed by FTA and the range of all single component failure effects identification can be done by using FMEA.

2.10. Causal loop diagram Modeling

A causal loop diagram (CLD) is a visual representation of a system's structure and feedback processes, as well as how interrelated variables affect each other (Morecroft, 2020). The polarity of a loop is determined by counting the number of negative links in the loop. If the number of negative links is even, the loop is reinforcing. Reinforcing loops are sometimes referred to as positive loops. If the number of negative links is odd, the loop is balancing. Balancing loops are sometimes referred to as negative loops (Loh et al., 2020). Hence, a CLD to demonstrate causal links between essential elements.

In general, CLD model comprised of balancing (negative feedback), reinforcing (positive feedback) loops (causal circles) and their causal relationships. To show the complexity of nonlinear relations among FMEA elements in the failed transformer components and its elements.

2.11. Different Maintenance Practice system

The distribution transformer would then be taken offline and corrective measures would be taken, like changing the oil or doing some remodeling, which only results in an increase in investment costs (Arumugam, 2021). However, it is anticipated that using monitoring techniques will be too costly. Big amount of money would be spent on corrective maintenance tests would help maintain the transformers' normal lifespan, decrease power fluctuation, increase customer satisfaction and avoiding costly scrapping and refurbishment. The researcher's idea on the current practice of maintenance system is corrective maintenance, which results in an increase of cost and loss incurs.

Unplanned maintenance: - When unexpected and unanticipated malfunctions occur, unplanned maintenance is typically carried out (Gackowiec, 2019). Specifically, it applies when a piece of equipment stops working. The installation of an immediate-operational piece of equipment is required for this kind of maintenance. The purpose of the actions, which are only carried out after the issue has been discovered, is to restore the equipment to its previous state of operation. This sort of support is called responsive upkeep and permits you to save time since there is no need in making a support plan and nothing is finished for however long everything is filling in as it ought to be. When compared to other methods of maintenance, this one has the major drawback of requiring a significant amount of asset downtime when a problem arises (Trojan, 2018).

Planned maintenance: - In the instances in which this policy is implemented, planned maintenance is organized well in advance and the utilization of previously established maintenance plans is carried out at the most suitable time. It is typically carried out at regular time intervals (Canfield & Ieee, 1986). There is no established procedure for this planning, but it involves the preparation and programming of the planned maintenance (PM). It depends on the information from experts and designers gained throughout the long periods of work (Gackowiec, 2019) . The recommendations provided by the Original Equipment Manufacturer (OEM) are another method by which PM is implemented. There are two main types of maintenance in PM: maintenance, both preventative and reactive (Gackowiec, 2019). The user is responsible for choosing the best approach to take to keep the equipment from breaking down or ejecting altogether.

Preventive maintenance: - The goal of preventative maintenance is to stop a failure from happening. Utilizing this kind of maintenance longer lifetime of the resource is conceivable and costs decreased, further developing accessibility (Trojan, 2018). This sort of support is expected to forestall disappointments or even the complete loss of the resource. They are based on information obtained through the processing and analysis of equipment data. The fact that a maintenance plan for the equipment must take into account the most pessimistic scenario in order to completely avoid any kind of shutdown is one drawback of this strategy (Gackowiec, 2019). Along these lines, support will be done more frequently than would be needed bringing about significant expenses for organizations.

There are two distinct categories of preventive maintenance methods that both contribute to improved maintenance decision-making (Trojan, 2018):

Time-Based Maintenance (TBM): - involves carrying out the equipment's scheduled maintenance tasks on a regular basis. Essentially, TBM assumes that the equipment's failure behavior can be predicted. However, this method may become costly if inspection intervals are short because of the need for specialized staff and unnecessary checks, shutdowns, and maintenance (Havbro, 2019). However, it is able to catch equipment problems early, which can save the business money in the long run.

Condition-based maintenance (Predictive maintenance): - According to the current development line, it is necessary to know the equipment's current condition in order to devise a plan that maximizes, for instance, the asset's life cycle (Gackowiec, 2019). Thus, the concept of condition monitoring serves as its foundation. Based on the analysis of the data gathered through its monitoring, this kind of maintenance results in periodic or continuous asset control (Havbro, 2019).

Corrective maintenance: - This kind of upkeep movement is performed upon the event of disappointment and it is the most basic sort of support (likewise called race to-disappointment or responsive support) (Gackowiec, 2019). The asset must be repaired so that it can perform its function once more because it can cause service interruptions (high equipment downtime) and affect system performance when it fails. To put it another way, the part is used until it breaks (Trojan, 2018). Due to the unpredictability of failures and possible repair costs, it is difficult to estimate the associated budget.

In addition, assuming the risks associated with failure, such as collateral damage to other assets, by only intervening when a failure occurs. Assets that are simple to replace or repair and perform a non-critical function or do not significantly contribute to the productive process should receive this kind of maintenance. In contrast to unplanned maintenance, in the event that components need to be replaced, they may already be stored and prepared to be used immediately (Arumugam, 2021). As a result, the failure is only dealt with as it appears, but the strategies for dealing with it have already been established and prepared.

Reliability-Centered Maintenance (RCM): The RCM has been used more extensively, and its primary goal is to maintain the system's functionality at a reasonable cost. The general purpose of RCM maintenance is to optimize the risk-based maintenance plan (Sabouhi et al., 2016). In order to lessen system risk, RCM combines proactive and reactive maintenance methods. In order to avoid or at least lessen the likelihood of a fault occurring, proactive maintenance procedures are carried out prior to its occurrence. After the fault occurs, reactive maintenance procedures are carried out (Emovon et al., 2016). Reliability and cost of maintenance are constantly examined as part of this methodology's continuous process. In addition, it aims to ensure adequate asset availability for production and high levels of safety for people and goods directly connected to the asset. RCM enables not only the prioritization of efficient maintenance actions, but also the creation of action plans that address replacement and re modelling issues, such as deciding whether it is environmentally preferable to maintain a transformer or replace it (Mirhosseini, 2021). However, the fundamental issue of how component maintenance affects system reliability is not addressed by reliability centered maintenance (RCM). The RCAM method links total maintenance costs and system reliability to preventive maintenance (PM). (t, PM) denotes the connection between component reliability and the impact of maintenance on failure mechanisms and causes of failure (Peeters et al., 2018). The main steps of reliability centered preventive maintenance method are as follows: 1. Identify the critical components (system level), 2. Modeling $\lambda(t, PM)$ outgoing from causes of failures (component level), 3. Implement maintenance strategies and perform cost analysis (system level).

Generally, the maintenance practice done by AACAEU is corrective type because AACEU and the four Addis Ababa district utility companies have almost no various diagnosis testing and measurement techniques according to standard and process except insulation checking. DT failure still occurs frequently, indicating the need to investigate a failure mitigation strategy development. Using a planned and RCM maintenance application has a cost benefit and has high level of safety for people and goods directly connected to the transformer. Some other benefits of maintenance preventive maintenance are reducing downtime, reduce the number of faults, increase safety, improve equipment performance, minimize costs and production losses, improve the quality of production and increase equipment life.

2.12. Application of Asset management techniques for Transformers

2.12.1. Asset management techniques

Nowadays, the term "asset" is used in a variety of contexts, each with its own unique meaning. Right now, it is feasible to distinguish five sorts of resources (Robert,2013). These are:1). Physical assets, such as buildings, machinery, and equipment; 2). Human resource include experience, knowledge, abilities, and responsibilities; 3). Profit, financial capital, shares, working capital, and debts are all examples of financial assets; 4). Elusive resources include notoriety, moral, social effect, picture, outer relations; 5). Data resources include information in advanced arrangement, association and client business information, monetary execution data.

The most crucial aspect of distribution network management is asset management for transformers. The distribution network's total reliability is determined by the transformers. While there are numerous methods for asset management, the most common asset management activities for power transformers are condition monitoring and maintenance plans (Abu-Elanien & Salama, 2010). These are: 1. Condition monitoring and condition assessment techniques, 2. Performing maintenance plans, 3. Aging, health and end of life assessments.

A comprehensive asset management technique emphasizes the significance of taking into account both life cycle costs and system quality in accordance with the specified requirements and regulations (Soares, 2017). As potential asset management strategies, the study recommends a combination of Condition Based Maintenance, Reliability Centered Maintenance, Corrective Maintenance, and Time-Based Maintenance (Mirhosseini, 2021). Similarly, from different studies on maintenance, it can easily conclude that mixed type of maintenance system like suitable for costly assets like transformers

2.12. 2. Transformers failure prediction and remaining life time models

According to Enoch et al., (2020), used models comparable to human mortality in their study of power transformer failure prediction, focusing primarily on transformer age. Power transformers are crucial assets in the distribution network and their Failure modes of their components have been well dealt with and documented. Prediction has evolved over the years and included variables other than ages, such as random events like lightning and collisions. Transformer failure modes and prediction can be modeled using a variety of models. The probability of a power transformer component, insulation paper, failing is predicted using an **Extreme Value Theory model**. Assuming that the deviation from the norm or standard would follow an extreme value distribution, the researchers used a sensor to examine the degree of polymerization over the transformer's lifetime (Foros & Istad, 2020). The transformer was not documented and only insulation paper degradation was considered a potential cause of transformer failure, the researcher's work focuses more on demonstrating the method than applying it to the actual issue. Previous researchers have used distribution fitting, probability density functions, and FMEA.

Generally**, t**ransformer failure mitigation strategies are part of asset management as they have as their main objective the maximization of the life cycle of the assets and the risks associated with them. Transformer failure modes and prediction can be modeled using a variety of models. A comprehensive assessment of the assets is required for ideal management and criteria. It will be necessary to collect, process, analyze, and then interpret a significant amount of data. Additionally, the critical asset information must be identified. This study uses a new and ideal asset management techniques to manage transformer health and failure.

Table 2.4: shows literature gaps identified from the scholars that study transformer failures.

No	Researchers	Literature Gap
1	Hoole et al., (2017)	They identified the cause of power transformer failures particularly lighting but they did not develop mitigation strategy.
2	Ndungu et al., (2017)	The scholars investigated causes of distribution transformer failures which are insulation material and fuse problem with suggested solutions but transformers can fail for a variety of reasons, including improper operation and maintenance.
3	Jan et al., (2021)	They identified transformer failures, cause but they did not show the impact and develop mitigation strategy.
4	Martin et al., (2019)	The researchers identify the causes of transformer failure only focusing on bushing failure and suggest preventive measures but they did not identify the other manmade and natural causes of failure.
5	Esteban et al., (2020)	Every fault in the transformer core and windings is a source of localized heating and decomposition of oil but the researchers did not show the impact of decomposed oil and no mitigation system developed
6	Murugan &Ramasamy, (2019)	They identified causes of transformer failure and its mitigation strategy using maintenance decisions such as: continue in service, be repaired, be refurbished, or be replaced but they did not show the impact of failure and failure due to workman ship skill not studied.

7	Tariku&Bekele, (2020)	They investigated the cause of transformer failures but no impact assessment and no detailed solutions against two other problems (Poor reliability and High losses).
8	Singh, (2020)	The researcher identified the causes of transformer failures but he did not show the impact of failure and no mitigation strategy developed.
9	Arumugam, (2021)	He investigated the cause of internal transformer failure using diagnosis system but he could not propose a mitigation strategy.
10	AJ et al., (2018)	Only identifies the cause of failure which lacks mitigation strategy
11	Soares, (2017)	The researcher shows different transformer failure maintenance systems but he can't show the causes and impacts of failure.
12	Guo et al., (2020)	They researcher developed a transformer diagnosis model without analyzing the cause and effect of failure.
13	Ramachandran, (2021)	The researchers show different European, and international standards of allowable transformer failure identified but causes, impact and mitigation strategy not discussed.
14	Naim et al., (2022)	They studied specific geomagnetic disturbance cause on power transformer with mitigation system but they could not show this problem is the actual and frequent problem.
15	(Sarajcev et al., 2020)	They developed preventive maintenance system for healthy power transformers and not dealing with the causes and effects of failure.

2.13. Gaps in the Literature

Previous studies on transformer failure analysis mainly relies on different causes, few study on specific components of transformers like bushing failure causes and very few on some remedial actions. However, in this study causes identification, analyzing the impacts and developing strategy for failure remedies and health upkeep of any distribution transformer. Researchers' have not given required attention for mitigating transformer failure strategically. Previous researchers like Chawda, (2015), Hoole et al., (2017), Ndungu et al., (2017), Jan et al., (2021) and Arumugam, (2021) have not given required attention for proactive health upkeep of transformers but this study focus on it . In addition, the methodology tools used by previous researchers' Ndungu et al., (2017), Chawda, (2015)and Jan et al., (2021) is statistical analysis tool whereas (Murugan & Ramasamy, 2019) and (Brier & lia dwi jayanti, 2020) used fishbone diagram and FTA methodology tools. Arumugam, (2021) uses diagnostic testing methods mainly, frequency response analysis (FRA), dielectric response analysis (DRA) and dissolved gas analysis (DGA) tools. However, this study applied descriptive statistics, FMEA tools together with causal loop diagram as analysis tools and asset management system as a mitigation tool. In general, this research study will fill the identified gaps.

Chapter Three

3. Research Design and Methodology

3.1. Introduction

A detailed research design is of paramount importance and the most crucial step in the research process. It helps a researcher to focus on the study and holds all the parts and phases of a research project together. Methodological aspects of the research have to focus on design and approach, sources of data, data collection tools, sampling techniques and sample size, data analysis, and presentation techniques, validity and reliability test and ethical considerations.

3.2. Research Design

The purpose of the research design was to provide a suitable framework for a study. The choice of research approach is very important for decision making in the research design process because it determines how relevant information for a study has been gathered(Jilcha Sileyew, 2020). This study employed Statistical, failure mode and effect analysis(FMEA) and Causal Loop Diagram (CLD) failure analysis methods to find root cause of transformer failures with its effects. The design approach was descriptive statistical analysis and exploratory analysis using FMEA and CLD. The types data required for analysis were operational failure causes, human related failure factors, effects, and work procedures. The developed mitigation strategy was based on asset management system, that included the company strategic viewpoints, mainly focused on proactive reliability centered maintenance and ISO55000 applied.

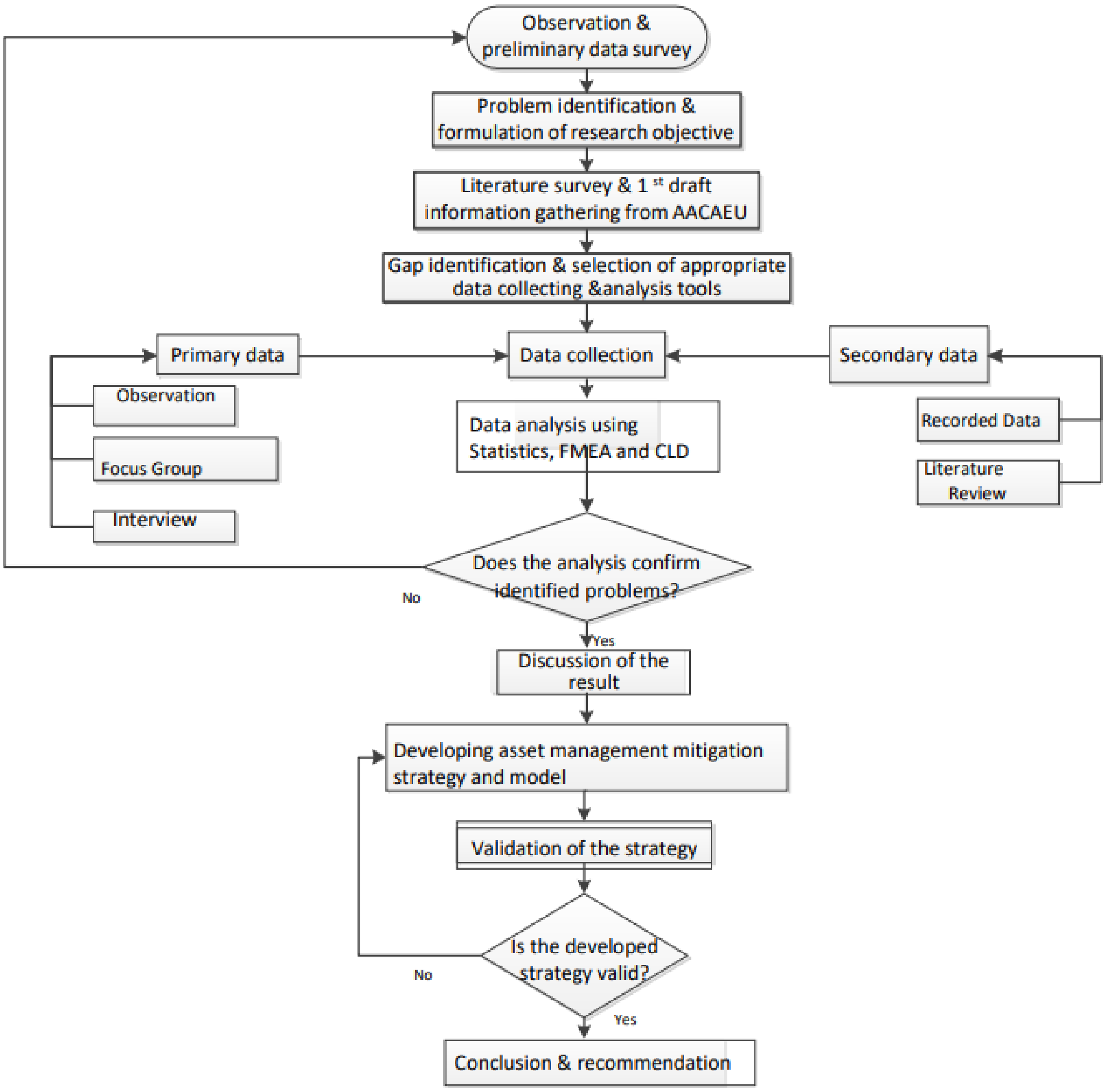

Figure 3.1: Research design and processes (authors design)

3.3. Study Area

The study area for this thesis was Addis Ababa, on transformer failure root cause analysis and developing mitigation strategy. The study has been determined based on 3,825 failed (major and minor) transformers. The primary and secondary transformer failure data collection has been conducted from 24 December 2022 to 10 March 2023, from AACAEU, Kotebe maintenance center, four district electric utilities in Addis Ababa. The collected data are rate of failure, failure causes and transformer component failure, failure related with Human factors, capacity ratings and age, economical failure effects, the existing maintenance practices.

