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Original Article

Application of the FMECA Tool in the Identification of Causes of Faults in Distribution Transformers in Cameroon: Case of the Buea Sub-Area Network

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Abstract - *The reliability of the distribution system is dependent on system components such as transformers. When faults occur in the distribution transformers, especially when they connect the power system to critical loads such as telecommunication systems, airports, hospital railways, etc., the failure could be catastrophic as it brings about material and economic losses to the utility company. This situation is even more serious in developing countries with mostly radial network topology. The energy utility company in Cameroon (ENEO Cameroon) has been facing several power outages on the distribution network caused by the failures of distribution transformers, and this has resulted in severe economic impacts not only on ENEO but extends on damaging of customers' equipment. The rationale of this research is to identify distribution transformer root causes of failures in the Buea distribution network. The area chosen for this study is Buea, a sub-area of the Southern Interconnected Grid (SIG) in Cameroon. The FMECA procedure was applied on the distribution transformers to identify the failure modes, effects and criticality analysis. The study found that the failure rate in Buea from 2019-2021 was 15% and on averagely 5% annually. The FMECA results revealed that windings failure and insulation failure were the most probable causes of failures in Buea, while vandalism, bushings and the core were also to be carefully monitored to prevent equipment failure.*

Keywords - *Criticality analysis, ENEO, Reliability, radial network, SIG.*

I. INTRODUCTION

Access to reliable, robust and affordable electricity supply is a prerequisite for the socio-economic development of any society[1]. It is, therefore, a precondition for the operation of industry, transportation, health care systems, education and in some high-value applications like computing and telecommunications [2]. The conventional power infrastructure is described by isolated components of generation, transmission, substation and distribution. The stability and reliability of electrical power systems are greatly influenced by system components. Amongst these components are transformers which play a central role in the transformation of voltage levels. The distribution transformers serve as the final connection between the power system and low voltage consumers. The failure of a distribution transformer is costly to the utility company and can also damage the equipment of connected clients. For example, one blackout in North Eastern USA and Canada caused estimated financial damage amounting to 6 billion dollars in 2003[3].

Unlike developed countries that are connected by the mesh network, developing countries like Cameroon are connected by the radial network architecture imposed by a lack of investments[4]. One of the drawbacks of this radial network architecture is that the addition of a new load necessitates the resizing or replacement of the distribution transformer in that line in order to avoid overloading[5]. ENEO Cameroon has incurred lots of financial losses due to distribution transformer failures. From 2019 to 2021, Buea recorded 24 transformer failures, while in 2020, ENEO lost 500 distribution transformers nationwide [4]. Because of the disastrous economic impact of distribution transformer failure on the utility company and its customers, identification of root causes of transformer failures is key to improving system reliability and preventing future failures. This has often led to riots of communities that are connected to the transformer and resentment towards ENEO staff.

List of abbreviations

ENEO	Energy of Cameroon
SIG	Southern Interconnected Grid
FMECA	Fault Modes Effect and Criticality Analysis
FRA	Frequency Response Analysis
FL	Fuzzy Logic
TF	Transfer function
TM	Tree Model
ANN	Artificial Neural Network
DGA	Dissolved gas analysis
SVDD	Support Vector Description Model
IDM	Imprecise Dirichlet Model
SVM	Support Vector Model
PCA	Principle component analysis
DP	Degree of Polymerization
NCC	Naive Credal Classifier
RSVDD	Robust Support Vector Data Description
RBM	Restricted Boltzmann Machine
IEEE	International Electrical and Electronic Engineering
PNN	Probabilistic Neural Network
RPN	Risk Priority Numbers
CA	Criticality Analysis

By virtue of their importance in the distribution system, many approaches for diagnosing distribution transformer failure modes have been extensively investigated. Bigdeli *et al.* [6] evaluated the fault type, frequency and severity of distribution transformers faults using Frequency Response Analysis (FRA) as well as the sort of faults that occurred. With this method, the transformer's Transfer Function (TF) is calculated in intervals and compared with the reference transfer function (TF) to determine the fault type, occurrence, and severity.

