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RESEARCH

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Transformer faults in tanzanian electrical distribution networks: indicators, types, and causes

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Abstract

Transformers are essential and costly components of electrical secondary distribution networks (ESDNs). Distribution transformers provide electricity to low-voltage consumers that need a consistent power supply for their daily tasks. Transformer faults have an impact on ESDN power reliability. Even though several studies have attempted to investigate fault parameters; types, causes, and indicators in transformers, it is still difficult to generalize these criteria based on diversifications. These diversifications are caused by the architecture of the ESDN it self, transformer type, and insulation materials. Therefore, this paper investigates fault types, causes, and indicators specifically on oil-based transformers in Tanzania's ESDN using the oil analysis technique and the Dissolved Gas Analysis (DGA) tool based on descriptive statistical analysis. Results show that cellulose deterioration accounted for 33.2% of all faults, and the leading causes are overload, aging, and moisture content. Despite cellulose deterioration issues, the arcing fault is 26.2% caused by trippings, short circuits, and flashovers. The outcome of this work may help the utility implement a more advanced monitoring tool and maintenance mechanisms to enhance power reliability and reduce transformer faults in ESDN.

Keywords: Distribution transformer, Faults, Types, Causes, Indicators

Introduction

The rapid expansion of the electrical secondary distribution networks (ESDN) creates a challenge for Tanzania electric supply company (TANESCO) to install and maintain new equipment. In some cases, the utility company decided to increase equipment utilization to supply electricity to the customers. As a result, the tripping statistics of distribution equipment such as transformers increase. The transformer overload issues and frequent tripping cases increase the chance of faults meanwhile reducing the lifetime of the equipment, which is 20 to 22 years in a normal situation [1]. The faults associated with the oil-immersed transformers include thermal faults, arcing, cellulose deterioration, and leaks in oil and tank contamination [2]. Transformer faults may result in unreliable power supply, safety issues, low power quality, and increased maintenance costs [3].

Authors [4] presented specific causes of transformer faults, specifically in the Onitsha electric distribution network in which the insulation issues are reported to be a significant cause of faults, followed by overload cases. Another study conducted in the Punjab state power corporation, transmission and distribution network by [5] reveals that many transformers have undergone premature failure due to the decrease in transformer lifespan, the effect of moisture content, and cellulose deterioration. However, studies suggest the adoption of preventive measures to reduce premature failure and unplanned transformer downtime is to apply intelligent online monitoring and fault identification techniques instead of an offline method [6, 7].

Several studies on transformer fault diagnosis and identification that applied an Online Gas Analysis approach are presented. For example, the scholars in [8] proposed an online learning-based classifier for fault diagnosis and root causes based on the DGA fault indicators. The study inputted 15 transformer fault indicators to the neural network model and found that an accuracy of 98% was achieved. The study by [9] claims that there is no single indicator generalized for transformer fault types. Thus, the study presents a fuzzy logic algorithm that diagnoses the faults related to PD cases. In another study, the researchers uses 7 fault indicators to analyze transformer aging issues. In such a study, the authors went far as to analyze the correlation dependences between oil indicators [10]. In another review process conducted by [11], the effect of chemical indicators based on the oil analysis approach for monitoring the aging condition of transformers was explored.

The research goes far as to examine the factors that have a significant effect on the condition of transformers. These factors include temperature, water, and oxygen. The effect of water content in transformer oil has been presented in the study conducted by [12]. In such a study, several methods to reduce the water content in oil are presented. The transformer fault types and critical variables for distribution transformers have been presented, and results show that overheating and insulation deterioration are the most common causes of the faults [13]. Another study by [14] shows that overloading is one of the main causes of transformer aging. It is true that a proper selection of DGA's fault-indicator parameters, together with their ratios, increases the accuracy of the fault identification process [16].

Based on the review, the DGA's characteristic transformer-fault indicator and influence variables are not generalized [15]. Based on the aforementioned fact, it is true that there is a need to investigate the appropriate fault indicator and influence variables in Tanzania's ESDN. Therefore, this paper investigates the typical transformer faults' indicators, types, causes, and conditions in Tanzania's ESDN.