3.4. Data Sources

3.4.1. Primary data sources

Primary data has been obtained through interviews, observations and focus group discussions from the AACAEU, four district electric utility and Kotebe maintenance center, which are the original sources of information. The collected data types through primary data collecting tools were human related failure causes, work and maintenance procedures, the operational failure causes of transformers and their impacts.

Interviews: semi structured interviews have been used to assess the existing working and maintenance procedures and workmanship skill in AACAEU, four districts and Kotebe maintenance centre in relation with distribution transformers. 5 Engineers, 3 Foremen and 5 switch gear heads have been participated in interviewing that directly linked with distribution transformers procurement, management, maintenance and operations.

Observation: failed transformers collected from different directions of Addis Ababa and stored in open yard around Kotebe maintenance centre workshop and personal observation of the damaged parts has been recorded.

3.4.2. Secondary data source

Secondary data collection has been conducted from reports, recorded data, book and related scientific journals, and other similar documents sources on transformer failure causes. The collected data types through secondary data are the causes transformer failures, assesses the sources of failures and 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). They can also assess the frequency of failures and degree of detection of the root causes once failures occur.

Recorded data: from four AACAEU districts and Kotebe maintenance center recorded transformer failure data was collected in soft copy and the data has many details like the quantity of failure, reason of failure, age of failure, manufacturer related failure, components suffer to failure, effect of failure, modes of failure and others.

3.5. Sampling Techniques

The sampling techniques used in this study was total population sampling which is a type of purposive sampling technique that involves examining the entire population (i.e., the total population) that have a particular set of characteristics.

3.6. Population and Sample Size Determination

3.6.1 Population

The population for this study has been used 3,825 failed distribution transformers in Addis Ababa city.

3.6.2. Sample Size

The sample size of the study was all the failed transformers in Addis Ababa indicated in the populations but taking the annual average of three years' failed transformers data 1,275.

3.7. Data collection methods

Data collection methods used to gather quantitative or qualitative information for this research purposes are interviews, group discussions, observations, and company recorded data analysis.

3.8. Data Analysis Tools

There are several root cause analysis tools and techniques such as 5why's, cause and effect (fishbone)analysis, FMEA, FTA and Pareto are the major one's that can be used in the investigation of a problem.

Table 3.1**:** Comparison of the analysis tools

FTA	**FMEA**	**RCA using Fishbone**
Deductive, top-down approach	Inductive, bottom-up approach	Structured way approach
Quantitative	Qualitative /quantitative	Qualitative
Showcases the correlation between multiple failures	Catalogs failures for each component and does not analyze the system as a whole;	Not useful for complicated situations
Considers external events	doesn't consider external events	difficult to represent the truly interrelated nature of problems
Does not consider partial failures	does not consider unexpected failures	It is a reactive process
Easy to update with proper software	often consists in Excel sheets that require constant updating	Fish bone like structure diagram and not easily update

Root cause analysis (RCA) is a structured way to address problems after they occur. From the comparison Table, the weakness of fishbone diagram is simplicity of the diagram may make it difficult to represent the truly interrelated nature of problems and causes in some very complex situations. The disadvantages of fault tree analysis are too many gates and events to be considered for large system analysis, it examines only one top event, common cause failures are not always obvious and difficult to capture time-related and other delay factors. Thus, the data analytical tools applied for this thesis are descriptive statistical analysis, root cause analysis using FMEA, the target sample size of failed transformer, potential failure modes and their associated causes and effects were identified and developing causal loop diagram to analyze the direct and indirect relationship among the FMEA components.

By using 1,275 mean value of the three years' failure data to summarize the raw data to understandable way and the causes and effects have been analyzed using descriptive statistical tools. Root cause analysis using FMEA is also a powerful investigating tool that analyzed the company's documents, viewpoints of experts through interviews, group discussions and the gathered data via observations. All obtained results together with the data collected through recorded data and interviews used in a causal loop diagram (CLD) modeling to show causal interactions among FMEA elements. At the final stage, asset management system was a tool applied to the developed mitigation strategy.

3.9. Methods of Data Analysis

Descriptive statistics involves collecting, organizing, analyzing, and summarizing data in understandable formats like charts, graphs, and tables. It simplifies large data sets and eliminates complexity, using quantitative or visual formats. Failure Mode and Effects Analysis(FMEA) is a structured way to identify and address potential problems, or failures and their resulting effects on the system or process before an adverse event occurs. Due to the high number of defined potential failure modes in the selected system and their associated causes and effects were chosen based on RPN values. The thesis work used MIL-STD-1629A standard, FMEA guidelines combined with utility maintenance staff opinion through interview and group discussion to rate the severity and probability of occurrence of failures. The CLD consisted of numerous feedback loops and developed to consider both linear and nonlinear relationships among failure modes, failure effects and failure causes not analyzed in FMEA. So CLD was used as a supplementary tool for fulfill the analysis gap in FMEA.

3.10. Reliability and validity

Reliability and validity are both about how well a method measures something what it is designed to measure and also helps to eliminate error. Reliability refers to the consistency of a measure (whether the results can be reproduced under the same conditions). Validity refers to the accuracy of a measure (whether the results really do represent what they are supposed to measure).

Pretesting of Interview Questions: - The interview question has been pretested through a pilot survey by the researcher, researcher adviser and selected workers from the sample size. Pre-tests also provide the most direct evidence for the validity of the data for most items.

Presenting to the concerned body of AACAEU, Ministry of Industry and MIDI, the validation of strategy was developed. From these concerned experts' positive response, the developed strategy was acceptable and that means it was validated.

3.11. Data quality management

This is the case regardless of the methodology that is chosen to measure the quality of the data. Ideally, real-world data are used to compare the data, allowing for validation and, if necessary, immediate corrective actions. The only way to measure the quality level of dimensions like accuracy and completeness is through this method, known as data auditing. So the quality of data was checked by compare and contrast the obtained data from operation and maintenance department by checking the receipt signed and stamped hard copy documents.

3.12. Inclusion criteria

The collected data from the concerned organization representative has been included in this study. Articles written in transformer failure analysis, transformer diagnosis and transformer health analysis has included in this study. Database information obtained in relation to articles of distribution system failure identification, impact of transformer failures, impact of power fluctuation and blackouts on business firms, industries and community household equipment's has included in this study. Recently published papers have up to date information but in order to access all available published papers, there was no specific time period chosen.

3.13. Research Ethical Consideration

Ethical Considerations specified as one of the most important part of the research. Throughout the whole research process including during the phases of data analysis and dissemination of findings to ensure that the final report of the thesis provides an honest, fair and unbiased account and does not negatively affect those who participated in the research. All the necessary acknowledgements have been given and cited properly to avoid plagiarism in the thesis work. The most important principles related to ethical considerations includes: respect for the dignity of research participants should be prioritized; Full consent should be obtained from the participants prior to the study; the protection of the privacy of research participants has to be ensured; any deception or exaggeration about the aims and objectives of the research must be avoided; affiliations in any forms, sources of funding, as well as any possible conflicts of interests have to be declared.

3.14. Research Dissemination Techniques

A planned procedure that takes into account the target audiences and settings in which the findings of the research to be received, as well as, when necessary, communicating and interacting with broader audiences in the policy and service sectors for research to be used in decision-making processes and practice(Wilson et al., 2010). In other words, dissemination of research findings involves careful planning, thought, consideration of target audiences, and communication with those audiences.

Chapter Four

4. Data Presentation, Analysis and Mitigation Strategy

4.1. Introduction

The management of distribution networks, including step-down transformers with less than 132KV, as well as the supply of electricity to customers in accordance with their requests, is the responsibility of the Ethiopian Electric Utility (EEU). Even though it was anticipated that the institutions' independent operation would resolve the country's remaining power issues, frequent power outages remained a concern afterward. Following the isolation of the organizations, AACAEU had been organized to oversee EEU to share responsibilities and to resolve the issue of customer in Addis Ababa. In recent years, the four districts and Kotebe maintenance center found under AACAEU can ease the management and operation of distribution networks as well as transformers for improved quality, better service and uninterrupted electricity supply.

The installed number of distribution transformers all over the city of Addis Ababa is nearly 9,000 which are connected to 33kV or 11kV distribution network to supply present power demand of the consumers. The average number of failed transformers (including minor failures and major failures) per annum in Addis Ababa for the last three years is around 1,275 which is more than 13.4% of the total installed transformers.

In this section, the data collected from AACAEU four districts, Kotebe maintenance center and national load center will be presented and analyzed using descriptive statistics and FMEA. Firstly, it is explained in tables and different charts structures, the necessary input data, calculated percentages and how the result is presented. Subsequently, a comparison will be made between parameters. Using FMEA failure modes, effects, causes and other parameters will be analyzed and severity and RPN can be drawn as conclusions of FMEA tabulated sheet. After doing FMEA, there were CLD to further analyze the indirect relation among different failure modes. The purpose of these tabulated, charts and CLD model design are to simplify the work of asset management techniques. The analysis output of will indicate the root cause of failure, its impacts, identifying the most exposed component to failure and risk of failure that helps for decisions to be made regarding maintenance, refurbishment or replacement. The developed mitigation strategy is based on asset management system by designing supervisory control and data acquisition (SCADA) system monitoring and applying reliability centered maintenance models of transformer components.

4.2. Data Analysis

4.2.1. Descriptive statistical data analysis

1. Failure Rate

AACAEU has 4 districts based on operation wise and distribution transformer average number of failure rates (including major and minor failures) of the four districts of East Addis Ababa district (EAAD), West Addis Abba district (WAAD), North Addis Ababa district (NAAD) and South Addis Ababa district (SAAD) are shown in Table 4.1 for the year 2020/21-2022/23.

Table 4.1: Distribution transformer failure rate data

Failure data from 2020/21 to 2022/23	Addis Ababa electric distribution districts			
	EAAD	WAAD	NAAD	SAAD
Number of installed transformers till 2023	3,236	2,400	1,294	2,571
Average number of failed transformers per annum from 2020/21 up to 2022/23	445	296	212	322
Transformer failure rate in %	13.75	12.33	16.23	12.52

Transformer failure rate of northern district is more than 16%. As per the table 4.1, northern district has higher failure rate than other districts and the 12.33% failure rate of west district is slightly lower than the other three districts. In general, Table 4.1 points out, the failure rate of distribution transformers in Addis Ababa is an average of 13.4%, which is very far from the developed countries 2 to 3% failure rate(Tariku & Bekele, 2020). The reason behind highest failure rate available in NAAD is the transformers are very aged and most of them working for long period of time in full load condition and majority of WAAD transformers are relatively not aged because of urbanization expansion and also condominium housing construction along the western Addis Ababa side.

2. Number of burned Transformer and their causes

Premature burned of distribution transformers have been further analyzed based on its causes. From the Pareto analysis shown in Figure 4.1 the root cause of distribution transformer burn in Addis Ababa is overloading. According to Kotebi maintenance experts and other researchers (Pandi,2017 and Chawda, 2015), to happen overloading, the primary failure causes are as follows: human related failure, no record of the transformer's loading, loading without authorized calculations and Power misuse.

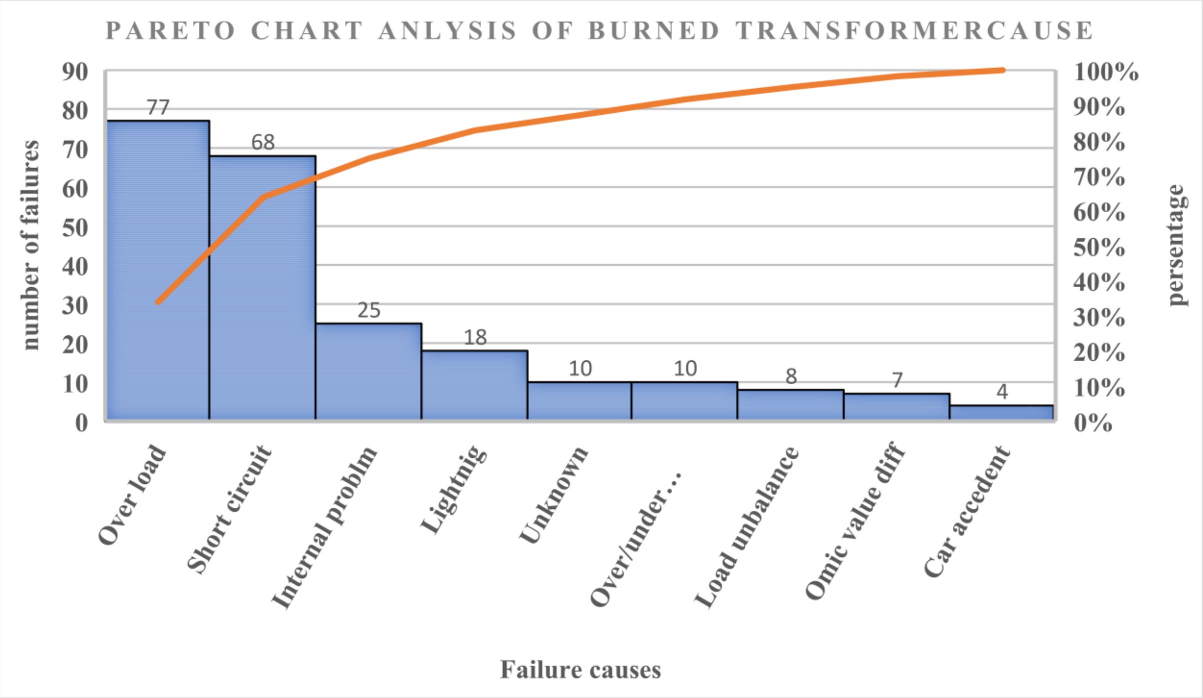

Figure 4.1: Transformers burned Causes per annum

Based on data obtained from Kotebe maintenance center during 2020 to 2023, Figure 4.1 indicates that the annual average total number of burned transformers are 227, over loading constitutes the most frequent burn (major failure) reason with 33.92% of burns followed by short circuit fault and transformer internal quality problem with 29.96% and 11% registered failures respectively. Comparison of the causes of burns against the number of failures happened shows that, one of the top three registered failure reasons, overloading, has been occurred many times in Addis Ababa because transformer suffer to carry loads greater than allowable loads. These types of cases should be analyzed with care by incorporating reasonable assumptions because overloading leads to fire. Overloading mentioned in the failure cause might have been confused with other failure reasons such as external short circuit or lightning for those failures. Overloading is happening due to additional load connected to the transformer beyond the capacity whereas lightning and short circuiting are a sudden rise of current strikes. The existing failure can be divided in to two natural and manmade failures (Naim et al.,2022). Thus, the natural failure causes which are lightning and bad weather condition (wind and rain) may contribute for short circuit to happen and can cover 57 number of burned transformers which constitutes 25.11%.

Table 4.2, shows that transformer burned parts due to the causes stated in Figure 4.1 from 2020 to 2023.

Table 4.2: Transformer burned parts and its quantity

No.	Burned(failed) transformer parts	Average number of burned(failed) transformer parts per annum
1	Insulation	35
2	Stud burn	40
3	Refurbishment	14
4	Bushing	33
5	Winding burn	26
6	Tap changer	24
7	Body damage	7
8	Fluid gasket	11
9	Other accessories	15
10	Oil problem	22

As shown in Table 4.2, the most frequent transformer burned parts that caused by overloading or loose contact is stud with 40 in numbers. Insulation, bushing, winding and tap changer failures with values of 35, 33, 26 and24 respectively. Other transformer failed parts such as body(tank), gasket, oil quality problem and other accessories with collectively 53 in number. Transformers that main components are severely damage simultaneously and unable to maintained which constitutes 14 in number has gone to refurbishment. So, a detailed analysis needs to be carried out in order to identify exact failure reason.

Figure 4.2: Burnet Transformer Picture due to overload

The picture shown in Figure 4.2 was burnet transformer due to overloading and the burned parts are stud, insulation cover and winding. For continuous operation, distribution transformers should work at a minimum load condition that are generally recommended (Jarrahi et al., 2019). In any case, overloading for a short time cannot be kept away from. Maintaining a record of a transformer's loading is one of the primary responsibilities. In the event of overloading, the additional loss causes more heat to be produced, affecting the burning of the winding insulation and ultimately leading to the transformer's failure.

Frequently, it has been seen that the workers utilize higher rating of fuses or revamp to keep away from regular breakdown of supply brought about by overloading requiring substitution of circuits. Due to the lack of availability of fuse carriers, employees frequently use fuse links without holding support carriers and this method is ineffective and must be discouraged. The likelihood of a transformer failing as a result of overloading will definitely decrease if fuses on the LV side are of the appropriate size. A reliable estimate of the distribution transformer's load demand can be obtained by regularly measuring load current with a Clip-on meter, particularly during peak loading times.