Although the researchers claimed that their methods were better in accuracy than other methods such as Fuzzy Logic(FL), Artificial Neural Network (ANN), Support Vector Description Model (SVDD), etc., their methods were limited to axial displacement, radial deformation, disc space variation, short-circuits and core deformation which is not the only transformer faults. Also, their method is fastidious since one has to measure the transfer function several times before and after the fault. Velásquez [7] provided an algorithm for high accuracy dissolved gas analysis (DGA) for transformer oil-kraft degradation using the Support Vector Model (SVM) and Tree Model (TM). This approach permitted the detection of high accuracy partial discharge, Oil-Kraft quality dissolved gas analysis (DGA), degradation and the remaining life of the transformer. His findings revealed a 94% accuracy for the evaluation of the arc degradation process using the tree model and 100% accuracy for SVM analysis of partial discharge and oil degradation. The neural network was used to evaluate the average remaining life of the transformer. All of the results obtained could only be applicable in a transformer in operation and, therefore, cannot be used to identify the root causes of a failed transformer. Secondly, all the analysis was internal and mainly limited to transformer insulation; hence it is not a reliable approach to identifying the root causes of a failed transformer. Murugan *et al.* [8] conducted a root cause analysis on the components of a power transformer using the Ishikawa diagram to describe the causes of the power transformer's possible failures. The results of their findings formed the basis for condition-based monitoring of power transformers which is a form of preventive maintenance. Besides, Zhao *et al.* [9] developed a novel approach for the diagnosis of transformer faults composed of the Imprecise Dirichlet Model (IDM) together with a naive credal classifier (NCC) based on the theory of imprecise probability. For transformers with limited historical faults records, the approach indicated a range of probability for every type of fault rather than single-valued probability showing the objectivity of diagnosis results. Per the Credel classifier criteria for classification, the approach suggested was expected to only output explicit fault type or possible latent faults frequently occurring in transformers. This method compensates for the disadvantages of other methods. This approach leads to the improvement of diagnostic accuracy and maintenance efficiency. Velásquez *et al.* [10] developed an intelligent diagnosis system for dissolved gas analysis (DGA) based on principle component analysis (PCA) and fuzzy logic for adaptive decision making. Their goal was to forecast the transformer's deterioration rates, degree of polymerization (DP), and health index. Their method was found to be accurate to about 97% for failure events on the transformer. Similarly, Zhang *et al.* [11] equally presented a robust support vector data description (RSVDD) technique for incipient faults detection. This method improved the sphere radius calculation via RSVDD by introducing normal and faulty samples for modelling. The researchers further proposed a restricted Boltzmann machine (RBM) based self-learning fault identification method also applying the probabilistic neural network (PNN). The Tennessee Eastman benchmark is used to validate the RSVDD and RBM-PNN scheme proposed. They claimed that the RSVDD method was better for incipient fault detection than KPCA and SVDD methods while RBM-PNN for fault identification performance was superior to KPCA-SVM and KPCA-BP approaches. Li *et al* [12] used the PCA-R-SVDD method to improve the performance of transformer fault detection. The fault detection was done using monitoring statistics distance-based SVDD. The proposed method beats previous methods significantly due to the greater distribution of fault data as well as stricter monitoring metrics. It is though vulnerable to six common flaws, including CdF, RfO, RfL, Ncg, not excluding; RCdW as well as EO. The method can successfully detect 50% fault data irrespective of the severity of the fault level. Furthermore, a restricted Boltzmann machines (RBM) method as well probabilistic neural networks (PNN) based self-learning algorithm for fault detection was developed. Velásquez *et al.* [13] presented an effective maintenance plan for power reactors of an energy transmission company, Red de Energia del Peru(REP), upon conducting failure analysis through the artificial neural network(ANN) diagnosis and root cause analysis (RCA) for visual inspection. Their research culminated in the development of a maintenance personnel guide for the identification of faults linked with designer errors.

In previous studies, many methods have been used for transformer failure analysis, most of which were transformer fault-specific, mainly focusing on insulation failure through dissolved gas analysis (DGA), alongside health index, as well as the transformer's remaining life by calculating the degree of polymerization (DP). Most previous methods deployed are based on artificial intelligence and are therefore mainly hypothetical and reported component-based failure analysis through statistical methods, either just identifying the main causes of failure or using inferential statistics to predict a component failure. Transformer failures could originate from one or more of its components, and hence, conducting a failure analysis requires the consideration of all its components so that some sources of failure should not be omitted. The previous studies, therefore, failed to adequately explore transformer failures holistically. This paper first identifies the failure causes reported by the utility company (ENEO Cameroon) and also investigates the potential modes of failure, causes as well as effects of failure on the transformer and the network in Buea, a sub-area of the SIG of Cameroon.