The theoretical and practical contributions of this work are as follows: First, is the establishment of the most influential variables that helps to determine the transformer's condition based on the oil analysis in Tanzania's ESDN. Second, is the identification of the transformer's fault types and indicators that can be used in the fault diagnosis and prediction processes. Proper identification of the transformer fault parameters will enable the building of a robust predictive maintenance system that adequately suits the Tanzanian environment.

Literature review

Tanzania electrical secondary distribution network

The power distribution network consists of two parts, a primary network, and a secondary network. Tanzania's electrical primary distribution networks comprise several electrical distribution components responsible for distributing electrical energy from generation to the secondary distribution part of the network. These components are transformers (33 kV-11 kV), Load Breaker Switch (LBS), auto recloser, metering unit, Drop-Out Fuse (DOF), and insulators (Polymeric or Disk).

The components of the Tanzania secondary electrical distribution include 400 V transformers, fuse, conductors, and meters installed for the customer as shown in Fig. 1. The more critical and costlier component of ESDN is the transformer. The Tanzanian ESDN feeders are experiencing many stress faults, which decrease the life span of transformers [17]. These stress faults include tripping (TRIP), overcurrent/overload (OC), and earth fault (EF), as reported by the Tanzania utility company. The effects of these stress faults may cause the degradation of insulation material and failure of the equipment unexpectedly. Therefore, the distribution transformers need to be monitored and controlled to reduce stress faults.

Table 1 shows substations, feeders, and their capacities in Dar-es-salaam. However, there is no online monitoring practice in distribution transformers in ESDN, especially for fault identification and classification. Transformer fault identification and classification are performed based on traditional methods and standards [18].

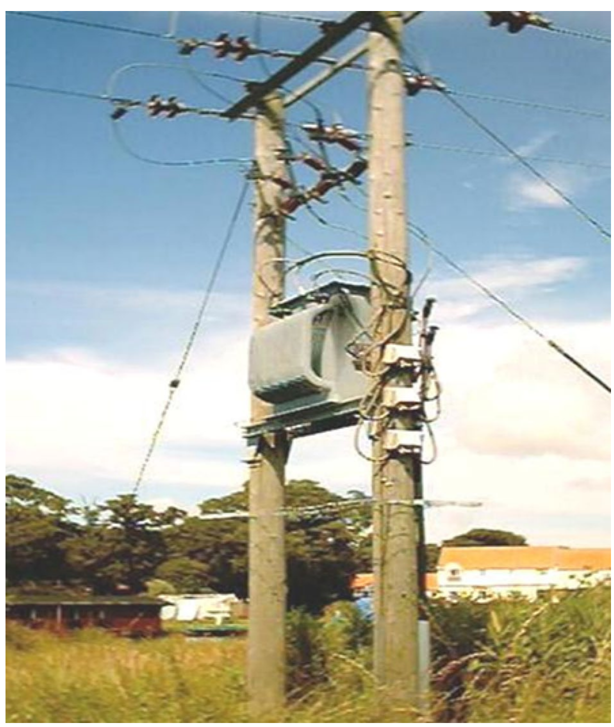

Fig. 1 Transformer as a component of Tanzania's ESDN

Table 1 Sample of substations, feeders, and capacities in Tanzania ESDN

Kunduchi		Ubungo		Makumbusho	
Feeder	**Capacity**	**Feeder**	**Capacity**	**Feeder**	**Capacity**
Wazo	132 kV	NORDIC	33 kV	Mikocheni	33/11 kV
Mbezi	33 kV	TEX	33 kV	Industrial	33/11 kV
Bahari	33 kV	NIC	33 kV	Makumbusho	33/11 kV
Jagwani	33 kV	TAN	33 kV	Msasani	33/11 kV
Bagamoyo	33 kV	WZI	33 kV		
Wazo	33 kV	T11	33 kV		

Table 2 Dissolved gas analysis results-TANESCO

Measured item	Unit (ppm)
Oxygen	–
Nitrogen	–
Carbon dioxide	691
Hydrogen	5
Carbon monoxide	152
Methane	3
Ethane	9
Ethylene	3
Acetylene	1.5
Total non-combustible gas	–
Total combustible gas	16
Water content	26.0
Total acid number [mgKOH/g]	–
Resistivity [TΩm at 80 ℃]	–
AC break down voltage [kV/2.5 mm]	–