The distribution transformer should ideally be loaded evenly across all three phases. However, distribution substation load readings indicate that even when a transformer does not overload one phase, it frequently exceeds its rated current. As a result, the load on one phase rises dramatically, resulting in operational issues thereby leading to transformer failure

3. Transformer failure related with Age

Table 4.3: shows Age against number of failures of east Addis Ababa district (EAAD) electric utility. Even though the failure rate of NAAD is 16.23%, which is higher than EAAD 13.75%, the number of failed transformers in EAAD is 445 is twice greater than EAAD 212. So the study focus on EAAD rather than NAAD.

Table 4.3: Transformer failure due to age

Age at Failure	Number of failures	Percentage
0 to 5 years	64	20%
6 to 10 years	32	10%
11 to 15 years	19	6%
16 to 20 years	20	6%
21 to 25 years	116	36%
Over 25 years	70	22%

The analysis shows, out of the distribution transformer failed in east Addis Ababa district (EAAD), about 30% of the transformers have failed before 10 years of their installation.

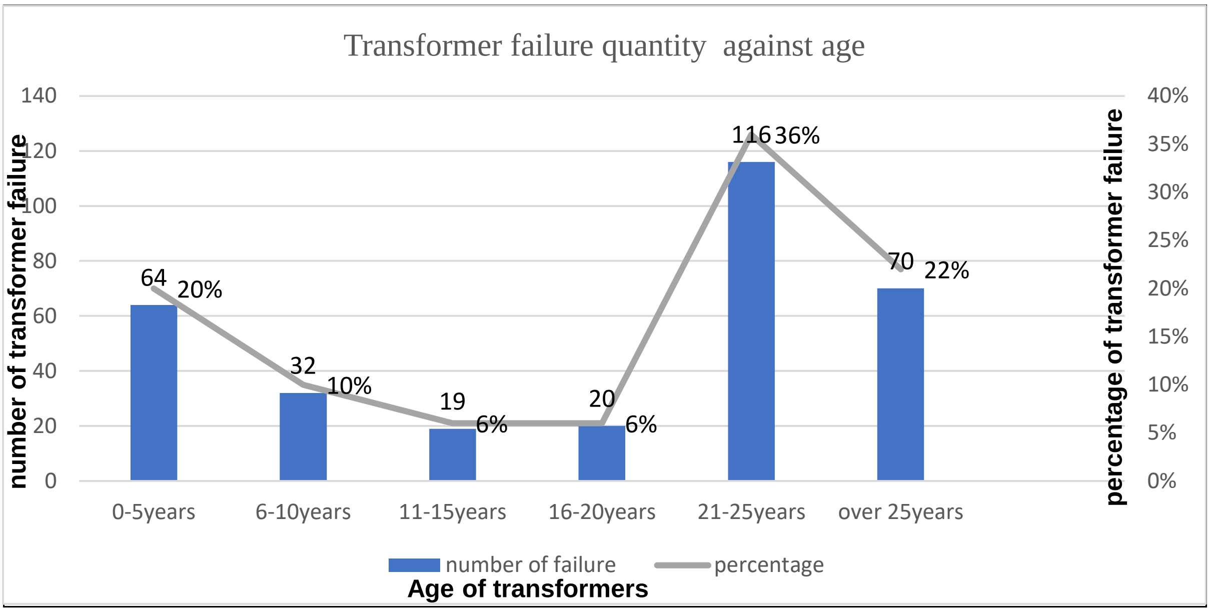

Figure 4.3: Age wise analysis of distribution transformer failures.

From the analysis of Figure 4.3, the general accepted average life span of distribution transformer is considered as 30-40 years (Murugan & Ramasamy, 2019), but age of transformers in Addis Ababa indicated is 21-25 years. That means the life of transformers in Addis Ababa is very lessened compared with the international average life span. Thus, transformers above 21 years can contribute 58% of failure and are not serving for the expected full life period, thereby putting severe strain on cash flows of EEU.

Following that, the transformer enters a near constant failure rate due to random failures known as the useful life period, which occupies the majority of the operating life from 6 to 21 years. Finally, the equipment enters the wear-out phase starts from 21 years of age, which is characterized by increasing failure rates. That means, 36% of failure occurs during 21- 25 years' interval and 22% failure occurs above 25 years. To upkeep the transformer life cycle for long period of time, it should work for 40% of the full load in the continuous load condition (Arumugam, 2021). But in the case of Addis Ababa transformer's the loading condition was over 85%.and hence, main cause of premature failure was overloading.

4. Failure by Transformer Capacity Ratings

The average annual transformer major failure(burn) data recorded from 2020/21 to 2022/23, which is three years' data, include ratings of the transformers when failure occurs. Table 4.4 shows the capacity rating of transformers against number failed in Addis Ababa city.

Table 4.4: Number of failures against Transformer Capacity rating

Transformer capacity ratings	Number of failures	percentage
25 KVA	4	1.76%
50 KVA	8	3.52%
100 KVA	27	11.89%
200 KVA	59	26%
315 KVA	108	47.60%
400 KVA	5	2.20%
630 KVA	7	3.10%
800 KVA	2	0.90%
above 1200 KVA	7	3.10%

Table 4.4 points out, capacity rating of 315KVA with 47.6% contributes for the highest share of failures from the failed transformers under consideration and 200KVA with 26%. Contribute the next highest failure next to 315KVA. 100KVA with failure percentage of 11.89% and the rest 25KVA, 50KVA, 400KVA, 630KVA, 800KVA, 1200KVA and above cover 14.51% only. The three capacity ratings of 315KVA, 200KVA and 100KVA, which cumulatively covers more than 85% failure rate. These capacity rating transformers are the main power source to many private home customers and small business firms. Since, these three capacity ratings are commercial items, not only the number of transformer failure but also number of installed transformers are maximum. Compared with other capacity ratings of transformers, such as above 400KVA has to supply power to big business organizations and manufacturing industries, these transformers are working continuously and loaded beyond their capacity ratings. Number of customers to these transformers are many in number and which is the cause continuously increasing demand of electrification that leads to human related faults.

5. Transformer failure by year

The total number of failed transformers during the recent three years of 2020 to 2023 were 3,825 and for the purpose of descriptive statistical analysis, mean value of this three years' data is 1,275.

Table 4.5 transformer failure in the recent three years

		Years		
No	Failure type	2020/21	2021/22	2022/23
1	Mainor failure	1,004	1,249	994
2	Major failure	274	224	183
Total		1,278	1,370	1,177

Table 4.5 point outs, the number of minor and major failure in distribution transformers during 2020/21 were 1,278, increased in the year 2021/22 to 1,370 and in the year 2022/23 decreased to 1177. The possible reason for most of the registered failures increment in the year 2021/22 were due to minor failure occurrence during replacement or upgraded the existing transformers. In this year many replacement and upgrading work were done on under rated transformers and restored to their normal conditions within 3 to 5 days. The total number of failures in the year 2022/23 were reduced compared to the last two years covered in the study. The possible reason could be the failure data was conducted in the middle of the year 2023, that means the research work did not include all of the failures in this year.

6. Failure by Manufacturer

Transformer failures due to manufacturer (supplier) product quality problem imply premature failure related with internal design problem. The existing distribution transformers installed in Addis Ababa are supplied from different manufacturers. Relatively aged transformers belong to Stromberg, Poland, Marison, Zenaro and Pauwels and the recently installed include METEC transformers (a national state owned manufacturer), local private companies like Advantage, Abebbie, Addis, Abay and Energo and the rest from India, China and Siri Lanka.

It is quite challenging to reach a conclusion in the failure analysis to directly attribute failures to manufacturers. Subsequently, different factors, for example, age at failure and other reasons of failure have been combined while dissecting the failures that exude from manufacturer(suppliers) of distribution transformers with failures. For EAAD, the failure data have been compared to the transformers' age at failure, which has been fully recorded.

Based on the interview information and recorded data obtained from districts as shown in Annex 5, METEC contributes the most to failures overall, it also contributes the most to the total number of transformers in service. The outcome shows that transformers made from METEC, India, China, Marison and Zenaro showed premature failure. Likewise, the failure information has demonstrated that Overload has been related with a large portion of the transformers with prominent failures. As a result, METEC transformers were unable to support the loads listed on the equipment's name plates. The load capacity of high voltage equipment should exceed 10% of its nameplate capacity(Metwally, 2011). In the case of transformers manufactured by METEC, this was refuted due to the frequent failures that occurred when the transformers were loaded exactly as indicated on their name plates. Even though, mandatory international standards for transformers is avail, Ethiopia has no quality assurance certifications for locally manufactured transformer, this would give options to local manufacturers like METEC produce unreliable transformer products.

7. Economic impact of the failure

When a failure occurs, the utility spends a significant amount of time and labor repairing the equipment and restoring service. The majority of personnel spend two to three days addressing work orders related to customer complaints and repairing or replacing transformers. Furthermore, during the outage, the company is unable to sell electricity. Old transformers often need to be replaced with in three days, and during that time, 50 to 150 customers who are linked to the transformer experience a loss of revenue due to the loss of electricity. Long-term clients may encounter sudden, unexpected outages and lose faith in the availability of electricity. If they conduct business while attending a customer service, they could not be able to offer such a service to their consumers, and as a result, they suffer an economic loss. The majority of consumers who experience outages don't receive compensation and bear the financial burden brought on by the outage, which makes them desperate with the situation.

Table 4.6: Unplanned Transformer Outage Economic Impact

	PERMANENT		TRANSIENT		MWH TOTAL	TOTAL BIRR
Districts	MWH	BIRR	MWH	BIRR		
WAAD	13204.42	3,938,217.86	556.91	166,098.11	13761.33	4,104,315.98
SAAD	20587.30	6,140,161.30	411.55	122,744.85	20998.85	6,262,906.15
NAAD	6182.54	1,843,943.98	139.74	41,678.44	6322.29	1,885,622.42
EAAD	22275.66	6,643,716.96	345.46	103,032.17	22621.12	6,746,749.12
AACAEU	62249.92	18,566,040.10	1453.66	433,553.57	63703.58	18,999,593.67

From Table 4.6, 2022 half year report on Addis Ababa City unplanned transformer outage has a huge economic impact on the utility company, house hold customer, industries, business entities and all citizens of Addis Ababa. The AACAEU financial opportunity loss recorded in six months is around 19,000,000, which is significant amount of money. From semiannual report of AACEU, it is clear that unplanned transformer outage has great impact on the customer’s day to day activity and opportunity revenue loss to the utility office.

8. Human factors of transformer failure

Everyone can make errors no matter how well trained and motivated they are. However, in the workplace, the consequences of such human failure can be severe. Analysis of accidents and power outages shows that human failure contributes to almost all transformer failures and exposures to substances hazardous to health. The insight gained from the responses continue to be relevant for the failure cause analysis study to keep the transformers reliability, availability, and maintenance.

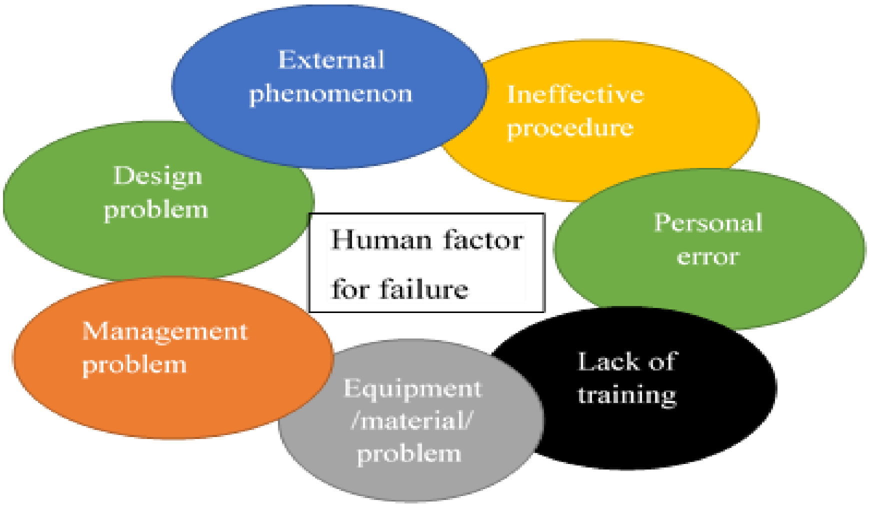

Figure 4.4: Human factor for transformer failure (from interview and focus group)

As indicated in the Figure 4.4, the results of majority of failures such as overloading, short circuiting, internal quality problem, load unbalancing, under voltage and manmade accidents which covers around 75% can be attributable to human factors. Because it was systematically calculated that except natural factors of failure (due to lightning, rain, moisture and wind), the rest failure causes were because of workers' faults or manmade accidents.

Inefficient procedures: the operation and maintenance procedure found in AACAEU is not written and traditional. But the events are recorded, that means when maintaining a single transformer, the first event is registering the detail of the status in the name plates, its location, receiving date, the end event is returning the maintained transformer by recording the date and parts repaired on a single letter to whom they received. But, there is no planning, there is no procedure for details of maintenance activities, no cost breakdowns, professionals required for maintaining a new arrival failed transformers not determined. However, for any organization's consistency, quality, and safety cannot be compromised without procedures. Similarly, there is no written procedure for operating and load dispatching. So that, many failures occur due to overloading because loading a transformer is not based on clear written procedure and calculation but only on experts' judgment. Employees who do not have procedures can have serious repercussions, such as safety risks, poor maintenance quality of transformers, decreased effectiveness, and harm to the company's reputation.

Personal error: this error occurs very often in operational workers of AACAEU due to lack of either of knowledge, skill or performance. When connecting a new customer load to the existing transformer, the trend of work in utility organizations is based on management order without knowing the scenario and expert judgment and these leads to personal error.

knowledge gap: the new arrival employees in AACAEU have not trained well about operation and maintenance of transformers. Hence, the new employees don't know the operation and maintenance of transformers so that to successfully complete the maintenance tasks, the understanding of how the work fits into the utility organization, or specific to a Kotebe maintenance centre should be known. **Skills gap:** the workers in Kotebe maintenance centre are divided into junior, senior, supervisors and managers. Based on the skill level supervisors and managers are chief skilled experts, senior experts have high skilled whereas junior experts have skill gaps. **Performance gap**: in four Addis Ababa districts and Kotebe maintenance centre, the performance gap occur is because of management firefighting order to resolve customer power outage issues unprofessionally. That means, when a transformer fails to operate for a long period of time and many customers complaining for not getting power, few managers in AACAEU orders maintenance professionals to supply power for those complaining customers from other nearby transformers until the failed transformers going back to work. However, this firefighting order leads to overloading of the healthy transformers and may even leads to burn.

Lack of training: for ensuring transformer proper operation, maintenance and supervision work, the need of continuous training for AACAEU staff is mandatory. When new hire employees join the AACAEU, districts or maintenance centre, trainings are organized on the basics of distribution transformer construction, what is phase balancing and load checking in transformers and similar basic knowledge concepts. But, giving continuous training based on how to properly upkeep the health of transformers, different maintenance techniques to maintain transformer lifecycle with minimum cost and method of operation and maintenance for the experts. Since, the maintenance department is composed of Emergency Unit, Engineering Unit, Switch Gear Case Team and Workshop Unit. The Emergency Unit is in charge of responding to calls from customers about issues with transformers and results from load checks that are unacceptable. So for this unit customer handling and emergency maintenance system training are very useful. When the issues cannot be resolved in the Emergency Unit's level, they sent to the Workshop Unit or the Switch Gear

Unit for further investigation. The implementation of new power rehabilitation programs is the responsibility of the Engineering Team. For workshop unit and engineering team, how to operate and maintain a transformer is very essential type of training package in order to deliver quality of power to the customers.

Transformer component material problem: transformer component failure due to human related failure like improper usage, design problem or operational failure, overloading, short circuiting or bad weather condition leads to the whole failure of transformers. The transformer premature failure related with some manufacturers are due to material quality issue. The name plate design rating capacity and the actual rating withstand had difference with 10%.

External phenomenon: one of the causes of transformer failures in Addis Ababa is related with natural failure factors like wind and lightning and human related factors like operational failures accidents and sabotage.

9. The Existing Maintenance Practice of AACAEU

The maintenance practice in AACAEU was preventive and predictive maintenance types. The preventive maintenance activity has been done on site in each districts whereas the corrective maintenance work has been done in Kotebe maintenance workshop. This workshop has the capability to maintain major failures like the winding failure, internal insulation problem, tap changer issues, damaged body and core, bushing burns and other similar item problems. The average annual repair rate of kotebe maintenance center was 268 major component failures(burns.) In the four districts of Addis Ababa the cumulative annual inspected transformers were not more 200. That means each four districts were inspected 50 transforms only which is very small number.

A). Districts Transformer Failure Diagnosis Check inspection

Check inspection of early failure diagnosis is one of the preventive maintenance activities in the distribution network. The minor failures noticed during inspection would be corrected at the time of inspection itself. Different defects at the earliest conceivable time should be inspected and diagnosed at every possible opportunity after scheduling a program ahead of time. However, manufacturer’s instruction is always given less due consideration while carrying out the diagnosis maintenance check on particular component of transformers.

Under the direction of the District Technical and Maintenance Section Head, the switch gear inspection team inspects the distribution transformer. The need of early diagnosis checks(inspection) of distribution transformer is determined by the increase of customer complaints or the failure rate of the transformers and other accessories. Based on the reports from the operation personnel or the latest inspection result of the distribution transformers, early diagnosis is mandatory for the health working life of transformers. In all cases, inspection observations are recorded and reported in an appropriate form for follow-up. For this purpose, inspection report formats for distribution transformers and other accessories were developed. As a preventive work, the inspected data was simply fill in and interpret using developed inspection formats attached in (Annex 01. Distribution Transformer Inspection Sheet).