This research was conducted based on failures of 24 distribution transformers recorded in the Buea distribution network from 2019-July 2021. The failure of distribution transformers usually causes power outages or completely damages the equipment of clients resulting in costly unplanned downtime incurred in repairs or replacement. This failure in the ENEO network in Buea does not only bring serious financial damages to ENEO and customer dissatisfaction, but it also leads to riots and resentment of affected communities towards ENEO staff. This research aims to identify the root causes of distribution transformer failures in the Buea distribution grid in Cameroon using the fault mode effects and criticality analysis known as the FMECA technique. The FMECA is used for system or product assessment used to identify potential failures that may impact customer expectations of quality of product or process performance developed by the US military. First used in the early 1950s to analyse Aircraft Power Plan based on Automotive Industry Action Group's requirements, FMECA is now widely used in a variety of industries, such as aircraft, autos, electronics, power system components, and medical equipment. [14][15][16]. Furthermore, FMECA is becoming more widely used in the service business, including in internet commerce [17] [18]. It was then integrated with the Kano model for tourism-related applications.

The main advantages of this method include the following:

- The FMECA is a pragmatic procedure identifying dominant failure modes rather than an intellectual assessment of failure, which identifies speculative failure modes. In the FMECA method, the contributions of operators and maintenance crews can have a significant positive impact.
- The FMECA assists in identifying potential design reliability problem areas that must be eliminated or their impact reduced through design changes or trade-offs.
- The FMECA provides information that can be utilized to diagnose equipment/machinery considering the likelihood (potential mode) and severity (failure mode) of failures, causing one to proceed with caution. FMECA, using its FMEA, analyses probable modes and now prioritizes the most critical machines.
- FMECA is a valuable tool for decision making on failure repairs or design integrity if properly applied

The paper is divided into three sections: Section 2 presents the methodology explaining the steps followed to collect data of failed transformers in Buea and discussing the (FMECA) procedure, results and discussions are presented in Section 3 while Section 4 concludes the study, formulating proposals and recommendations.

II. MATERIALS AND METHODS

This study is based on failure modes, causes of failures as well as the effects of failures on the transformer and the entire utility network to identify the distribution transformer root causes of failures in Buea, a sub-area in the southern interconnected network in Cameroon. The research is conducted based on 24 failures recorded in Buea out of the 160 installed distribution transformers in the distribution network from 2019-July 2021. The study was conducted in two stages; firstly, records of previous maintenance works performed on the transformers of this area were consulted, and the utility staff was also interviewed. The data collected included cause of failure, transformer capacity and year of failure using the modified IEEE Std C57.125-2015, Transformer Failure information collection form, a procedure to obtain probable causes of distribution transformer failure through failure analysis [19]. Thereafter, the data was analysed statistically using descriptive statistics (percentile) to establish the primary reported causes and percentages of annual distribution transformer failures in Buea.

Furthermore, the FMECA was conducted on the distribution transformer to determine the causes and modes of transformer component failures by calculating and allocating RPNs to failure modes depending on the severity, occurrence frequency, and detectability of the fault to determine the transformer's most critical component [20]

The FMECA is performed in two stages; firstly, the fault mode effects analysis (FMEA) is developed primarily to identify all important components or equipment to record possible failures modes and conduct effect analysis. Tables 1, 2 & 3 present failure severity, failure occurrence frequency, and failure detection ranking standards for distribution transformers, defined after interviews with the utility staff. Moreover, the criticality analysis was done by assigning risk priority numbers to the faults to conclude the FMECA process.