Oil-immersed transformers

The oil-immersed transformer is constructed with cores, windings, cooling, bushing, and insulation [19]. Paper insulation is a transformer's essential part which is made up of fluid (either oil or gas) [20]. However, for the oil-immersed transformer, paper insulation degradation produces several gases, such as carbon dioxide, carbon monoxide, and moisture that migrate to the transformer oil [21]. Usually, the dissolved gases and moisture content in the oil are measured using the DGA test [22]. The DGA method analyses the sampling process, records the gases dissolved in oil, and presents them in parts per million (ppm) (Table 2) [23].

The DGA data established can be used to determine transformer conditions. The authors proposed different methods and standards for determining transformer faults. For example, IEC-60599 and IEEE C57.104 standards are mainly used for transformer fault identification and classification [24]. The Tanzania utility company categorizes transformer conditions into four levels; normal, caution, warning, and critical as seen in Table 3.

The DGA method can identify different types of transformer faults, including Partial Discharge (PD), discharge of low energy (D1), discharge of high energy (D2), thermal

Table 3 Health status based on gas levels (in ppm)

Condition	Gases								
	CO_2	H_2	CO	CH_4	C_2H_6	C_2H_2	C_2H_4	H_2O	TDCG
Normal	< 2500	< 100	< 350	< 120	< 65	< 1	< 50	< 20	< 700
Caution	2500–4000	100–300	350–900	120–400	65–100	1–7	50- < 100	20–37	700–900
Warning	3000–7000	300–700	900–1400	400–600	100–150	7–35	100	37–50	1900
Critical	> 7000	> 700	> 1400	> 600	> 150	> 35	> 100	> 50	> 1900

Table 4 Oil-immersed transformer fault types and causes (Source: TANESCO)

Fault type	Causes
PD	Discharge phenomenon occurring due to gas bubbles produced, e.g., by drying defects or oil infusion defects and voids in paper
D1	Include spark-type partial discharge or low-energy arcs and carbonized perforation in the paper
D2	Significant damage to paper, formation of large quantities of carbon parties in oil, metal dissolution, and device tripping by gas alarms resulting from perforations due to high–energy arcs, flashovers, and short circuits
T1	Overload or oil flow duct blockage. Paper discoloration: Brown (< 200°C), black or carbonize (>300°C)
T2	Occurrence of carbonization of paper or formation of carbon in oil, e.g. to contact faults, welding defects, or circulating current
T3	Occurrence of formation of large quantities of carbon parties in oil, for example, excessive circulation of current in the tank or iron core or lamination layer short circuit
DT	Electrical abnormalities

Table 5 Typical standard values for dissolved gases (ppm)

Standards	Gases values								
	CO_2	H_2	CO	CH_4	C_2H_6	C_2H_2	C_2H_4	H_2O	TDCG
IEEEC57.104–2019	9000	80	900	90	90	1	50	NS	720
IEC 60599–2015	4000–6000	50–150	400–600	30–130	20–90	NIL	60–280	NS	700–900
PLN-UIJBT	6500	85	900	180	300	3	45	NS	NIL
TANESCO	< 2500	< 400	< 300	< 100	< 65	< 1.5	< 10	< 20	< 700

fault below 300°C (TI), thermal fault above 300°C (T2), thermal fault above 700°C (T3), and a mixture of heat and electrical abnormalities as shown in Table 4 [25].

Standard values for dissolved gas analysis

Usually, the setting of a typical abnormal gas limit depends on the number of connected customers to a particular transformer [26]. Therefore, the standard gas limit is not always applicable to every utility company. With that fact, the guideline for gas interpretation of 2019 recommends each utility company establish its abnormal gas limit level [26]. Examples of the standards set are the IEEE C57.104–2019, IEC-60599–2015, and Indonesian utility (PLN-UITJBT) [27]. The proposed standard threshold for the TANESCO is shown in Table 5.