Table 4.7: Early Diagnostics Check Lists on Distribution Transformers and Accessories (from interview and focus group)

- Oil levels are below normal value
- Oil leakage is observed
- Thermometer glass is broken
- Unusual noise on transformer is heard
- Bushing arc horn gaps are misaligned
- Silica jell changes its normal color or broken
- Lightning arrestor is cracked or damaged
- Ground connections of arrestor, neutral and transformer bodies are in abnormal condition
- The earth resistance at the grounding point of transformer is at acceptable value
- Fuse rating and the height of distribution box is based on the standard
- Supports (poles, cross-arms and stays) are in bad condition
- Tap changer position is appropriate
- Radiator damage is observed
- Accumulation of dust on insulators
- Unscrewed bushings
- Cracked solid insulators
- Broken wire strands
- Side trimming and twisted wires
- Sag & tension adjustment of wires
- Loose connection of wires
- Burned wires
- Burned jumper wires
- The insulation resistance is below the permitted value
- Bolts, nuts & cable lugs are damaged or burnt
- High Tension side terminals are burnt or damaged

B). Visual Inspections

Primary data analysis of Kotebi site indicates, when a failed transformer was collected to determine the extent of the damage (failure), the Kotebe maintenance team was starting the maintenance work by visual inspection. The observation from Kotebe maintenance center indicates transformer insulation was the most exposable to failure by many failure causes like, overloading, short circuit, damage due to accidents, lightening. Stud and oil are the most frequent replaced components of transformers and it was easily inspected visually. In general, the visual inspections include (1) the burnt insulation, burnt oil, the color of the oil, indication of humidity and location, and check water in the tank and its amount (2) burn evidences, discoloration, or slag deposits due to overheating or due to arcing on tank Walls, on bushings and on flow tank connections (3) displacement of windings and conductors (4) Core condition and signs of core damage. (5) Evidence of loose connections or connections to bushings, flanges, spacers, etc.

After Inspection there are two important actions, namely reporting and failure correcting. Minor failures identified during the visual inspection are rectified as quickly as possible to prevent them from developing into a serious(major) failure.

C). The existing corrective maintenance

The existing maintenance practice in kotebe maintenance center

1. The center carries out repairs on a need basis and receives failed transformers from districts based on the format and application letter. The format contains name plate information (serial number, manufacturing date, manufacturer, capacity rating and others), issue date, owner of transformer district, short history of the failed transformer and others.
2. The center carries out maintenance after visual identification of a problem.
3. The center carries out maintenance after breakdown/burned of transformer components
4. The center does condition monitoring of the transformer
5. The center carries out unplanned tasks that maintain all critical parts of a transformer in optimum operating condition
6. The center has been used well trained personnel to carry out repairs on the transformers.
7. The center ensures that the repairs are verified before the transformer is returned into the incoming districts for operation
8. The center carries out corrective maintenance on breakdowns not stopped by preventive maintenance.
9. The center has 23 maintenance staffs that are readily available to correct failures
10. The center postpones maintenance tasks until the first come first served repair finished
11. The center detects component failure with a view of taking corrective action after failure occurs
12. The center documents what it carries out corrective maintenance after equipment failure
13. The firm carries out maintenances based on given maintenance rules

14. The center carries out corrective maintenance while the electric power supply line to customers is in total stoppage or if possible the AACAEU may give electric supply from other nearby transformers to the household customers.

15. The firm carries out replacement of elements or parts of transformers when they reach the end of their economic expected life because of damage or age.

4.2.2. FMEA Analysis

The FMEA is a significant system for failure analysis to find out of failure modes, reasons for failure(causes), effects of the failure and their seriousness and preventive actions to be made. To conduct FMEA, failure data of 1,275 transformers of different capacity rating is utilized to analyze failure modes, failure causes, their effects and calculation of risk priority numbers. FMEA is put into action in two parts. The first section conducts failure modes and effect analysis (FMEA), and the second section categorizes failure modes based on severity and likelihood of occurrence.

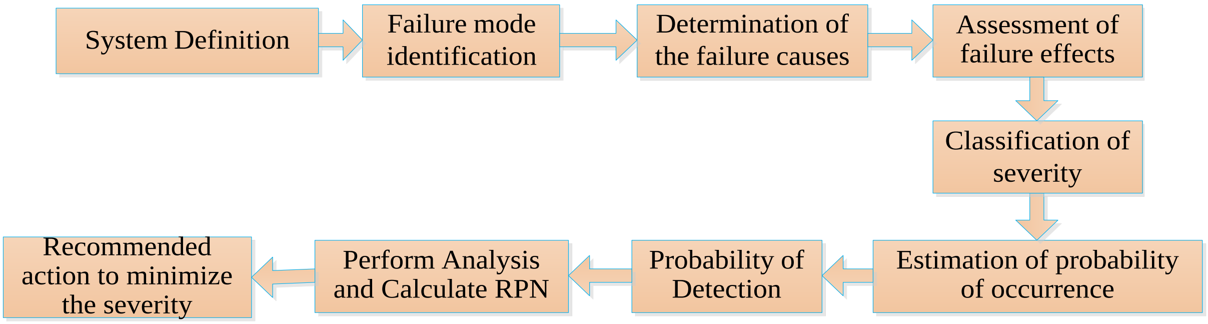

Figure 4.5: FMEA qualitative model

1. FMEA Elements

I. System definition: to conduct FMEA first step is to define a system. The transformer, its components, and its various functions constitute the system.

II. Failure Modes Identification: The failure mode is the manner in which a failure occurs and is observed, and how it affects the operation of the equipment. Transformer failure modes are identified based on failure investigation conducted from AACAEU and the modes of failure can be classified into the following categories as shown in Figure 4.6.

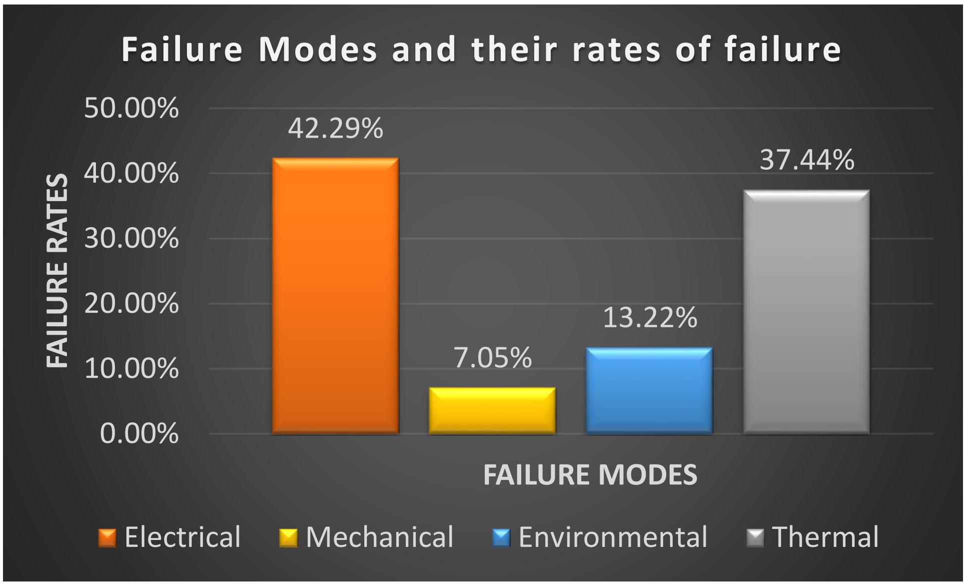

Figure 4.6. Failure Modes and their rates of failure

A. **Electrical Failure Modes**: Electrical breakdowns are classified into three major categories:
   - Overvoltage or transient situations
   - Poor contact or Short circuit
   - Switching surges and lightning
   - Partial discharge

These failures are electrical failure modes which contributes 42.29% of the rates of failure that might occur separately or in combination. As a result, it is critical to assess all of the components in order to build an appropriate failure scenario to investigate the transformer failure.

B. **Mechanical Failure Modes**: Mechanical failure modes that covers more than 7% of the failure rate, which is caused by distortion, rupture of its solid components and breakdowns. The following are the principal mechanical failure modes that cause transformer failures:
   - Electromagnetic Forces
   - Conductor tipping
   - Damage during transportation
   - Buckling of the conductor in the innermost winding
   - Vibration and mechanical movement in transformer
   - Failure of coil clamping system

- Displacement of the core

C. **Thermal Failure Modes:** Transformer component deteriorates under the influence of heat, oxidation, and thermal stress that covers37.44% of failure rate The following are thermal failure modes that cause transformer failures
    - Continuous transformer overload
    - Abnormal load conditions
    - Clogged oil passages
    - Cooling system failure
    - Transformer over excitation

D. **Environmental Failure modes**: is due to bad weather conditions like lightning, wind, heavy rain related flooding and humidity which covers 13.22% of the failure rate.

Due to the failure modes described above, failure may occur in various parts of the transformer.

Insulation degradation caused by overloaded situations, switching surges, lightning, and other factors is the most common failure in transformers. The heating of the transformer can raise the temperature of the insulation system, reducing the efficacy of the insulation. Damage to a transformer insulation system is caused by electrically induced factors. The most prevalent cause of electrical failure in transformers is turn-to-turn insulation breakdown. Insulation deteriorates as a result of a sudden increase in voltage or current. This insulation breakdown produces flashover of winding turns and short circuits.

Transformer insulation should be tested with extreme caution since internal electrical failure can result in a catastrophic failure and have far-reaching consequences.

overload leads to deterioration of cellulose insulation, which acid and moisture and this leads to a loss of dielectric strength of the insulation in the transformer winding. Other factors responsible for increased thermal stress and insulation loss in transformers

The most important parameter to extend transformer life would be the winding hot spot temperature. By directly measuring the temperature at the hot spots of the winding, the exact condition of the device can be assured.

III. Failure Cause Identification: The most common causes of major failures (burns) of transformer analyzed in Figure 4.1 are overloading, short-circuiting, internal problem, lightning and others. Using FMEA further failure causes are identified as shown in the Table 4.8, 4.9 and 4.10 which leads to transformer minor failure and even may result in transformer burns.

IV. Failure Effect Identification: The effect of transformer failures in Addis Ababa is shown in Table 4.9 and 4.10 by dividing local and end effect of minor ad major failure causes. The effects identified through FMEA are from temporary power outs to complete damage of transformers (burn) which leads to financial loss for AACAEU, individual and business firms. Customer dissatisfaction, repair or replacement cost and an issue to environmental health and safety are also the effect of transformer failure in Addis Ababa.

Local Effect: Consequences of the failure mode on the operation, function or condition of the analyzed transformer element and the details in lower outcome level are shown in Table 4.9 and 4.10.

End Effect: Consequences of the failure mode on the operation, function or status at the upper outcome level are shown in Table 4.9 and 4.10.

V. Compensation provision: The process by which each potential failure mode of the system is analyzed to determine the RPN value by using annex 3 and what actions are required to correct it.

2. Transformer minor and major failure causes

A minor failure is anything that causes an inconvenience to users but is unlikely to cause an accident or can be solved onsite by field workers. happened for long period of time. Major failures are serious faults that could cause an accident and may take long time to maintain the damaged parts.

Table 4.8: Transformer minor and major failure causes

Failure	Minor failure modes and their cause	
	General Power Outage causes	Specific causes of minor failure
Minor	Electrical failure	Failures of: ✓ Instant over current (IOC) ✓ Buchholz and pressure relief (B&P) ✓ Fuse burns (FB) ✓ Earth fault protection(EFP) ✓ Phase to ground connection (PGC) ✓ Differential protection (DP) ✓ Outage of incomers (OI)
	Mechanical failure	✓ Body pore and damage (BP&D) ✓ Loose connections(LC) ✓ Firefighting system (FFS) ✓ Oil or Air leakage (O&AL)

	Environmentaloutages	✓ Bad Weather condition (BW) ✓ Animal and birds(A&B) ✓ Human mistakes (HM)
	Thermal failure	✓ Hot joint(HJ) ✓ Fatigue ✓ Short circuit
Major	Failure modes	Main Components failure as a cause of transformer major failure
	Electrical, Mechanical, Environmental and Thermal	Tank Insulation System Oil Tap changer Winding Core Bushing Cooling system Others

Tables 4.8 point outs all possible faults, major and minor, which can lead to an interruption in transformer operation. The influence of minor failure on the lifespan of the transformer is not significant. Therefore, the ultimate impact of minor failures is interpreted as repair time duration requirement. However, frequent long-term over current/voltages resulting from overloads that cause insulation degradation over time. Major failures are the failures associated with the main components of transformers like, core, winding, insulation, tank, tap changer and cooling system. The most common failure in transformers is insulation degradation due to overloading conditions, switching surges, lightening etc. The heating of transformer can increase the temperature of insulation system and eventually can decrease the effectiveness of insulation.

The FMEA shown in Table 4.9 and 4.10 include a list of transformer component failures collected from Kotebe maintenance center and 4 districts experts' idea, observation and company available recorded data. These are causes of failures, the local and end effects relating to the impact of each potential failure on the components and transformer. Alternatives remedial actions suggested to solve the analyzed failure in FMEA is based on experienced experts' opinion and data recorded from the AACAEU, Districts and Kotebe maintenace center. Finally, a risk priority number (RPN) for each failure mode have to be calculated (RPN = S*O*D). Based on FMEA Guidelines, the occurrences, severity and detection ranking criteria is indicated in annex 3.

Table 4.9: FMEA of Transformer Minor Failures

Failure	Failure mode	Possible failure cause	Local effect	End effect	Compensating provision	S	O	D	RPN
Minor	Electrical (B&P, OC, EFP, DP, OI, PGC,FB)	Overloading	Thermal ageing	Intermediate repair time	System monitoring	5	9	4	180
		Internal arcs	Excessive pressure and combustion gases	Longer repair time	Dissolved gas analysis	6	3	6	108
		External faults	Power loss	Short repair time	System monitoring	4	4	4	64
		Internal fault within the protected region	Loss of power	Intermediate repair time	Preventive maintenance	5	4	3	60
		Fuse burns	Power loss	Short repair time	Replacement	4	7	2	56
		Faults at bus bar incomers	Immediate transformer shutdown	Short repair time	System monitoring	4	3	3	36
		Phase to Ground Failure	Power loss	Medium repair time	Preventive maintenance	5	5	5	125
	Mechanical (BP&D,FFS, LC, O&AL)	Transformer main circuit HV equipment breakdown	Power loss during equipment replacement and FFS not working	Long repair time	Preventive maintenance,checkup insulation status and electrical test	7	3	3	63
		Loose connections	Power flactuation and spark of fire at the contact point	Short time for repaire	Preventive maintenance and checkup the contact points	4	7	5	140
		Oil leakage from main tank	Low level of oil to operate buchholz relay	Long repair time	Periodic visual inspection	6	4	3	72
	Environmental (A&B BW,, HM)	Wind and rain	Slippage of transformer accessories and protection device	Intermediate repair time	Checking protection wires, cable clearance distances	4	6	4	96
		Wrong switching of power due to animal intervening actions	Short circuiting, safety risk and loss of power	Short repair time	Safety first rule	7	3	2	42
		Operators error when power connection to customers	Overloading risk on nearby transformer	Medium repair time	Corrective maintenance and calculated balanced load distribution	6	7	4	168

					usage				
	Thermal (HJ, Fatigue, Short circuit)	Malfunction of circuit breakers, stud glow/burn, over flux protection failure, abnormal sounds of operation control	Power loss	High repair time	Preventive maintenance	6	3	7	126

The minor faults analyzed using FMEA in Table 4.9. are very common in any distribution transformers due to the lack of proper testing and diagnostic procedures. The high RPN associated with these faults can be significantly reduced by regularly performing a sweep rate analysis, oil test, turns ratio test, and insulation resistance test. Mechanical failure modes related to winding include loose coils and loose terminals. Both errors lead to winding damage due to the deflection of the electromagnetic force. Loose windings and loose connections are very common when experiencing operational problems related to overloads and coil connections breaking due to high current flow through the coils. The high RPNs associated with these failures can be reduced by avoiding overloads and high clamping pressures during functioning of transformers. From the FMEA of Transformer Minor Failures, the overall solutions of any minor failure was applying reliability centered preventive maintenance. Temporary failures due to mechanical damage to the insulating paper can be protected by using protective fuses on the high-voltage side of the transformers.

3. Transformer Main Components

Core: The core provides a low reluctance path for electromagnetic flux and supports the primary and secondary windings. It is made by stacking thin sheets of high-grade grain-oriented steel which are separated by thin insulating material.

Winding: The winding consists of several turns of copper or aluminum conductors, insulated from each other and the transformer core. The type and arrangement of winding used for transformers depend upon the current rating, short circuit strength, temperature rise, impedance, and surge voltages. Out of the primary winding and secondary winding, the one which is rated for higher voltage is known as High voltage (HV) winding and the other is known as Low voltage (LV) winding.

Insulation: Insulation failures can cause the most severe damage to transformers. Insulation is required between the windings and the core, between windings, between each turn of the winding, and between all current-carrying parts and the tank. The insulators should have high dielectric strength, good mechanical properties, and high-temperature withstand ability. Synthetic materials, paper, cotton, etc are used as insulation in transformers.

Tank: The main tank is a part of a transformer that serves two purposes:

1. Protects the core and the windings from the external environment.
2. Serves as a container for oil and support for all other transformer accessories.

Bushings: Bushings are insulators that form a barrier between the terminals and the tank. They are mounted over the transformer tanks. They are a safe passage for the conductors connecting terminals to the windings. They are made from porcelain or epoxy resins

Transformer oil: Transformer oil provides added insulation between the conducting parts, better heat dissipation, and fault detection features. Hydro-carbon mineral oil is used as transformer oil.

Tap changers: Tap changers are used to adjust the secondary voltage of transformers. They are designed to change the turn ratio of the transformer as required. There are two types of tap changers: On-load tap changers and Off-load tap changers.