Table 1. Criteria for the Assessment of fault Severity[20][21]

Classification	Description of the severity	Rank
Catastrophic	Burning the transformer or blackout	10
Critical	Complete failure components or damage to components	7-9
Moderate	Considerable degradation of components	5-6
Marginal	Minor degradation of components	3-4
Minor	Negligible effects on components	1-2

Table 2. Criteria for the Assessment of Frequency of fault occurrence[19][20]

Classification	Description of failure	Rank
Most frequently	inevitable equipment failure	10
Frequently	Failure every month or more	7-9
Occasional	Failures once in 6 months	5-6
Low	Failure once per year	3-4
Very unlikely	Failure hardly ever occurs	1-2

Table 3. Criteria for Failure Detection ranking[20][22]

classification	Description of Possibility of detection	Rank
Very difficult	Impossible to detect the failure	10
Difficult	Very difficult to detect the failure	7-9
Medium	50% chance of detecting	5-6
Easy	Highly detectable	3-4
Very easy	very easy to detect	1-2

The FMEA process is used to identify potential fault modes and analyse the impacts of the fault on the system's state of health [23]. When a fault occurs, its impact, otherwise known as severity, is ranged on a scale of 1 to 10, where 1 indicates "no failure" and 10 indicates "most severe" impact. Similarly, the frequency of occurrence of a fault mode is assessed on a scale of 1 to 10, with 1 representing "zero incidences" and 10 representing "high occurrence." The probability of discovering failure mode before it occurs is known as Detection. A high detection is graded on a 10-point scale, with 10 being the most difficult to detect. It should be noted that the severity assessment presented above is strictly based on interviews conducted together with previous maintenance records consulted and on literature review

Criticality analysis (CA) is the process of calculating the risk priority numbers (RPN) of fault modes [22]. This denotes the seriousness, frequency, and detection of the situation

$$RPN = S \times O \times D \text{....................................(1)}$$

where S is severity, O is failure occurrence, and D is detection. The higher the risk priority number (RPN), the more critical the failure mode. Improvement steps must be implemented if RPN reaches 100 and S is more than or equal to eight. [14]. The new RPN value for resolved failure is recalculated to measure the effectiveness of corrective action taken after the failure has been resolved [24]. RPN values are used to identify prospective problems, make failure predictions and can be utilized to implement a proactive maintenance system[25]. Using the definitions of the 9 FMECA elements and completing the corresponding FMECA sheet, the important components were identified, and the summary was presented in Table 6.

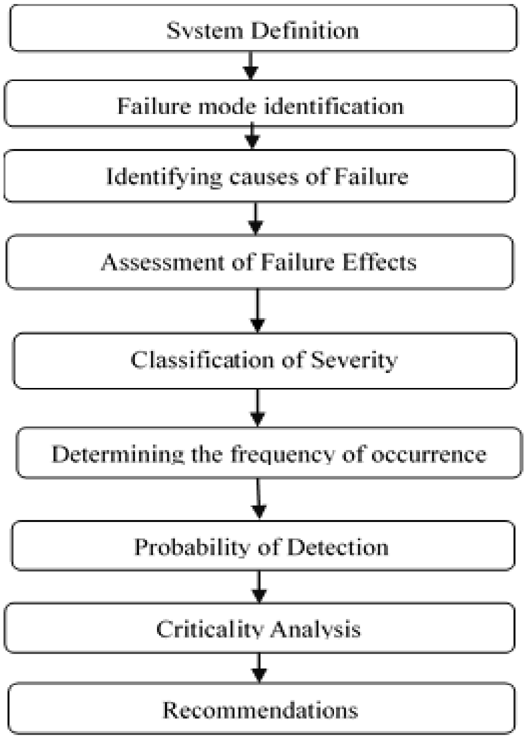

Fig. 1 FMECA procedure[20]

III. RESULTS AND DISCUSSION

A. Statistical Analysis

Descriptive statistics(percentile) was applied to the 24 analysis revealed that 24 transformers failed in 3 years, representing a 15% failure rate and an average annual failure rate of about 5%. The rated voltage of 30 kV and power ratings of 25 kVA to 630kVA are common in this distribution network. The data in Table 4 shows the transformer data and their annual failure statistics.