The standard gas concentration limit proposed by TANESCO is lower than the IEEE C57.104–2019 and IEC-60599–2015, except for H_2, in which TANESCO has a high value of 400 ppm. Furthermore, transformers in Tanzania ESDN are highly affected by water content; therefore, TANESCO proposed the standard value of water content (H_2O) which is less than 20 ppm. In contrast, the standard value of H_2O was not set by other companies. Therefore, Table 5 presents the proposed typical standard values proposed by TANESCO to be used as a guideline for transformer Fault Type and Causes Analysis (FTCA) based on the DGA data. This guide provides the procedure to identify the fault type and causes of the transformer based on the oil analysis.

Fault causes in an oil-immersed transformer

Several transformer fault types are reported in the literature. The first one is overloading; this is a situation where the transformer operates beyond its capacity. Overloading is assumed to be an economical way of expanding the electricity network though it may result in premature failure of the transformer [28]. Furthermore, excessive transformer overloading usually contributes to cellulose deterioration and thermal faults [29].

The second cause of a fault in a transformer is a moisture content exceeding reaching 3 to 4% which may lead to partial discharge and cellulose deterioration [30]. Apart from linkage into oil, the low-quality cellulose material usually produces moisture content. The concentration of moisture content can be measured directly by using an oil analysis tool such as a DGA. In addition to moisture content, the acceptable concentration based on the proposed standard by TANESCO is less than 20 ppm (see Table 5). Also, the moisture content may migrate out of cellulose insulation and can lead to transformer failure [31].

The third cause of transformer fault is short-circuited, where the electric current flows in an unexpected pathway with a low impendence. The result of a short-circuited is the generation of heat that can damage the transformer's insulation material [32]. Therefore, to reduce the effect of abnormal voltage, the utility company performs the Breakdown Voltage (BDV) tests to monitor the input and output voltage. The standard voltage range depends on the transformer capacity. In addition to the fault causes aforementioned above, the DGA tool cannot recognize other fault causes such as vandalism, lighting surges, loose connection, lack of automated maintenance planning, and floods [4].

Transformer analysis techniques

Various analysis techniques that are used to investigate transformer state are available. Such techniques include oil analysis, thermography, vibration analysis, ultrasonic method, and electrical current monitoring [33]. The DGA is a widely used technique for assessing the condition of an oil-immersed transformer based on oil analysis [34, 35].

Significant research has been done on transformer fault diagnosis based on oil analysis in an electrical distribution network [36]. Traditional and more advanced approaches have been used in the transformer fault analysis process. Traditional techniques include the key gas, doernenburg ratio, Rogers ratio, IEC ratio, Duval triangle, and Duval pentagon methods [2]. These methods are simple and easy to implement, but they require a significant amount of gas, making it difficult to evaluate the condition of equipment at its early stage. However, studies show that intelligent techniques have high accuracy compared to traditional ones [37].

Several artificial intelligent methods have been proposed for transformer fault identification in distribution networks, such as artificial neural networks support vector machines, deep learning, and recurrent neural networks [27, 36] proposed a fuzzy logic approach to determine the transformer fault severity and gas increase rate based on gas level, gas rate, and DGA interpretation. To increase the accuracy, [38] proposed the hybrid MVO-PNN method and significantly improved the accuracy of the fault-identification process. The accuracy of the fault identification and classification processes depends on the instructive input parameters chosen from the DGA method [39]. Among the 24 input parameters from DGA, [40] selected the most appropriate eight parameters to attain an accuracy of 99.7% using the J48 algorithm. In choosing the proper fault indicator parameters, the coefficient correlation of the DGA parameters was performed. The transformer fault identification process based on DGA by correlation coefficient increases the accuracy by 32.7% [41].

Materials and methods

This study applied qualitative and quantitative techniques to identify transformer fault indicators, types, causes, and conditions. The information for the transformer was obtained through observation based on the field visit to TANESCO. Microsoft Excel and Statistical Package For Social Sciences (SPSS) 28.0 were used for data analysis. The general research design approach applied in this work is presented by the research design process shown in Fig. 2.