Buchholz relay: Buchholz relay is one of the most important parts of oil-immersed transformers rated over 500kVA. It is an oil and gas actuated relay that is used to sense faults occurring in the parts immersed in the oil. Short circuits occurring under the transformer oil generate enough heat to decompose the oil into hydrogen, carbon monoxide, methane, etc.

Table 4.10 FMEA Worksheet to Analyze Transformer Failure in Addis Ababa

NO	**Components**	**Function(s)**	**Failure Mode(s)**	**Failure Cause(s)**	**Failure Effect(s)**		**Control(s)**		**Risk Rating**					
					Local Effect(s)	**End Effect(s)**	**Prevention Control(s)**	**Existing Failure Detection methods (control)**	**O**	**S**	**D**	**R PN**	**Priority Ranking**	**Recommended Action(s)**
1	**Insulation** (enameled wire, paper, glass, thermoplastic insulating tape, glass fabric, wood, resins, porcelain, gasket materials, internal paints, and mineral oil or synthetic fluid)	For Isolation, Protection, Proper functioning and Safety	Mechanical Electrical Thermal	Excessive moisture of winding insulation paper, Damage during transportation, short circuits, Ageing of insulation Oxidation, high acidity, overloading , low quantity of oil, generation of copper sulphate	Dielectric and mechanical strength reduction of insulation paper, Hot spot on studs	Mechanical damage & high arc fault in winding insulation and burn occurs	Not loading above its allowable capacity, Transporting the transformers with high care, Prevent direct entry of moisture from the air to the winding through the proper sealing , proper drying of insulation	Formation of bubbles in the insulating oil during transformer operation (Visual Inspection)	7	8	8	448	4	Dry out internal paints and porcelain and Dehumidifier the transformer, eliminate leaks and re-sealing
								Over current (using power meters)	8	9	8	576	1	
								Overheating (measured by power meter)	8	9	7	504	3	
2	Transformer Oil	Isolate and cool active part of transformer and for insulation purpose	Environmental Mechanical Thermal	Oil contamination due to overheating and ageing of insulation, water and dirt particles in oil due to ageing of insulation, acids in oil, High temperature due to failure of oil circulation and over heating	Reduce the insulation strength & Breakdown voltage, Reduction in dielectric strength, overheating and short circuit	Overheating & short circuit in the transformer. Partial discharge/Corona, Carbonizations of the oil & environment pollution, Insulation breakdown	IEC 156 test the dielectric strength of an insulating oil. Transformer replacement, Pump bearing monitor, correct oil sampling procedures,	Particle contamination (Visual Inspection)	6	8	8	384	6	Avoid atmospheric openings & use oil filtering. Oil replacement, Regular sampling and testing of the transformer oil, Avoid damaged gasket
								High arcing (visual)	5	9	7	315	10	

								Breakdown voltage due to crack (visual)	5	9	8	360	8	
3	Core	For inducing magnetic field (electromotive force)	Thermal Mechanical Insulation	Over Excited core, wrong grounding of core, Displacement of core steel due to dc magnetization	High core temperature due to high eddy current losses	Excessive heating or burning of insulation lamination, efficiency loss	Proper grounding of core, Correct alignment of core	Condition Monitoring Through DGA, Furfur aldehyde Analysis (FFA),	2	8	9	144	15	Use soft magnetic materials like silicon steel, Make corrective actions on core ground connections and displacement of core
								Core grounding test(using multi meter)	3	8	8	192	13	
4	Windings	Conduct and carrying current	Electrical Insulation	continuous overloading, oxidation, Loose clamping, twisted turns, short circuit, transient overvoltage due to lightening, manufacturing problem	Winding deformation, the clamps of the coil will get apart	High inrush currents, Protective relay tripping, Insulation ageing, damaged winding	Use of higher density insulation and higher clamping pressures during manufacturing/maintenance.	Leakage reactance	6	9	8	432	5	Reclaiming/ repacking, Condition assessment through DC resistance, Turn ratio testing of winding
5	Tank	The outer most enclose for oil and protect the active parts(core and windings)	Mechanical	Mechanical damage due to accidents & handling error, Environmental stress, High gas pressure build up due to short circuit, corrosion and gasket leakage due to manufacturing defect or insufficient maintenance and ageing	Tank body damage, Corrosion, Oil leakage	Loss of power and transformer replacement	Monitoring of the inhibitor content according to IEC 60666. external examination for oil leaks	Visual inspection	4	7	2	56	17	Proper tightening of terminals and joints and replacement of burnt gaskets, , tank repair, Proper sealing of valves
6	Bushings	Isolator between tank	Electrical Mechanical	Seal breaking of bushings, Loose	Insulation damage,		Use high insulation material, Periodic	Power factor measurement	7	9	6	378	7	Replacement of bushing,

		and windings& safe passage of high voltage		connection, poor maintenance/insulation failure, porcelain damage/ fault in material	deficiency of oil due to spillage, Discharge current on the surface of insulation	Damage of bushing, Short circuit, , Personnel safety	inspection of the oil level & Periodic cleaning of bushings	Visual inspection of oil leakage	7	8	3	168	14	sealing gasket and connections
7	Tap Changer	Regulate the voltage level	Mechanical	Wrong position of tap change, Loose spring, low insulation of oil, Old capacitors, breakdown	Overheating and excessive pressure	Mechanical damage, fire spark occurs	Proper positioning of tap changer and replace old capacitors	Visual inspection	6	8	6	288	11	Corrective actions in all the parameters of tap changer (oil flow, pressure, oil level, moisture in oil, temperature etc.) or oil replacement
8	Cooling System (Pump, fan, Radiator)	Used for cooling purpose	Mechanical l	Physical damage of the cooling system & pipes, poor maintenance, overuse/wrong due to bad thermostats, unbalance loading	Reduction in the oil level, Low heat exchange	Over heating	Proper handling of the cooling system, Apply balancing load	Visual inspection	6	7	6	252	12	Maintain regularly
9	Others	Used for performance improvement	Electrical Mechanical Thermal Insulation	Operational errors, Lack of maintenance, power theft/ unbalance loading, Vandalism/sabotage, single-phase loading, Worn contact	Overloading, Short circuit, bushing failure, High carbon build- up	Possible flash over and burn	Give training for workers, preventive maintenance, contacts replacement	Visual inspection,	5	9	2	90	16	Replacement of bushing and other theft items, Corrective maintenance
								DGA	8	8	5	320	9	
								use multi meter for voltage and current measuring	8	8	8	512	2	

FMEA in Table 4.8 identifies transformer components, functions, failure modes, failure causes, impact of component failures in terms of local and ultimate impact, risk priority numbers (RPN) based on severity, probability of occurrence and probability of detection of all components of a failure that could affect the reliability of the electrical system. The RPN ranking (Risk Priority Number) indicates the criticality of the components, the higher RPN indicates the most critical component. Thus, insulation failure has the highest RPN, followed by winding failure, bushing failure and oil degradation indicate major failure shares.

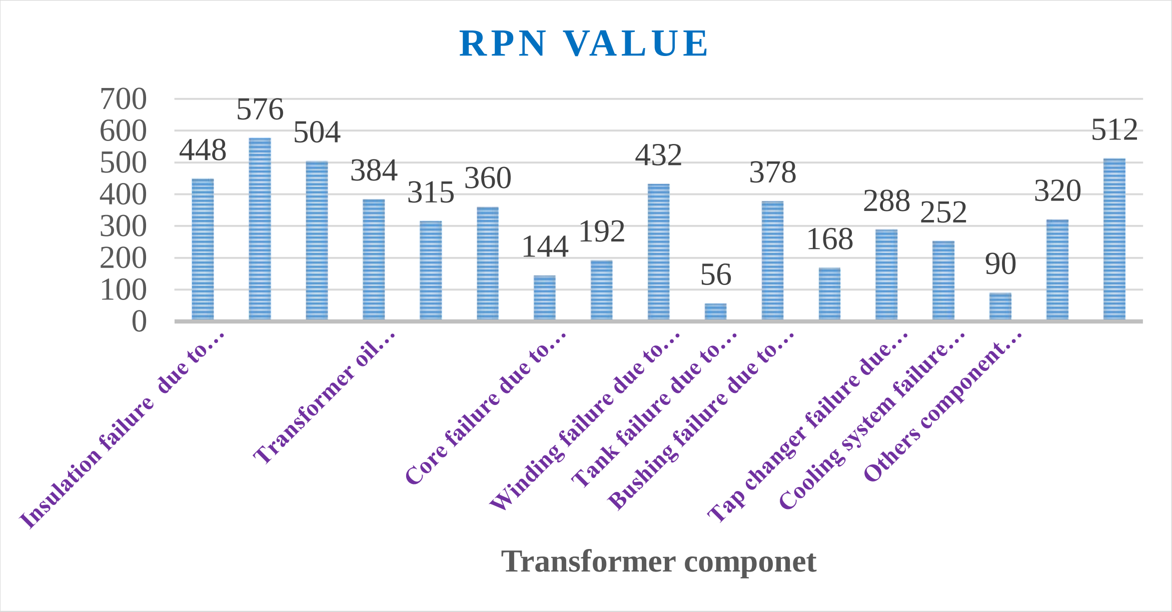

Figure 4.7: RPN values against transformer component failure modes

The failure modes summarized in the FMEA Table 4.10 and figure 4.7 show the RPN ranking of component failure modes based on the recorded data obtained from four districts in AACAEU, expert interviewing and on site inspected data. The highest RPN value of 567 is belongs to insulation failure due to electrical failure mode, the next RPN value is 512 which belongs to operational electrical faults and 504 is thermal cause insulation failure. Thus, the distribution transformers higher failure rate associated with insulation failures is due to overloading or developing high current. All causes of faults related to overloading and short circuits belong to the electrical failure modes and result in insulation deterioration that leads to either winding damage or electromagnetic disturbances in the secondary windings of transformers. These faults are very common in oil natural air natural(ONAN) distribution transformers due to the lack of proper diagnostic and testing procedures. The magnitude of the probability of failure, the severity of the consequences and the probability of failure detection that could determine the RPN numerical values and arranging in ascending order to easily identify the root cause of transformer failure. The high RPN associated with these faults are significantly reduced by regularly performing reliability centered preventive maintenance. For safe and reliable working of transformers, specially designed Miniature Circuit Breaker (MCB) is an electro-mechanical device which protects the transformer in case of overload and short circuit faults. MCB detects the fault condition and automatically switch off to interrupt the circuit current and manually switched ON after removing the fault. Other methods to reduce this RPN value related with overloading and short circuit are Sweep Frequency Response Analysis (SFRA) testing provides insight into the mechanical and electrical integrity of transformers, reactors, and other equipment with windings., oil test, turns ratio test, and insulation resistance test. Mechanical failure modes related to bushing and tap changer include loose connector terminals, physical accidental damage, bad weather and vandalism. All faults lead to insulation damage and oil leakage which covers 378 and 288 RPN value respectively. Loose windings and loose connections are very common in ONAN distribution transformers when experiencing operational problems related to overloads and coil connections breaking due to high current flow through the coils and the RPN value is 512. The high RPNs associated with these failures are reduced by avoiding overloading of the and high clamping pressures during manufacturing.

Common causes of core failure associated with thermal failure modes are core overheating, ground faults and core loss. These failure causes include local effects of high transformer temperatures and ultimately core damage or transformer failures. The 192 RPN values associated with thermal types of faults are reduced with regular oil testing, insulation resistance testing, and core iron leakage testing. In addition, the installation of thermal protection devices on the LV side protects the transformers from serious damage due to overloads. Core losses are significantly improved by continuously monitoring and estimating the losses in the transformer. The RPN values associated with these failure modes are improved by subsequent performance of a core bottom insulation resistance test and a furfural analysis (FFA). On the other hand, the distorted magnetic flux associated with the core of transformers is the result of mechanical deformations during transport, handling and assembly. Therefore, transformers must be checked before and after each shipment, transport from storage and assembly. The causes of transformer oil problem are water in the oil, acids in the oil and an oil level that is too low. These causes of failure are mainly related to the aging of the transformers, since the insulating paper ages over time and there is a risk of water accumulation in the insulating system. Significant RPN values which is 384 for these failure sources are reduced by regularly checking the oil's dielectric strength, checking its acidity, and regularly monitoring the oil level and silica gel vent. Failures related with oil can also be avoided through regular sampling and testing, the use of appropriate seals and the use of contamination testing to prevent deterioration. High RPN values are also observed with cracked insulating paper due to mechanical damage. Generally, most types of faults that occur in Addis Ababa ONAN distribution transformers are significantly reduced with RC preventive maintenance testing, diagnostics and protections. FMEA-based recommended actions can be prioritized based on the RPN values associated with each root cause.

4.3. Causal Loop Diagram(CLD) to Analyze Failure

Systematically analyzing of the failure causes and the end results as independent and dependent variables respectively. Transformer failure is the result of human related causes, material quality issues and/or bad weather condition. So the failure of transformers depends on either of the causes that can affect the normal operation of transformers. The general failure cause of transformers is listed in Table 4.11 below.

Table 4.11. General Failure cause

No.	Independent variables	Dependent variable
1	Human factor for failure	Transformer failure
2	Material quality problem	
3	Environment problem(bad weather)	

Considering the human factor for failure sub system and identify the failure causes of this exogenous variable. The endogenous variable for this variable is transformer failure. To use human factor failure causes of failure in CLD, primary failure cause leads to secondary and then followed by the third failure cause and effects.

Table 4.12 Human factor for transformer failure three step cause lists

No	Primary cause	Secondary cause	Third cause and effects
1	Knowledge gap and using untrained workers	Transformer acceptance and installation without testing and verification, unable to do proper operation and maintenance work.	Premature failure winding, bushing, insulation, etc.
2	Transportation problem or poor handling	Mechanical damage	breakdown of transformer components (bushing, insulation, cooling system and tap changer)
3	Car accident	Physical damage to transformers and components	Pole breakdown, tanker, bushing, cooling system,

			insulation and winding damage. Core displacement
4	Lack of employee’s motivation and incentives	Operators’ negligence and lack of commitment to the organization.	Overloading and faulty wiring connections, accidents & frequent error.
5	lack of skill	Poor maintenance of transformer and components,	Positioning error, Overloading and faulty wiring connections, accidents
6	Lack of work procedure.	Poor operation and maintenance of transformer quality,	Overloading and faulty wiring connections, electrical and oil spill accidents
7	Reworks due to mistakes	Decrease life span of transformers	Cost overrun
8	Shortage of workman force	unable to do the inspection work and breakdown maintenance in the time of what the customers required	Failure of transformers and its components
9	Management problem	Ineffective planning and scheduling of the preventive maintenance	Failure of transformer and its components

Reinforcing (R) loops describe a positive feedback process where the loop generates a self-reinforcing behavior

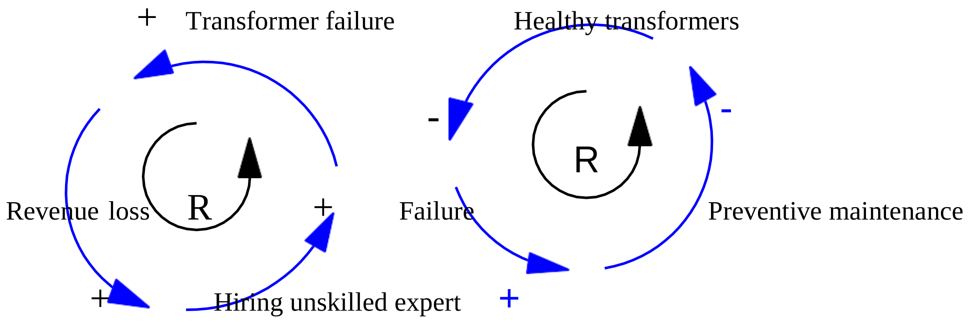

Figure 4.8: Two Reinforcing Feedback Loops

From the Figure 4.8, when transformer failure increases lead to revenue loss to the customer and utility, this may be the cause of hiring unskilled expert, in turn this may cause transformer failure. If transformer failure increases then heathy transformers decrease, this may due to lack of preventive maintenance practice Thus, the loop reinforces each other to yield transformer failure.

Balancing (B) loops describe a negative feedback process where the loop generates a self-correcting, goal-seeking, or stabilizing behavior.

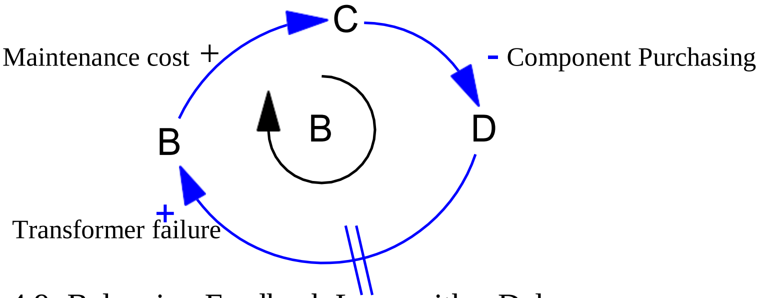

Figure 4.9: Balancing Feedback Loop with a Delay

Figure 4.9 indicates when transformer failure increases maintenance cost also increases but purchasing of quality component for may decrease due to big demanding cost.

CLD of the effect of human factor for failure on transformer failure as shown in Figure 4.10, the CLD model was developed to consider both direct and indirect connections among FMEA components, that is, failure modes, causes and impacts. In the proposed model, not only failure causes led to failure modes, and failure effects occurred as the consequences of failure modes, but also non-direct relationships among all of the three elements. Moreover, failure rates and their cause rates maximized because of failure and their causes maximizing. By using either reactive maintenance or preventive maintenance, failure can be eliminated/minimized.