From table 4, only 3 transformers have been added to the distribution network in Buea in the last 3 years, which is attributed to the lack of investments[4]. This is in contrast to the increasing demand for electricity supply due to the increasing population. Table 4 also reveals an increasing failure rate in the Buea area network, while Table 5 shows that 22 of the 24 failed transformers were caused by overloading, and 2 failures were caused by vandalism. Fig 2 represents a plot of the number of transformers that failed against their capacities

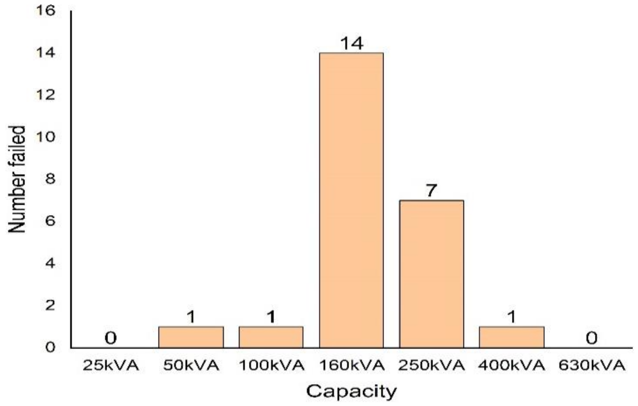

Fig. 2 Capacity wise failures

failed distribution transformers against 160 installed in Buea using Microsoft excel to obtain the failure percentage for the research period as well as annual percentages. The statistical

From table 5, the major causes of transformer failure include overloading caused by uneven loading, power theft, deterioration of insulation materials, short circuits, line surge

Vandalism was also highlighted as a cause of failure. This further provoked short circuits, oxidation, moisture, tank crack, leakage, oil spillage and so on.

Besides, flawed maintenance practices equally contributed to the transformer's failure.

This was justified by the presence of loose connections, no replacement of failed motors, fans and insulation oil, no replacement of burnt bushing sealing gasket, no replacement of LT rots oversizing and under-sizing of cables and protection fuses and circuit breakers

Contamination and acidity of liquid insulation could impair the strength of the transformer oil's dielectric substance, producing deposits and sludge on windings and disrupting liquid insulation circulation, leading the cooling system to fail and the transformer to fail. The failure of some Transformers can also be attributed to manufacturer design errors resulting from improper sizing of the tank, welding of the tank, poor material for insulation, weak strength of short circuit, loose connection etc. Unbalance loading can also result in overloading, deterioration of insulation materials, both solid and liquid, overheating and so on [26][27].

Table 4. Yearly Capacity wise failures reported in Buea

		2019		2020		2021		
S/N	**Capacity**	**Installed**	**Failed**	**Installed**	**Failed**	**Installed**	**Failed**	**Total failures**
1	25kVA	35	0	35	0	25	0	0
2	50kVA	15	0	15	0	50	1	1
3	100kVA	29	0	29	1	29	0	1
4	160kVA	47	5	48	4	50	5	14
5	250kVA	17	1	17	2	17	4	7
6	400kVA	8	0	8	1	8	0	1
7	630kVA	5	0	5	0	5	0	0
Totals		**157**	**6**	**158**	**8**	**160**	**10**	24
Percentage failure		**4%**		**5%**		**6%**		**15%**

Table 5. Causes of failure and number of failures 2019-2021

Cause of failure	Number of failures
Overloading	22
Vandalism	2
Others	0

B. FMECA of Distribution Transformers

The report from Table 5 states that overloading is the main cause of failure in Buea but does not indicate which components of the transformer are causing premature failures and also how severely these failures affect or are likely to affect the customers and the entire network. Considering the adverse effects on clients and the utility when a distribution transformer failure occurs, it is important to identify the cause of failures in distribution transformers in Buea and propose remedial actions to prolong their service life and enhance grid reliability.

To properly dissect the causes of these failures, component-based Failure Modes Effect and Criticality Analysis (FMECA) was applied to failure data in Buea, and the summary is presented in Table 6.

C. Component-Based Failure Modes of Distribution Transformers

The distribution transformer has been broken down into numerous subcomponents to examine it and create an FMEAC sheet, including windings, tank, bushings, cellulose isolation and cooler, and oil insulation. Figure 3 depict transformer components, and a brief description will follow soon. The tap changer is also included, even though this component is considered steering equipment instead of a transformer component[28]