Data collection

Information about transformer faults which was then used as an input for the knowledge base was collected through a field visit. Such information was also obtained from the

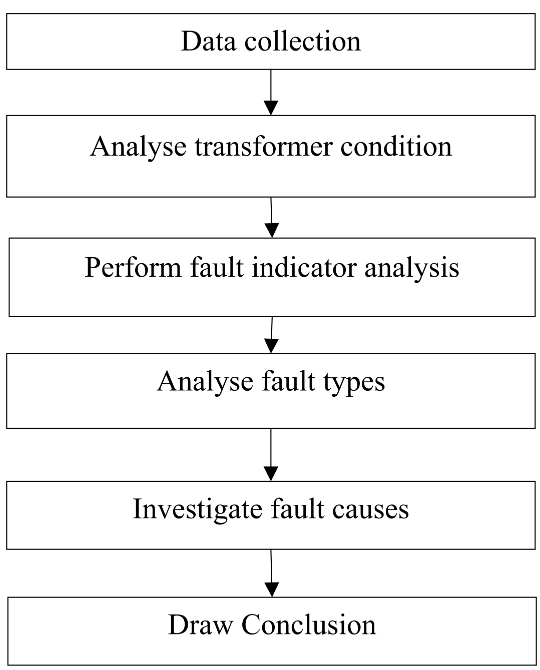

Fig. 2 Research design flowchart

historical records available from TANESCO. This information includes 144 historical data collected from 2016 to 2020 using DGA as well as using transformer tripping statistics recorded in 2017. Furthermore, data were collected by TANESCO engineers and the results of each transformer were recorded. The obtained historical data from TANESCO was then recorded in Excel showing the transformer ID, its fault indicators, fault type, causes, and status. The fault type and status were identified based on the standards provided by TANESCO.

Analysing transformer condition

Based on standard gas values proposed by TANESCO in Table 5, the SPSS was used to analyze the percentage operation condition of ESDN transformers from the DGA data collected from 2016 to 2020. In addition, TANESCO categorizes transformer conditions into either normal or abnormal. The abnormal condition includes caution, warning, and critical state.

Transformer fault indicator analysis

The transformer data is loaded into the SPSS data value window. The data contained 11 variables of which 10 were concerned with fault indicators and one with transformer status. Thus, the variables were given their actual names and the property of each variable was identified. A descriptive statistical analysis was performed to analyze the impact of fault indicators on the transformer's condition. The descriptive statistical analysis was achieved using the frequency approach. Visual tools such as tables, histograms, and pie charts were used to present during the analysis process.

Analysing fault types and causes

The transformer data was loaded into the SPSS window with two variables; fault type and causes. The data was then statically analyzed to obtain the most frequently occurring fault type and causes. The procedure for this analysis was the same as the one presented in the previous section.

Table 6 Classification of fault types, causes, and occurrences

Fault type	Fault causes	Fault occurrence	
		Frequency	Percentage
Discharges of high energy	Significant damage to paper	78	26.2
	Formation of large quantities of carbon particles in the oil		
	Metal dissolution and device tripping by gas alarms resulting from perforations due to high energy arcs, flashovers, and short circuits		
Cellulose deterioration	Moisture, aging, and overload	99	33.2
Partial discharge	Gas bubbles	72	24.2
Thermal fault	Overload or oil flow duct blockage	49	16.4
Total		298	100

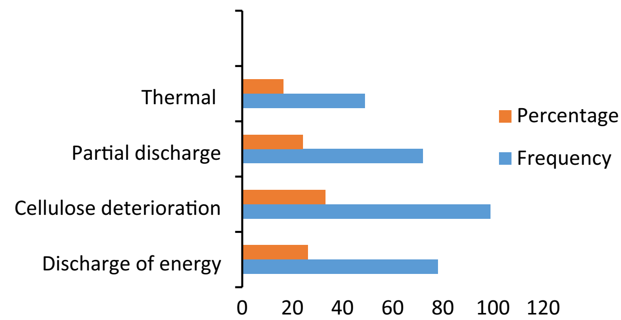

Fig. 3 Classification of fault type and causes by percentage

Results and discussion

Transformer fault types, causes, and occurrences

This study conducted the FTCA by collecting the DGA data and analyzing the fault types from 2019 to 2020. The analysis reveals that cellulose deterioration is a severe problem in distributed transformers. The leading causes of cellulose deterioration are overloading, aging, and moisture content. Other fault types identified are presented in Table 6. The different causes of transformer faults identified based on dissolved gas analysis in Tanzania ESDN are also presented in percentages, as shown in Fig. 3.