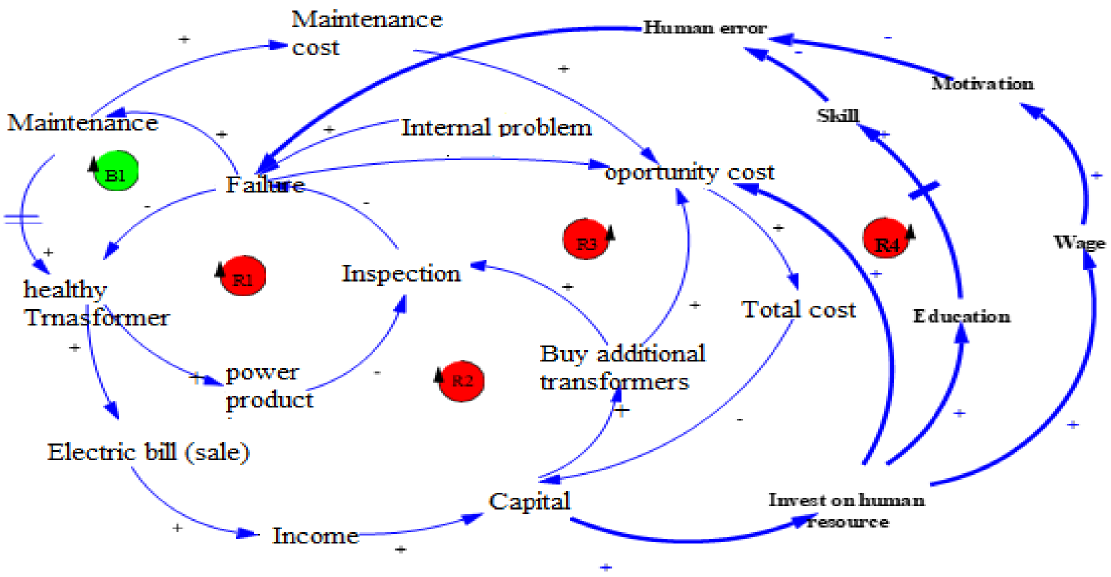

Figure 4.10: CLD of the effect of human error on transformer failure

As shown in Figure 4.10, human error occurred due to skill gap and unavailability of motivation factor was not seen in FMEA. So, to show the effect of human factor related failure and to solve this error, investing on human resource to fill the skill gap and wage increment have to be recommended. Even though investing in human resource requires big additional cost, the benefit gained after is incomparable and optimum. The worst the internal problem is, the more transformer failure has been occurred; moreover, less inspection activity implemented, the more failure occurred consequently more maintenance work has occurred. The healthier transformers available, the electric bill increases and this leads to maximizing of income to the AACAEU and this boosts the capital amount to reinvest for buying new transformers.

4.4. Relationships among Descriptive analysis, FMEA and CLD analysis

Descriptive analysis used to identify the most common causes of transformer failure, the most affected components, different causes of failure and the impact of failure. This information is then used to prioritize the FMEA effort and focus on mitigating the most critical failure modes. This analysis showed that the most common causes of failure are overloading, internal problems, lightning strikes and others. Due to these failure causes the transformer components that commonly affected are insulation, bushing, stud, winding, transformer oil, cooling system and others. In some cases, human factors can be the primary cause of transformer failure. For example, a transformer may fail due to overloading if it is not properly sized for the load it is expected to carry.

FMEA (Failure Mode and Effect Analysis) is a systematic method for identifying and evaluating potential failure modes in a transformer. It can be used to assess the severity of each failure mode, its likelihood of occurrence, and its detectability. This information is used to prioritize mitigation strategies and to improve the reliability of the transformer. This analysis showed that insulation failure due to electrical and thermal failure modes of overloading is the most severe, with a high likelihood of occurrence and a low detectability.

Causal loop analysis is a method for understanding the relationships between different factors that can affect the health of transformers. It is used to identify feedback loops that lead to unintended consequences or failures. This information is used to design mitigation strategies that break these feedback loops and improve the stability of the healthy transformers. This analysis showed that transformer failure is primarily due to human factor related failure that leads to overloading, short circuiting, internal problem and inadequate cooling system.

By combining these three methods together, this research was conduct a comprehensive transformer failure analysis that identifies the root causes of failure, assesses the risks, remedial actions and can develop mitigation strategies to prevent future failures. These transformer failure analyses can improve the reliability of power grids and reduce the risk of power outages, fires, and other accidents.

4.5. Transformer Failure Mitigation Strategy Development

Transformer failure mitigation strategy is developed using asset management system and supervisory control and data acquisition (SCADA) system after descriptive analysis, FMEA and causal loop diagram analysis. Asset management system is used to collect and store data on transformers, such as their location, age, condition, and maintenance history. This data is used to identify transformers that are at a higher risk of failure. SCADA can be used to monitor the real-time condition of transformers and to detect early signs of failure.

4.5.1. Proper Receiving and Installation of Transformer

Transformers should be thoroughly inspected upon arrival to ensure that no mechanical damage occurred during transportation as identified in the Table 4.10. After receiving the transformer, it should be carefully examined for any damage caused by handling. The nameplate rating on the unit ought to be checked against the job details to guarantee establishment of the right transformer and just qualified personnel should to inspect and install based on the 14 transformer installation procedure expressed in the Jefferson electric guideline manual. As a result, transformers' successful operation is dependent on proper receiving, installation, loading, and upkeep.

4.5.2. Testing and commissioning of transformers

One of the causes of failure of transformer in Addis Ababa is quality issue related with manufacturers. So testing a transformer in the field after installation is one of the most important aspects of commissioning. This is a thorough examination of the transformer with the goals of: 1) finding any issues with the transformer's components, as a transformer is subjected to a lot of stress on its way to the site and is susceptible to moisture intrusion during installation and other unanticipated problems; 2) ensuring that the transformer passes the same tests as it did when it was last tested at the manufacturer's facility; and 3) establishing a baseline against which to compare the results of subsequent tests.

4.5.3. Maintenance Strategies using Reliability Centered Maintenance

The fundamental objective of maintenance is to maximize the life cycle of a transformer asset and to reduce the risk of failure ensuring that it properly works under the best possible conditions. Hence, transformer asset management has to take into account reliability centered maintenance for up keeping the reliable life of transformers in Addis Ababa.

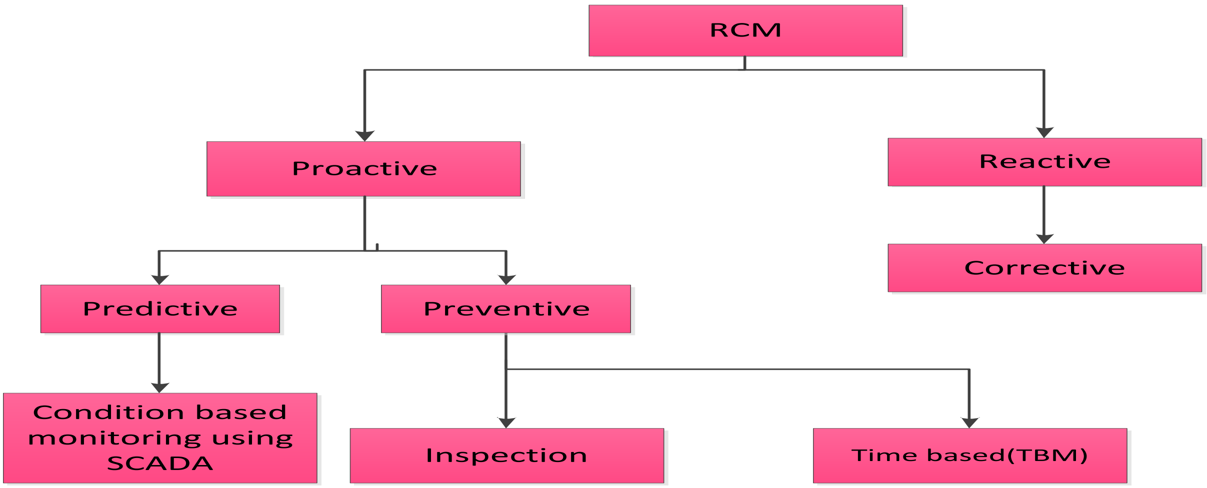

Figure 4.11. Reliability Centered Maintenance Qualitative Model

As shown in the Figure 4.11, Reliability Centered Maintenance (RCM) which combines proactive and reactive maintenance methods that provides a logical and structured framework for up keeping essential transformer assets, understanding the consequences of their failure, and selecting the most cost-effective maintenance strategies to mitigate those consequences. To avoid or at least lessen the likelihood of a fault occurring, proactive maintenance procedures are carried out prior to its occurrence. After the fault has occurred, reactive maintenance procedures are carried out. Reliability and maintenance expense are constantly evaluated as part of this method's ongoing process. In addition, it aims to ensure adequate asset availability for production and high levels of safety for people and goods directly connected to the asset. Nasa Reliability Centered Maintenance Guide for Facilities and Collateral Equipment (2008) which is very important for maintenance after FMEA analysis carried out and also as guide for operation of transformers

I. Transformer Monitoring Systems using SCADA

Any data that is accessible from the systems that they monitor and control can be gathered by Supervisory Control and Data Acquisition (SCADA) systems (Peharda et al., 2017). In addition to the primary functions of monitoring and control, numerous advanced tools and applications utilize this diverse data in smart grid transmission control centres. Some of the data that can be used for centralized transformer monitoring are available in modern SCADA systems. Continuous monitoring varies by user and is associated with sensor selection, its functionality, and system monitoring architecture, despite its growing popularity. Because it enables performance evaluation and ensures the safety of the transformers' operating conditions, continuous monitoring has become an essential component of transformers.

The transformer asset data is listed in Table 4.14 and solutions should be based on relevant and up-to-date information about assets.

Table 4.14 Transformer asset information

Type of information	Descriptions
Demographics	Location, type, voltage level
Condition	Inspections, tests, maintenance history, loading levels
Performance	Failure history, age, environment
Functional	Capacity ratings, obsolescence issues, safety compliance
Criticality	Number of customers, priority customers, load, environment, safety
Costs	Operation and maintenance (O&M), refurbishment, replacement costs

The transformer unit in a distribution network is an essential, costly, frequently failed component which is difficult to replace. For all of these reasons, transformers require constant care throughout their lifespan.

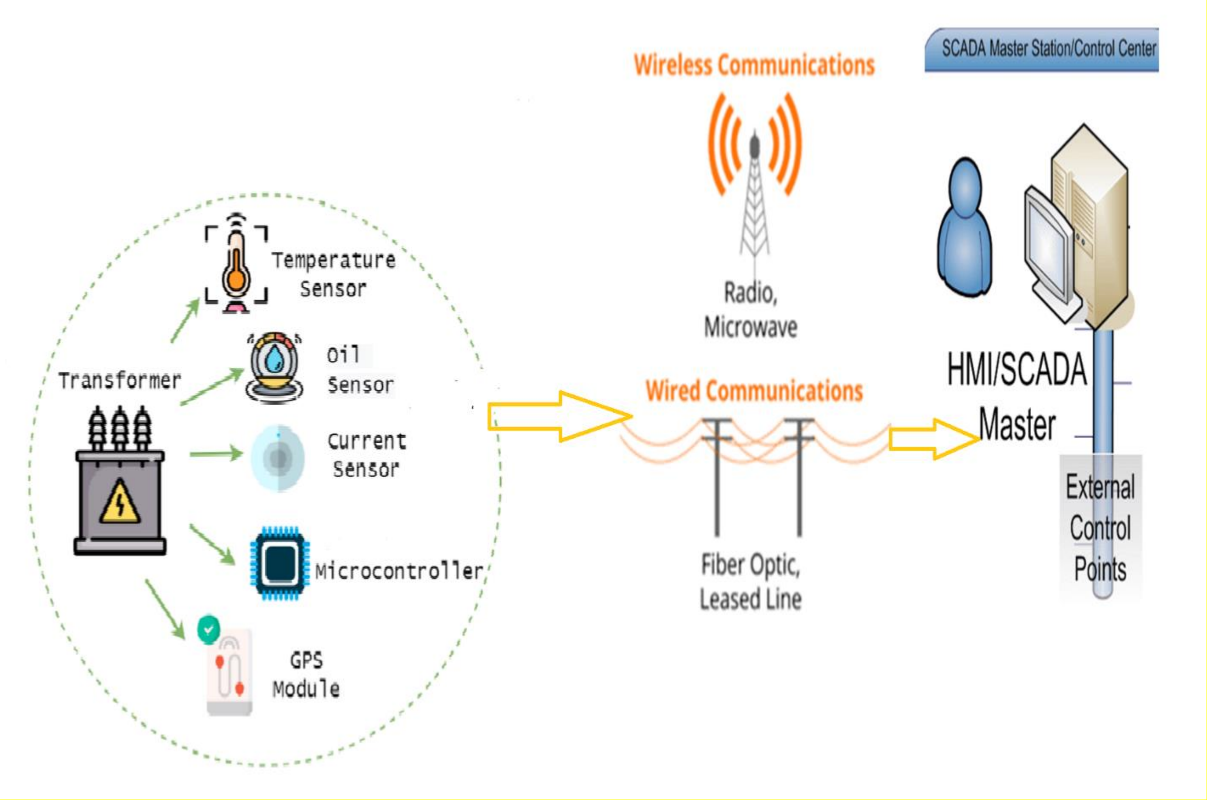

Figure 4.12: SCADA System Architecture Conceptual Model

The architecture of SCADA shown in Figure 4.12 allows for high visibility on processes and data from key components in the control system display such as windings, bushings, oil, valves, temperature, voltage, current and transmitters. Monitoring and control of smart operation of transformers is made possible by using SCADA master display board systems. The automation and supervisory control allow for centralized control during times of concern opposed to the need to access the physical location of the control system component causing concern.

Taking into account the data that could be gathered from the various usual systems that are currently in use, it is now possible to identify the information potential that exists within transformers. As a result, it is necessary to transform the data inputs (factory tests, inspections, and diagnostics, transformer history, and continuously collected data) into useful and intelligent outputs that will enable the owner of the transformers AACAEU to make the most effective technical and business decisions. In a short amount of time and regardless of their volume, these systems enable the transformation of a set of inputs into valid information. Intelligent features ought to be present not only in the storage component but also in the analysis case of this kind of system. In addition, it ought to serve as a data and information source for a number of individuals, including maintenance staff and operations personnel.

To utilize and operate the SCADA system, the operators have enough knowledge and skill to operate and to monitor state of the transformers and can easily detect the fault conditions. In this perspective, the SCADA system offers plenty of sensors, computer display board monitoring systems, analysis algorithms, power cable based transmission line and data acquisition software systems for condition evaluation that will help its users in decision making.

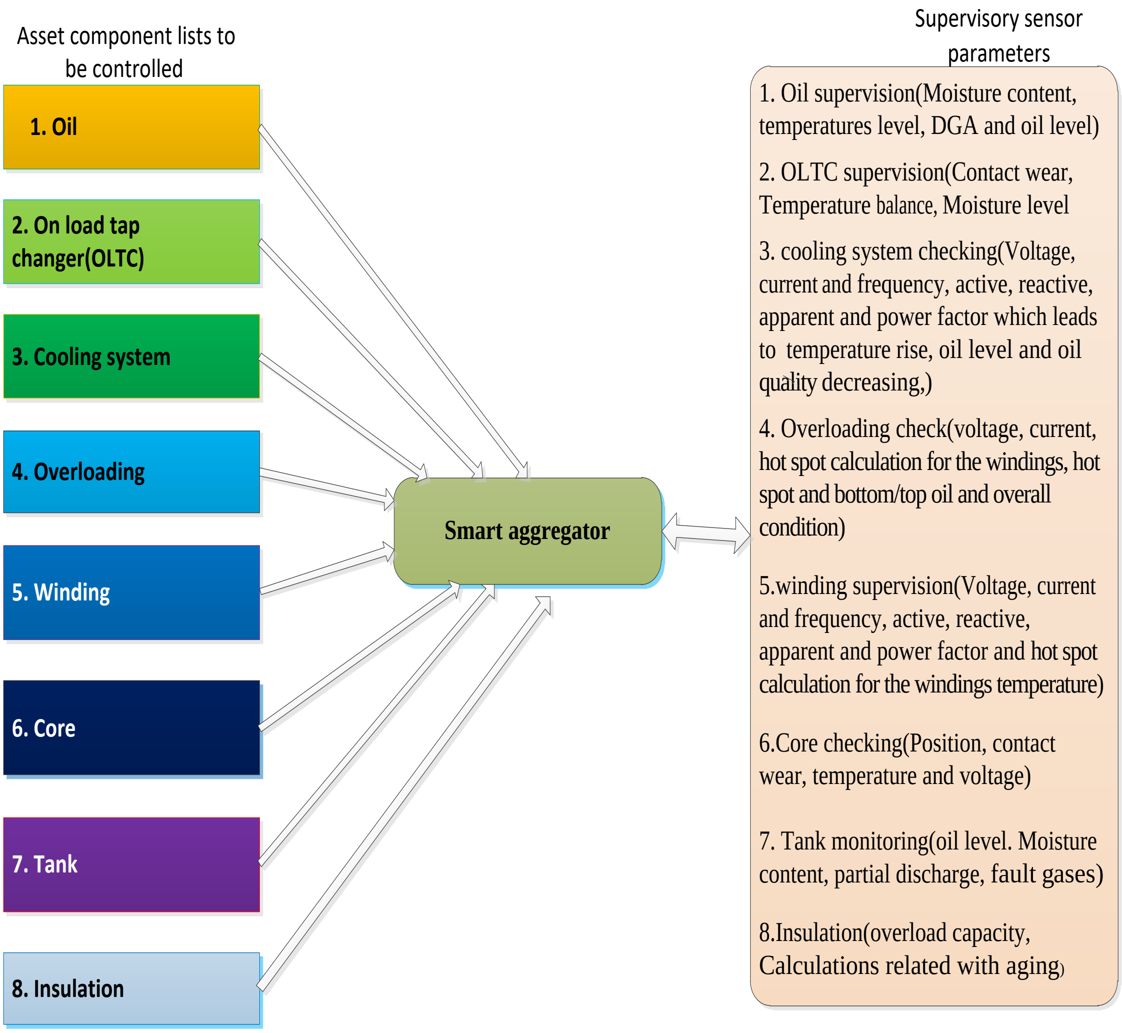

Figure 4.13. Asset management platform model of SCADA

According to Figure 4.13, the transformer oil serves as both an insulator and a cooling agent, its moisture, temperature, and dissolved gases needs be monitored. Oil degrades by losing its properties over time, as shown in Table 4.10 of the FMEA worksheet and timely detection enables the prevention of failure modes. The DGA diagnosis allows for the detection of an increase in gases, which can indicate high temperatures in the transformer or discharges. Regarding the moisture sensor, oil quality can be deduced from that measurement. Between windings, flashover is more likely to occur when moisture is higher.