- Core failure can be caused by overvoltage, DC magnetism, poorly insulated core's screws, cooling oil duct obstruction, core system dislocation of core steel etc., resulting in high core temperature as a result of high eddy current losses, efficiency loss, high inrush current, and excessive core heating[19][8] [28][29].
- The failure modes in windings include electrical (lightning surge, overvoltage and connection faults resulting from unbalanced loading and power theft), mechanical (vibration, manhandling during transportation, and electromechanical forces), thermal (overloading, cooling system failure, low quality of oil, unbalanced loading and excess temperature) and failures in solid insulation (insulation over-heating, contamination of oil and Cooling system failure). These failures can affect the functioning of the transformer in several ways, such as turn-to-turn insulation breakdown, short circuit, Insulation ageing, winding deformation and so on[8] [28][30]
- The tank's mode of failure is mainly mechanically caused by environmental stress, erosion, moisture, solar radiation, gaskets leaks, short circuits[28][31].
- The fault mode in the bushings is either mechanical(damage of the porcelain, insulation failure, vandalism) or electrical(short circuits) [28][19]. The failure of a bushing can result in damage of insulating material, damage of bushing, deficiency of oil due to spillage and short circuit. Inadequate maintenance results in both water and dirt entering the bushings. [32][33]
- The failure mode in solid insulation can be mechanical, electrical or thermal caused by mechanical damage, fault in material, overheating, ageing, unbalanced loading, overloading and so on. The effects of Cellulose(solid insulation) failure include a decline in paper's mechanical and dielectric strengths, transformer overload or even mechanical damage due to insulation failure [34][35][36][37][38]
- The liquid insulation or cooling oil can fail because of one of two things: either there are no heat transfers from the primary cooling circuit to the secondary cooling circuit, or there is an issue with the oil circulation system. As a result, the transformer oil becomes more viscous, and the secondary cooling circuit's temperature rises to dangerous levels. Heat combines with moisture and oxygen to generate conducting particles, which contaminate the oil. As a result, the transformer's temperature rises, and the oil insulation fails, causing a short circuit[39]
- The cooling systems of a transformer are made up of a pump, fan, radiator gauge and control circuit. If the pump of a forced oil circulation transformer fails, the temperature of the transformer oil will rise, causing the transformer to overheat. Failure of the Pump or fan leads to poor air/water circulation, causing the exceedingly high temperature in the water or air. The high temperature from the exterior of the transformer can raise the temperature of cooling air[40]
- The failure modes of the tap changer can either be electrical, caused by a short circuit resulting from improper maintenance and oil contamination or mechanical, caused by wear. These failures can result in the wrong position of the tap changer or fragile spring.