The type of faults identified after the analysis process conducted on the ESDN transformers are cellulose deterioration (33.2%), discharge of high energy (26.2%), partial discharge (24.2%), and thermal faults (16.4%). The thermal fault includes faults below 300 ℃ (TI), above 300 ℃ (T2) as well as those above 700 ℃ (T3). Moreover, the pie chart in Fig. 4 presents the fault types identified from the analysis process.

From the state analysis conducted in this study, findings indicate that 41.7% of transformers reached a critical stage, which can lead to unexpected failure. The study also identified the most helpful transformer fault indicators. This study reveals that carbon dioxide, water content, total combustible gas, and ethylene are the fault indicators that must be included in the fault-type analysis process. These indicators contributed to 76.4%, 75.0%, 74.5%, and 72.9% of the transformer abnormality, respectively as shown in Fig. 5.

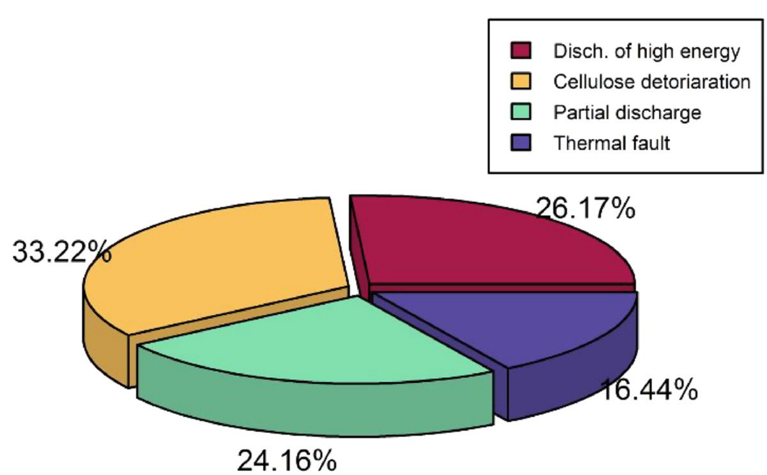

Fig. 4 Results of fault type analysis

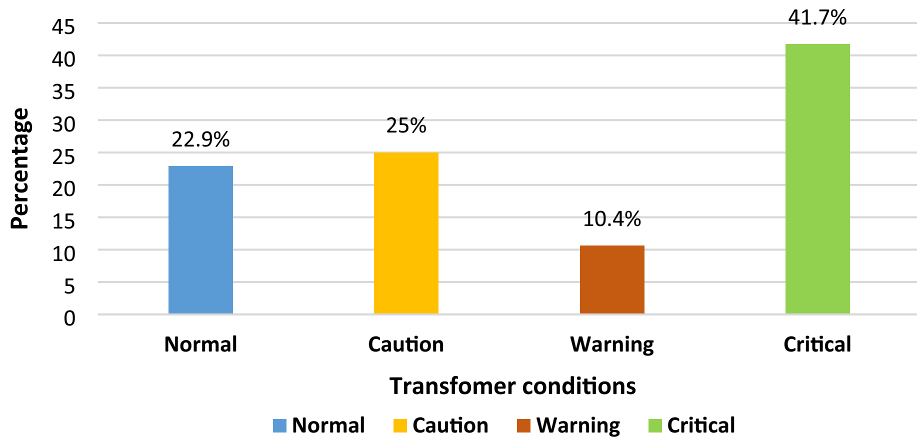

Fig. 5 Transformer's running state in ESDN

Transformer fault Indicators

The result of the indicator sensitivity analysis is presented using bar charts in Fig. 6. The finding indicates that the generation of carbon dioxide gas seems to be a leading factor to cause an abnormal transformer condition by 76.40%, followed by water content (75%). This work reveals that these two indicators are the most sensitive and should be considered during the transformer fault identification process.