Monitoring the OLTC sensor will reveal when the switching mechanisms begin to wear out. This is done by collecting data such as the number of tap-change operation positions. If this is not done, an electric current interruption may occur, resulting in arcing and the release of gases. This switching mechanism capability, which is also found in other systems, allows the capacitance measurement and dissipation factor to be used to determine the isolation state of the bushings or the condition between the windings. Capacitance changes imply mechanical displacements of windings or partial bushing breakdown.

The cooling system will be monitored to ensure that the heat generated by the transformer operation is dispersed. The lifetime of a transformer that is operating 10℃ cover its rated temperature is reduced by half (Salama et al., 2020). It is crucial to identify any issues with this system as soon as possible. As a result, detecting early issues in this system is critical. The existence of a partial discharge sensor and an ambient temperature sensor is utilized to correlate data from other sensors with the cooling system. The ambient temperature aids in transformer cooling and is one of the parameters used to compute hot-spot temperature. Because this capability is not as vital as others, it is not present in all systems.

Active parts (winding, core and insulation): The amount of heat produced in the winding is determined by the current flow and it should be measured. On the other hand, the transformer needs protection from the short circuit current and safeguard the windings from electromechanical stresses. To regulate the transformer's thermal state, it is necessary to keep an eye on the oil and winding temperatures. The transformer core is intentionally grounded at one point. However, the stray magnetic field that results in the formation of oil hotspots and gases causes a circulating current to flow through the ground loop in the event that the core is unintentionally grounded at another location. By measuring the core ground current, which is nearly zero in a normal situation, this defect can be identified.

For the purpose of early fault detection, three additional parameters are measured in addition to the temperatures and ground current: partial discharge (PD), dissolved gases in the oil, and moisture. Under high voltage stresses, PD is a localized electrical breakdown of the insulation that does not completely bridge the two electrodes. The movement of the partial discharge is the beginning of some failure situations and thus, it is gainful to be monitored. Both the PD and confined areas of stress, which are unusual for a transformer, deteriorate the oil and create a few gases. Identification of these gases can reveal the situation abnormality ahead of time.

Oil and other cellulosic materials make up the transformer insulation system. Moisture initiates significant degradation effect in the cellulose and diminishes the dielectric strength of the oil by actuating unique breakdown strategies. In the presence of moisture, the oil's high temperature accelerates the degradation of cellulose, reducing the transformer's lifespan.

In general, it is possible to verify that some sensors are employed in all systems due to their relevance, while others are not. It should be noted that selecting optional sensors for specific systems raises the cost of the system. It is up to the utility company AACAEU to determine what is most interested in measuring with what values the most in the transformer. If they believe that bushings are not important, they will not purchase a system with this sensor.

In general, it is possible to verify that there are some sensors that given their relevance are used in all systems like temperature and others that that are specific to some transformer components. It should be noted that the choice of optional sensors for certain systems increases their cost. It is up to the client to know what is interested in measuring with what he values the most in the transformer. If, for example, AACAEU consider bushings are not so important to detect using SCADA, they will not acquire a system that has this sensor.

II. Preventive maintenance (Inspection)

The inspection system currently in action in districts are more of visual inspection so this study proposes inspection strategy which can help to prevent failure. Implementing a preventive maintenance schedule is one strategy to avoid transformer failure. This entails inspecting the transformer component on a regular basis for any potential difficulties or concerns. If there are any component problems, they should be reported as soon as possible so that repairs can be made before something major goes wrong. Consider scheduling regular maintenance for bushing, tap changer, oil, ground faults, overload and insulation, as well as other equipment like tanker and cooling system. In addition to the existing inspection techniques found in each districts Annex 4 Table1 contains a distribution transformer maintenance and inspection guide with recommended frequency. Routine transformer inspection and maintenance entail visual evaluation of the transformer's operational state.

Time based maintenance (TBM) entails carrying out the equipment's scheduled maintenance interventions on a regular basis. Basically, TBM accepts that the failure behavior of the transformer is predictable. However, if the inspection intervals are too short due to the need for specialized staff to undergo maintenance, unnecessary checkups, and shutdowns, and., this method could become costly However, it can able to detect equipment problems at early stages, which can save money in the long run. Time-based maintenance on transformers will guarantee trouble-free operation for many years to come. Transformer is a very important and durable asset that is frequently overlooked until it fails. However, transformers should be properly maintained because they are very pricey component of the electrical distribution system. The load that is connected to the transformer and its criticality or non-criticality should be taken into consideration when planning maintenance schedules for transformers. Transformer liquid maintenance and testing, transformer winding insulation maintenance and testing, and any other special maintenance that the transformer's manufacturer recommends should all be part of regular time based maintenance.

III. Corrective maintenance

The most basic sort of maintenance is corrective maintenance, which is performed when a failure occurs (also known as run-to-failure or reactive maintenance). When an asset fails, it can disrupt service (high equipment downtime) and affect system performance, and it must be repaired so that it can fulfil its function again. To put it another way, the component is used until it fails which is common in AACAEU Kotebi maintenance center. Because of the unpredictability of failures and possible repair costs, estimating the associated budget is difficult. Furthermore, just intervening when a failure happens exposes you to the risks connected with the failure, such as collateral harm to other assets. This sort of maintenance is advised for assets that have non-critical functions or do not offer significant value to the productive process and can be readily replaced or repaired. The difference between planned and unexpected maintenance is that if it is essential to replace components, they may already be in storage and ready to be used as needed. So, the failure is only treated when it appears, but the measures to deal with it are previously stated and prepared.

In general, the goal of having a maintenance strategy is to have solutions to prevent or restore transformer asset breakdowns. Maintenance strategies must be combined in accordance with the goals to be achieved:

- Reduce the number of failures;
- Improve transformer component performance;
- Reduce maintenance expenses;
- Improve service quality;
- Extend transformer life.

4.6. Chapter summary

A comprehensive analysis of 1,275 annual minor and major failures of transformer was carried out to determine the root causes and effects of distribution transformer failure. The presented statistical analysis indicates that the rate of transformer failure is 13.4% annually and that transformers are failing 14 years earlier than their internationally accepted lifespan, resulting in poor reliability and financial loss for the AACAEU.

The failure of insulation due to overloading has been identified as the main cause of transformer failure that covers around 34% and followed by short circuit and internal problem. Transformer capacity rating of 315KVA and 200KVA have the highest failure rate of 47.6% and 26% respectively. Human factor for failure is a failure due to procedural error, knowledge gap, skill gap, performance gap, external factors influence, lack of training, management problem, design issue and material quality problem. Human factor for failure was the primary failure cause for many minor and major failures which contributes more than 75% of transformer failures. That means the main cause of overloading, short circuiting, internal problem, accidents and other factors excluding natural means to failure (wind, moisture and lightning) were due to human factor for failure. Failure due to manufacturer or supplier has been analyzed and the local company METEC contribute the maximum number of premature failure because of less withstanding to 10% additional overload happened and the transformers could have burned out. The current maintenance practice in AACAEU Kotebe center has been identified as preventive and corrective maintenance. By using inspection checklists attached in annex 1, the preventive maintenance activity was done. However, the level of inspection application was very limited because of the broadness of failure issue of the transformer. The corrective maintenance performed in the center was very traditional and without maintenance guiding manual.

In order to anticipate potential failure modes and causes, failure modes and effects analysis (FMEA) of distribution transformer components has been presented. By calculating risk priority numbers (RPN) according to severity, detection and occurrence, the in-depth analysis that assist in determining the local and long-term effects of these factors, as well as the critical transformer components that are susceptible to failure. Systematic failure data analysis of the distribution transformer components with the application of the FMEA has been presented which emphasizing the minor and major component failures of the transformer. The calculated RPN value of minor faults was maximum of 180 due to overloading and minimum of 36 due to bas bar incomers fault whereas the RPN value of major failures was highest 567 is belongs to insulation failure due to electrical failure mode and the least is 56 tank failure due to mechanical mode.

The causal loop diagram to analyzed the direct and indirect relationships among failure causes, failure modes, failure effects. This CLD is very helpful for showing the unseen failure causes and effects and could strengthen the FMEA.

Asset management system using reliability centered maintenance specifically applying SCADA system monitoring, which is a powerful tool that can be used to develop effective transformer failure mitigation strategies. By using these tool, the AACAEU and district utilities can improve the reliability of their power grids by keeping the health of transformers and protect their customers from costly and disruptive outages.

Chapter Five

5. Conclusion and Recommendation

5.1. Conclusion

Frequent power outages and fluctuations is still a serious problem in Addis Ababa. Problems related with electric distribution network are mainly associated with power carrying line wear-outs, mounted poles fall down and switchgears faults and failure of distribution transformers. From these network components, transformers are very costly, hazardous and frequently failed. So, this thesis aimed to identify transformer failure root causes, its effects and mitigation strategy development.

Related literatures have been reviewed on transformer failure analysis of different causes, effects, methodological tools used and maintenance systems applied for their research paper. FMEA has been used for prioritize actions needed to protect critical assets by determining the modes of failure, consequences of failure, and likelihood of root cause occurrence and detection. Fishbone diagram and failure tree diagram also applied by researchers to analyze the root cause of failure

The study addresses 3,825 number of distribution transformers from the year 2020/21 to 2022/23 and using statistical analysis, FMEA and CLD tools to analyze the failure modes, causes and effects of distribution transformers. Similarly, the tool that applied to mitigate the transformer of failure occurrence was asset management system.

Using descriptive statistical tools, graphical charts and tabular analysis could be harmonizing to reach the needed more effective actions. The result of this thesis generally shows that the existing problems in Addis Ababa related with 13.4% failure rate of distribution transformers are caused by human factor for failure which accounts around 75%. Human factor for failure includes improper operation and maintenance, inadequate testing and inspections, lack of skilled workmanship to carry out repair and maintenance, and improper handling and transportation also have significant contribution to failure of the transformers either on the time of installation or immediately thereafter. As indicated in the statistical analysis, operation related failures of distribution transformers are mainly associated with overloads followed by short circuit, internal problem, lightning and over/under voltage. Studies reveal that distribution transformers continuously work without the risk of failure at 40% of the full load. So, this paper showed that distribution transformers were overloaded during expansion urbanization along the western Addis Ababa and during power sharing operation when a nearby transformer fails. The FMEA has been used to systematically analyze failure data that emphasis on the minor and major component failures of the transformer. Based on severity, detection and occurrence value the risk priority number (RPN) was calculated, and the local and long-term effects of these factors, as well as the critical transformer components such as insulation 576 RPN, winding 432 RPN, bushing 378 RPN, oil 366 RPN and tap changer 288 RPN were identified as the most susceptible to failure. The direct and indirect connections among FMEA components, that is, failure modes, causes and effects were diagrammatically analyzed through CLD. Hence, human factor for failure which is the main failure cause of transformers was demonstrated using this model.

The developed failure mitigation strategy is based on asset management system. This system consists of proactive and reactive reliability centered maintenance(RCM), ISO 55000, company strategic plan and pre operation activities. This mitigation strategy mainly focusses on proactive based predictive SCADA monitoring system and preventive inspection maintenance. The developed model has been included the asset management system components to the lifecycle of the costly transformer asset.

5.2. Recommendation

This study recommends the following points

- Due attention for healthy transformer delivery, testing based on manufacturers' instructions and name plates before installation and commissioning
- In order to implement predictive control using SCADA system, the AACAEU should change the ordinary transformers into smart ones by installing sensors and actuators.
- Use asset management system to track the condition of transformers over time. This can help to identify transformers that are aging or that are showing signs of wear and tear.
- Use SCADA to monitor transformer temperatures and currents. This can help to detect early signs of overheating or overloading, which can lead to failure.
- Use asset management system and SCADA to schedule preventive maintenance for transformers. This can help to prevent failures by identifying and correcting problems before they cause a major outage.

- Use asset management system and SCADA to develop contingency plans for dealing with transformer failures. This can help to minimize the impact of failures on the power grid.
- Improved visibility of transformer assets and SCADA can provide utilities with a real-time view of their transformer assets, including their location, condition, and maintenance history. This information can be used to make better decisions about transformer maintenance and replacement.
- Increased efficiency of maintenance operations. Asset management system and SCADA can automate many of the tasks involved in transformer maintenance, such as scheduling and tracking work orders. This can free up staff time to focus on more strategic activities.
- Reduced risk of human error. Asset management system and SCADA can help to reduce the risk of human error in transformer maintenance and operation. For example, SCADA can be used to automatically shut down a transformer if it is overheating or overloaded.
- Improved communication with stakeholders. Asset management system and SCADA can be used to communicate with stakeholders, such as customers and regulators, about transformer failures and mitigation strategies. This can help to build trust and confidence in the utility's ability to manage its transformer assets.
- To avoid lightning related failures, distribution transformers should have lightning arrester in the high voltage side and high rupture capacity(HRC) fuses in the low voltage side.
- During power sharing operations, distribution transformers should be loaded not more than 40% their designed capacity.
- To improve lack of motivation, the AACAEU have to consider the increasing of wage based on performance and add some other incentive mechanisms
- AACAEU distribution transformers maintenance staff and operators should get receive continuous training on asset management system, skill improvement and attitude change.
- Implement proactive and reactive types of reliability centered maintenance (RCM)
- Implementing ISO 55000 asset management system to keep transformer health condition.

5.3. Future Research area

1. The work environment safety effect of oil spillage during maintenance of failed transformer requires further study
2. Identifying failure of transformers due to manufacturer or supplier also needs future attention

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Annex 1

Ethiopian Electric Utility

NAAD TRANSFORMER & SWITCHGEAR
DISTRIBUTION TRANSFORMER HISTORY CARD

	Sign	Date
Autorized		

Transformer Inspection format

No.	Location	Service center	KVA/15 KV	Serial No.	Manufacturer	Year	L.Arrester	Links	Drop out fuse/MV Breaker	Ground	Silicagel	Bushings	Oil level	Leakage	pole status	GPS	Cable size(mm2)/Fuse rating(A)			Transformer Load(A)				Remark
																	F-1	F-2	F-3	R	S	T	N	

Annex 2

For Managers and senior professionals use only:

This interview is prepared to collect primary data on transformer failure and its effect on the functions of the company. In addition, I would like to express the confidentiality of the information and that is required only for conducting study.

1. What are the impacts of transformer failure on the company efficiency?

____

2. What work procedure, workman skill and working environment is suitable for transformer reliability?

____

3. What are the frequent failure causes of distribution transformers and the solution taken?

____

4. What are the functions and performance standards of the item in its current operational context? - Identification of functions ____________________________

5. In what way, does it fail to fulfil its functions? - Identification of functional failures

____

6. What are the un seen failure causes and its impact?

____

7. What happens when each failure occurs? - Effect of failure and its severity measurement

____

8. In what way does each failure matter? - Consequences of failures

____

9. What can be done to predict or prevent each failure? - Maintenance tasks

____

10. What should be done if a suitable proactive task cannot be found?

____

Annex 3

Ranking Criteria for the FMEA

According to FMEA guidelines (1992), the FMEA uses three criteria to assess a problem: A) the severity of the effect on the customer, B) how frequently the problem is likely to occur and C) how easily the problem can be detected.

Severity Ranking Criteria

A classification ranking that includes safety, loss of life and money, scrap, and other factors can be obtained by calculating the severity levels. There may be additional aspects to take into account (that contribute to the event's overall severity). Table 1 serves as a guide; The supplier and the customer ought to work together to formally establish severity ranking criteria that provide the most useful output data.

Table 1: Severity Ranking Criteria (FMEA guidelines, 1992)

Rank	Description
1–2	Failure is of such minor nature that the customer (internal or external) will probably not detect the failure.
3–5	Failure will result in slight customer annoyance and/or slight deterioration of part or system performance.
6–7	Failure will result in customer dissatisfaction and annoyance and/or deterioration of part or system performance.
8–9	Failure will result in high degree of customer dissatisfaction and cause non-functionality of system.
10	Failure will result in major customer dissatisfaction and cause non- system operation or non-compliance with government regulations.

Occurrence Ranking Criteria

The probability of a failure occurring during the system's expected lifespan can be expressed in terms of potential occurrences per unit time. The probability of each failure mode is organized into distinct, logically defined levels. Table 2 depicts the recommended occurrence ranking criteria for the FMEA.