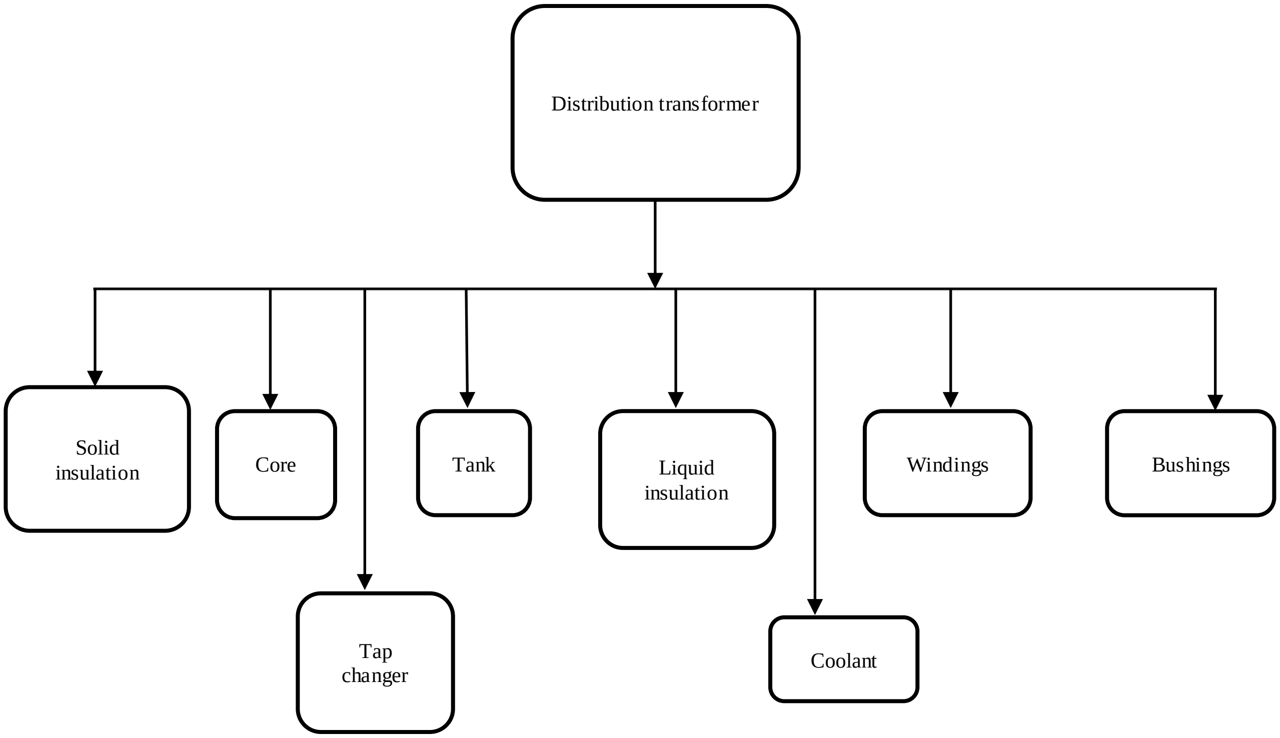

Fig. 3 Transformer and its components

Table 6. **FMECA sheet for distribution transformer in Buea.**

Failure mode effect and criticality analysis										
Components	**Function**	**Failure modes**	**Failure causes**	**Failure effects**	**Existing detection methods/control**	**Corrective Action/ Recommendation**	**S**	**O**	**D**	**RPN**
Cellulose (Solid insulation)	insulate windings by acting like dielectric	Electrical Mechanical	-Overloading/ Unbalance loading -mechanical damage -Fault in material -Aging	-weakened cellulose strength - Mechanical damage - overloading	None	None It cannot be replaced	8	5	9	360
Liquid insulation (Oil)	Insolation and coolant.	Thermal Electrical	-thermal decomposition -contamination from moisture - oil oxidization/high acidity - overloading & overheating - ageing insulation	- Degradation of oil properties - overheating - short circuit - oil quality degradation	Visual inspection	None It cannot be replaced	9	8	8	576
Windings	carry current in the transformer	Electrical Mechanical Thermal Insulation	- over-voltage & lightning surge - vibration & shipping damage - overloading& Unbalance loading - cooling system failure -low oil quality/contamination - overheating of winding insulation.	- turn-to-turn insulation failure -short circuit -Insulation ageing - winding deformation	None	Change insulation/cooling material	10	8	8	640
Bushing	high voltage electrical conductor	Electrical Mechanical	-Seal breaking of bushings -Loose connection -poor maintenance/insulation failure - porcelain damage/ fault in material - Vandalism/sabotage	- insulation damage - damage of bushing -deficiency of oil due to spillage - short circuit	Visual inspection of oil leakage	replacement of bushing sealing gasket	7	4	7	196
Tank	container for the oil	Mechanical	- solar radiation/corrosion/humidity -gasket leakage/ short circuit - Environmental stress, -high gas pressure in the tank	- leakage of oil -reduction of oil level - insulation failure -Corrosion	Visual inspection of oil level	Replace tank Refill tank	8	2	3	48
Core	concentrate the magnetic flux	Electrical Mechanical Insulation	-overvoltage & DC magnetism -Unbalanced loading - oil circulation obstruction - core system ungrounded	-High temperature of core/efficiency Loss - excessive heating of the core	It cannot be detected	N/A	9	2	8	144
Cooling System (Pump, fan, Radiator)	Used for cooling	Cooling System	-leak in the oil/water pipes -poor maintenance, -overuse/wrong due to bad thermostats -unbalance loading	reduction in the fluids low heat exchange	Visual inspection	Maintain regularly	8	2	6	96
Tap changer	regulate the voltage level	Mechanical	- mechanism fail/ Old capacitors - Lack of maintenance - motor breakdown	-Wrong position of tap changer -fragile spring	None	N/A	7	3	4	84
Others	N/A	Mechanical Electrical Thermal Insulation	-Operational errors -Lack of maintenance -power theft/ unbalance loading -vandalism/sabotage -single-phase loading	-Failure of transformer -overloading -short circuit -bushing failure	N/A	Capacity building of staff	9	4	8	288

The FMEA process included components failure mode, failure cause, effects of the failure on the transformer/network and recommendations were formulated to curb future failure. The criticality analysis of each failure mode was performed by assigning to each failure mode a Risk Priority Numbers(RPN), and the results of the entire FMECA process is represented in table 6. Table 6 summarizes the failure modes of transformer components, failure causes, effects of component failure of the transformer units or the entire grid and the Risk Priority Numbers based on how severe the effects of a failure are, how frequent a fault occurs in a month and how easy is it to detect the failure before it occurs.