Table 2: Occurrence Ranking Criteria*(FMEA guidelines, 1992)*

Rank	Description
1	**An unlikely probability of occurrence** during the item operating time interval. Unlikely is defined as a *single failure mode (FM) probability < 0.001* of the overall probability of failure during the item operating time interval.
2–3	**A remote probability of occurrence** during the item operating time interval (i.e. once every two months). Remote is defined as a *single FM probability > 0.001 but < 0.01* of the overall probability of failure during the item operating time interval.
4–6	**An occasional probability of occurrence** during the item operating time interval (i.e. once a month). Occasional is defined as a *single FM probability > 0.01 but < 0.10* of the overall probability of failure during the item operating time interval.
7–9	**A moderate probability of occurrence** during the item operating time interval (i.e. once every two weeks). Probable is defined as a *single FM probability > 0.10 but < 0.20* of the overall probability of failure during the item operating time interval.
10	**A high probability of occurrence** during the item operating time interval (i.e. once a week). High probability is defined as a *single FM probability > 0.20* of the overall probability of failure during the item operating interval.

NOTE: Quantitative data should be used if
it is available. For Example:

0.001 = 1 failure in 1,000 hours
0.01 = 1 failure in 100 hours
0.10 = 1 failure in 10 hours

A. Detection Ranking Criteria

This section provides a ranking based on an assessment of the probability of detection of a failure mode given the controls in place. The detection probability is ranked in reverse order. For example, "1" means a very high probability of detecting an error before it reaches the customer; "10" indicates a low to zero error detection probability; Thus, the customer would suffer an outage. The recommended criteria are listed in Table 3.

Table 3: Detection Ranking Criteria (FMEA guidelines, 1992)

Rank	Description
1–2	Very high probability that the defect will be detected. Verification and/or controls will almost certainly detect the existence of a deficiency or defect.

3–4	High probability that the defect will be detected. Verification and/or controls have a good chance of detecting the existence of a deficiency or defect.
5–7	Moderate probability that the defect will be detected. Verification and/or controls are likely to detect the existence of a deficiency or defect.
8–9	Low probability that the defect will be detected. Verification and/or controls not likely to detect the existence of a deficiency or defect.
10	Very low (or zero) probability that the defect will be detected. Verification and/or controls will not or cannot detect the existence of a deficiency or defect.

Annex 4

Table 1. Transformer Inspection Checklist

General inspection items	Expected Frequency
Cooling system	Every 6 months
Transformer body	Every 6 months
Load current	use recording meters
Voltage	use recording meters
Liquid level	use recording meters
Temperature	use recording meters
Protective devices	Annually
Protective alarms	Monthly
Ground connections	Every 6 months
Tap changer	Every 6 months
Bushing	6month
Lightning arresters	Every 6 months
Pressure-relief devices	Every 3 months
Breather	Monthly
Auxiliary equipment	Annually
Internal inspection	5 to 10 years
Insulating liquid	Frequency
Dielectric strength	Annually
Oil Color	Annually
Moisture content	Annually
Gas-analysis test	Annually
Frequency analysis test	Annually
Polarization recovery voltage	Annually
DC winding resistance	Annually

Annex 5

Table 4.5: failure of transformers related with origin of manufacture sample data

በምስራቅ አዲስ አበባ የተቃጠሉ ትራንስፎርመሮች ዝርዝር (2011)							
ተ.ቁ.	**ቦታ**	**ሲሪያል ነምበር**	**ምርት**	**G.C.**	**ኬ.ቪ.ኤ.**	**ቀን**	**ምርመራ**
1	ሰሚት ኪዳነ ምህረት	85234	ህንድ	1995	500	13/9/2011	unkown
2	ካሳንችስ አጎዛ ገበያ	82455	ህንድ	1997	315	29/9/2011	leakage under transformer
3	ገርጂ ካዲስኮ	o2497	ሚቴክ	1997	100	3/10/2011	Due to lightning
4	ሲኤምሲ ፊጋ	oo285	ሚቴክ	2000	400	6/10/2011	Due to lightning
5	ኮተቤ ቤዛለም አካዳሚ	86741	ህንድ	2001	315	6/10/2011	over load
6	መሪ መስጊዱ ጋር	86732	ህንድ	2001	315	4/10/2011	over load
7	አያት ሰንሻይን	o1347	ሚቴክ	2002	200	1/10/2011	ohmic value is different
8	ሰሚት ከ 211 እስከ 213	100087	ቻይና	2003	100	21/10/2011	over load
9	የካ ሜከኤል	o3786	ሚቲክ	2004	315	5/10/2011	over load
10	መሪ ተክለብርሃን አምባየ	o5-288	ህንድ	2004	200	7/10/2011	over load
11	ላምበርት ኢትዮቻይና ጎን	1274	ሚቴክ	2004	100	18/10/2011	over load
12	ሰሚት ዲቦራ ት/ቤት	0251/R	ሚቴክ	2005	315	27/10/2011	short circuit fault
13	ኮተቤ ካራ ኬላ ደረጃ	T-012R781	ሲሪላንካ	2006	200	30/10/2011	over load
14	ወሰን ፖሌስ ጣቤያ	T-11452	ኤቤቤ	2006	200	4/11/2011	short circuit fault
15	ቦሌ ብርሃኔ አደሬ አካባቤ	1077177	ህንድ	2007	100	5/11/2011	short circuit fault
16	ቦሌ አራብሳ ፕሮጀክት 15	oo571	ሚቴክ	2007	315	8/11/2011	
17	ካራ ስላሲ ውሃ ታንከሩ ጋር	561942	ኮንከር	2008	315	23/11/2011	over load
18	ሰሚት ብሎክ B/91	ooo26	ሚቴክ	2008	315	27/11/2011	Due to lightning
19	አዲስ ህይወት ሆሰፒታል	28578	ዚናሮ	2008	200	30/11/2011	Due to lightning
20	ጎሮ አሳማ እርባታ	561828	ኮንከር	2008	200	1/12/2011	short circuit fault
21	ሰሚት ኮንደሚንየም B/240-244	ooo80/R	ሚቴክ	2010	100	5/12/2011	over load
22	ገርጂ ሪንጅ ማቅለጫ	1535	ቻይና	2010	315	6/12/2011	short circuit fault
23	ሲኤምሲ ልዩ ቤቶች	1044866	ህንድ	2010	200	10/12/2011	over load
24	ሲኤምሲ አሞራው ጤና ጣቢያ መደስት ካፊ	42842	ዚናሮ	2013	315	15/12/2011	over load
25	ሲኤምሲ አሞራው ጤና ጣቢያ መደስት ካፊ	T-12049	ኤቤቤ	2013	315	17/12/2011	over load
26	ኮተቤ ኪዳነምህረት ቤተክርስትያን መውጫ	oo699	ሚቴክ	2013	50	5/12/2011	over load

27	አራብሳ ሁለት ኮንደሚንየም	o1717	ሚቴክ	2013	315	21/12/2011	leakage under transformer
28	ፈረንሳይ እስላም መቃብር አካባቢ	86614	ህንድ	2013	315	22/12/2011	over load
29	የረር አለማየሁ ህንፃ ፊት ለፊት	o1615	ሚቴክ	2017	315	2/13/2011	over load

በምስራቅ አዲስ አበባ የተቃጠሉ ትራንስፎርመሮች ዝርዝር(2012)

ተ.ቁ.	ቦታ	ሲሪያል ቁጥር	ምርት	(G.C.)	ኬ.ቪ.ኤ.	ቀን	ምርመራ
1	ሞኒኮ አድዋ ፓርክ	T-11214	ኤቤቤ	1954	100	3/1/2012	Due to lightning
2	ጃክሮስ በጉና ተገብቶ	86514	ማቭሰን	1969	315	3/1/2012	over load
3	ሽፈራው ዘይት ቤት	2500252	ሚቴክ	1985	315	6/1/2012	over load
4	ሰሚት ለስላሳ ፋብሪካ ግቢ ውስጥ	42836	ዚናሮ	1987	315	9/1/2012	over load
5	ቦሌ አራብስ ብሎክ 400 ለብሎኬት ማምረቻ	oo496	ሚቴክ	1987	200	14/1/2012	Due to lightning
6	አያት ዘን 5 መንገድ 9	2290	ቻይና	1988	315	18/01/2012	short circuit fault
7	ኮርያ ስፈር 05 ቀበሌ	00166/R	ሚቴክ	1995	200	18/1/2012	over load
8	ፈረንሳይ አሰፋ መጋዝን	28870	ዚናሮ	1995	315	23/01/2012	over load
9	ሚሪድያን ሆቴል			1996		26/1/12	
10	መገናኛ እግዜአብሄር አብ ቤተ ክርስትያን	o3-1	ቻይና	1997	50	5/2/2012	
11	ቦሌ ሆምስ ኮንከርድ ጋር	82429	ህንድ	1997	315	11/2/2012	
12	አያት ዘን 8	oo681	ሚቴክ	1997	200	12/2/2012	
13	ጎሮ ገብርኤል አካባቤ	oo259	ሚቴክ	2000	200	18/3/2012	over load
14	ሽፈራው ዘይት ቤት	85312	ህንድ	2000	630	29/3/2012	
15	ገርጂ ሠላም ስፈር	86712	ህንድ	2001	315	2/4/2012	over load
16	ሾላ በግ ተራ	82527	ህንድ	2001	315	6/4/2012	Short circuit fault
17	ኮተቤ መድሃኔአለም ራያ ግሮስሪ	oo746/R	ሚቴክ	2002	200	14/04/2012	short circuit fault
18	ገርጂ ሠላም ስፈር	29045	ዚናሮ	2002	315	15/04/2012	over load
19	ፈረንሳይ ፊልም ምአከል	89444	ሚኔል	2003	50	27/04/12	over load
20	ኮተቤ ኮሌጁ ጀርባ	oo94	ሚቴክ	2003	200	27/04/2012	overload
21	ገርጂ ሠላም ስፈር	00530/R	ሚቴክ	2003	315	15/05/2012	
22	መገናኛ ማራቶን	oo153	ሚቴክ	2003	200	23/05/2012	
23	ቀበና ኦሮሚያ ደንና ዱር እንስሳ	15172	ህንድ	2003	100	2/6/2012	Short circuit fault
24	ካራ ጥሩ መናፈሻ	2782	ሚቴክ	2004	25	6/5/2012	because of oil

25	ገርጂ ጉልቱ ጋር	1182765	ህንድ	2004	100	6/6/2012	
26	ካፒታል ሆቴል ጀርባ			2004			
27	ጎሮ አሳማ እርባታ አረቡ ግቢ	o3-66	ቻይና	2004	50	17/06/2012	overload
28	ሃና ማርያም ስላም ህፃናት ማሳድግያ	42449	ዚናሮ	2004	200	26/06/2012	no resistance in low voltage side
29	22 ብሉ በርድ ሆቴል ጀርባ	T-11378	ኤቤቤ	2005	200	24/06/12	
30	ሰሚት ፍየል ቤት ጎላጉል ሪል እስቴት	5180194	ስቱምበርግ	2005	100	1/7/2012	overload
31	እግዚአብሄር አብ ቤ/ክ	o1888	ሚቴክ	2005	50	12/7/2012	
32	ሸቦ ኤጀርሳ ት/ቤት	o2683	ሚቴክ	2005	315	13/07/2012	
33	ፈረንሳይ ኮካ ማከፋፈያ	9616296	ፖለስ	2005	315	14/07/2012	
34	ባጃጅ ማዞሪያ ስላም ስፈር	T007R782	ሲሪላንካ	2006	315	14/07/2012	
35	አያት ዞን 3 መንገድ 2	85184	ህንድ	2006	400	15/07/2012	Short circuit fault
36	መሪ ስኩል ኦፍ ቱሞሮ ጀርባ	oo340	ሚቴክ	2006	315	16/07/2012	Short circuit fault
37	ኮተቤ መሳለሚያ ገብርኤል	86542	ህንድ	2006	315	19/07/2012	car accident
38	ፊጋ መሄጃ አየር መንገድ	oo268	ሚቴክ	2007	100	19/07/2012	
39	ፊጋ መሄጃ አየር መንገድ			2007		23/07/2012	
40	ገርጂ ፓርላማ መኖርያ ቤቶች	T-12077	ኤቤቤ	2008	315	23/07/2012	lv short
41	አያት ዞን 5	/1141	ቻይና	2009	315	16/07/2012	pole fail on transformer
42	መከላከያ ቤላ ግቤ ውስጥ	CT0640-561744	ኮንከር	2009	200	29/07/2012	
43	መሪ ባሃታ	94406725	ፖውለስ	2009	200	25/07/2012	
44	24 ቀበሌ ኮኮብ ህንፃ	54161	ሚላኖ	2009	200	9/8/2012	
45	አያት ፈረስ ቤት			2009	50		
46	አንቆርጫ ወንድየ ሱቅ			2009	315		
47	ፈርንሳይ ለጋሲ ልእልት			2009	200		
48	ሾላ በግ ተራ			2010	200		
49	02 ኮተቤ መካነ እየሱስ	86531	ማርሶን	2010	315	15/08/2012	
50	አቦሪ እንሳሮ ሆቴል	T-12093	ኤቤቤ	2013	315	15/08/2012	Short circuit fault
51	ቦሌ 2000 አበሻ ጀርባ	548	ሚቴክ	2013	200	16/08/2012	
52	ሰሚት ወርቁ ግሮሰሪ			2013	315		
53	ፈርንሳይ ለጋሲዎን			2013	315		
54	ሰሜት ዲቦራ ት/ቤት			2013	200		
55	ላምበረት አዲሰን ሆቴል	85204	ህንድ	2013	315		
56	ቤላ ንግድ ባንክ	05-468	ቻይና	2013	315	19/08/2012	load unbalance
57	ኮተቤ ሀና ማርያም	T032R782	ሲሪላንካ	2013	315	28/08/2012	Short circuit fault
58	ባልደራስ ባሻ ወልዴ			2013	100	03/09/2012	

60	ስላም ስፍር ደረጃ ወፍጮ ቤት አካባቤ	86644	ማርሶን	2013	315	16/09/2012	
61	ገርጂ መብራት ሀይል	85104	ህንድ	2013	400	22/09/2012	Short circuit fault
62	ገርጂ ሰንሻይን	08-198	ቻይና	2013	315	28/09/2012	Short circuit fault
63	ሰሚት ፍየል ቤት	oo116	ሚቴክ	2013	400	03/10/2012	overload
64	ሰሚት ፍየል ቤት			2013	500	04/10/2012	
65	መሪ ብሃታ	ooo72/R	ሚቴክ	2013	200	08/10/2012	
66	አንቆርጫ አከባቢ	561939	ኮንከር	2015	315	08/10/2012	
67	ሽቦ ኤጀርሳ ት/ቤት	1812	ቻይና	2016	100	13/10/2012	
68	ኮተቤ መጠለያ ሃና መቃብር	85136	ማርሶን	2017	400	26/10/2012	overload
69	ጉርድ ሾላ ጆርጅ ዘይት ቤት	374	ቻይና	2017	315	4/11/2012	
70	አያት ዘን 5 መንገድ 11	561960	ኮንከር		315	6/11/2012	
71	መገናኛ ምንጭ ግሮሰሪ	86569	ማርሶን		315	9/11/2012	short circuit fault
72	ጎሮ ባጃጅ ተራ	o1420	ሚቴክ		315	15/11/2012	infinite resistance on winding so it has disconnection(cut) in winding
73	72 የሸዋ ድልድይ ስር	1428	ሚቴክ		315	27/11/2012	it has zero impidance on lV. side(short)
74	አያት ዘን 3	1077624	ህንድ		315	30/11/2012	Short circuit fault
75	አያት 49 ሀይሌ ሪል ስቴት	285	ሚቴክ		315	4/12/2012	
76	ሰሚት ቂሶች ሰፍር 40/60 ኮንደሚንየም	86735	ማርሶን		315	3/12/2012	
77	ካሳንችስ ከማእከሉ አለፍ ብሎ						
78	ቦሌ 17 ወረዳ 17 ጤና ጣብያ	86719	ማርሶን		315	13/12/2012	over load
79	ገርጂ መብራት ሀያል						
80	ኮተቤ ወስን ንግድ ባንኩ ጋር	82533	ማርሶን		315	20/12/2012	there is leakage of oil
81	አባዱ ብረሃኑ ጉታ	15819	ህንድ		200	21/12/2012	Short circuit fault In low voltage side the resistance is zero/short
82	ቤዛለም ት/ቤት	420161388	ቻይና		315	22/12/2012	ohmic value differ because of over load
83	መገናኛ ምድር ሚዛን 40/60 ኮንደሚንየም	8416048	ፓውልስ		200	2026/12/2012	
84	ሰሚት 30 ሚትር	o3349	ሚቴክ		315	28/12/2012	short circuit fault

በምስራቅ አዲስ አበባ የተቃጠሉ ትራንስፎርመሮች ዝርዝር(ጳጉሜ)

ተ.ቁ.	**ቦታ**	**ሲሬያል ቁጥር**	**ምርት**	**(G.C.)**	**ኬ.ቪ.ኤ.**	**ቀን**	**ምርመራ**
1	ቀበሌ 24 ወጣቶች ማእከል	T011010R782	ሲሪላንካ	2005	315	1/13/2012	overload
2	ቀበሌ 24 ኮንደሚንየም አጠገብ	o2887	ሚቴክ	2006	315	1/13/2012	overload
3	ኮተቤ ኮሌጅ ግቤ ውስጥ	oo222	ሚቴክ	2007	100	2/13/2012	short circuit fault
4	ቦሌ ሰላም ሲቲ ሞል	40000206	ሚቴክ	2008	400	3/13/2012	internal problem
5	ኮተቤ በግ ተራ	20000393/R	ሚቴክ	2009	200	3/13/2012	Due to lightning
6	ቦሌ ለሚ	1077008	ህንድ	2009	100	5/13/2012	overload
7	ላምበረት መንሃሪያ እራሱ	10000966/R	ሚቴክ	2017	100	5/13/2012	on high tension side has opening