Risk Priority Numbers assignments to failure modes are referred to as criticality analysis and specify the critical nature of each component failure. The highest RPN shows the components on which much attention should be tilted. From table 6, windings have the highest RPN values, followed by both liquid and solid insulation, respectively. These findings correspond to the results of the interviews presented in table 5, showing that the majority of the distribution transformer failures in Buea are due to overloading. This is equally supported by literature positing that overloading is one of the causes of the failure in transformer windings, cellulose and oil. The RPN value of "OTHERS" is high, agreeing with the data in table 5, which suggest that vandalism is the next cause of failures in Buea after overloading.

Transformer failures associated with liquid insulation can be prevented by regularly performing chemical analysis of oil, as well as dissolved gas analysis (DGA), and any oil leaks should be repaired promptly.

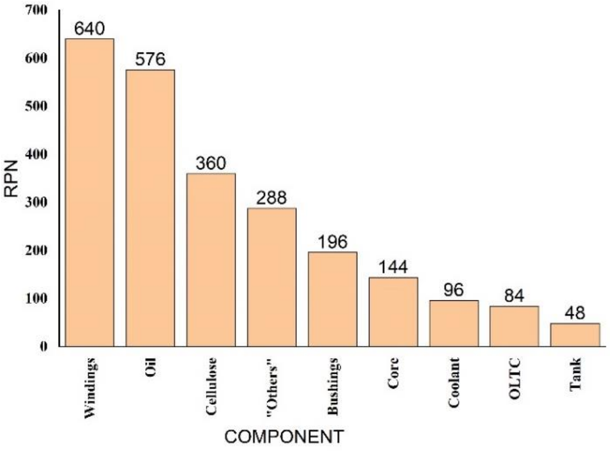

Fig. 4 Variation of RPN per component

Windings failure could be caused by manufacturer defects, short circuits due to insulation failure resulting from overloading/unbalanced loading, overvoltage. Transformer windings failure is the most disastrous because it causes complete damage to the transformer. Transformer failures caused by windings failures can be minimized by conducting turns ratio test, sweep frequency response analysis (SFRA) and DC resistance test regularly on the windings. Concerning vandalism and power theft, the government should embark on the sensitization of the population and clearly define the punishment of defaulters.

IV. CONCLUSION

Because of the critical role of a distribution transformer in the operation of the electrical power distribution system, its reliability must be assured through preventive maintenance.

Primary data on distribution transformers failures such as power ratings, the number of failures and causes of failures in Buea was collected by consulting previous maintenance records and interviewing ENEO staff. The 24 distribution transformers were found to ha failed in the period 2019 to 2021, and the findings are reported in tables 4 and table 5. This data suggested that up to 91% of failures occurred due to overloading and 9% due to vandalism. The results of the FMECA study highlights windings, liquid insulation and solid insulation as the root causes of transformer failures in Buea, as seen in their RPN values. This result agrees with the finding of Singh *et al.* [19]. Vandalism and power theft also witnessed high RPN value agreeing with the results in table 5. The FMECA study facilitated the identification of potential failure modes, causes of failure and effects of failures on the transformer through the calculation of RPN values. The FMECA study culminates in recommendations needed to prevent the failures of distribution transformers. Conclusively, since the overload of Transformers constitutes the major cause of Transformer failures in Buea, a systematic upgrade of overloaded Transformers, balancing of low voltage phases, and the creation of new Transformers in the fast-growing town would be the most suited preventive measure from damages. Preventing failures would enhance grid reliability and stability as well as minimise economic losses incurred by both customers and the utility company.

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B. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

C. Credit Authorship Contribution Statement

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