Conclusion and recommendation

This study investigated the transformer fault indicators, fault type, and causes based on the transformer's historical DGA data collected between 2016–2020. We collected other information through interviews conducted in collaboration with stakeholders from the utility company. The collected data were analyzed using SPSS. The findings of this study show that transformer cellulose deterioration occurred more times (33.2% of all Transformer faults) than any other fault type within five years. This

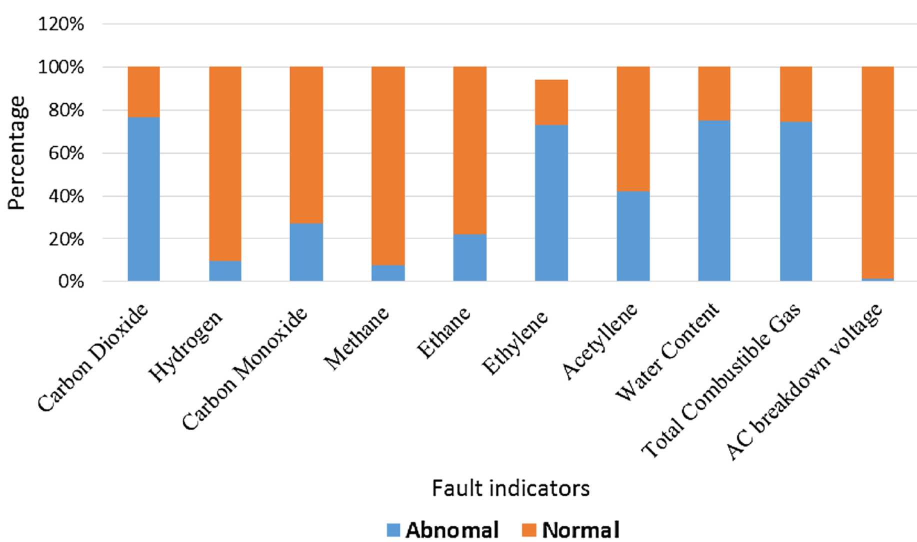

Fig. 6 Transformer fault indicators

finding about the leading fault type has also been reported similarly in the studies by [4, 5, 8, 11, 14, 20]. In addition to the fault types, the study found that the leading causes of cellulose deterioration are transformer aging, overloading, and moisture content (water content). According to the expert knowledge, the findings from this research reveal that the large amount of water content in the oil-immersed transformer is due to the quality of the material used or the linkage to the oil.

The study also discovered that the abnormality of the transformers is mainly caused by the large generation of carbon dioxide gas (76.40%) followed by water content in oil (75%). This finding indicates that carbon dioxide gas is the leading fault indicator in Tanzania's ESDN and contradicts the one found in [5, 10, 12] in which the leading fault indicator is water content. Furthermore, this work agrees with [4, 5, 8, 13, 14] that the leading cause of transformer faults is overloading. Contrarily, [9–11] found that the leading cause of transformer faults is the aging of the equipment.

Unlike other studies, the new observation from this work is that; the main fault indicator parameter of the distribution transformers in Tanzania is carbon dioxide gas content. Identifying this factor as the leading one paves the way for TANESCO to reconstruct proper equipment monitoring strategies such as preventive maintenance and so on. Therefore, the study recommends the installation of self-monitoring tools in Tanzania ESDN; TANESCO needs to reconfigure the ESDN to achieve automation functions for the smart grid. Installation of the new transformers to reduce the overloading to increase the life span of the transformers. With the DGA tool for data acquisition, the robust controller needs to be installed for maintenance decision-making based on the transformer fault type and transformer condition.

Future research should attempt to explore the use of advanced methods, such as Artificial Intelligence, for fault identification and prediction. Furthermore, future predictive maintenance applications in Tanzania should use the findings obtained from this work to develop robust predictive maintenance that can efficiently reduce system downtime, and maintenance costs that will in turn increase power reliability.

Abbreviations

ESDN	Electric secondary distribution network
DGA	Dissolved gas analysis
TANESCO	Tanzania electric supply company
DOF	Drop-out fuse
BDV	Breakdown voltage
LBS	Load breaker switch
AI	Artificial intelligence
FTCA	Fault type and causes analysis
SPSS	Statistical package for the social sciences

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Author contributions

HM crafted the idea and was mainly involved in the literature review, proposition of the research gap and research design processes. Meanwhile, HB was involved in the implementation and results representation. Furthermore, both authors participated in content writing, rendering and compilation from the first to the final draft of the manuscript.

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Availability of data and materials
The data used in this research is private and belongs to TANESCO. Therefore, the data can be available on the request sent to the authors of this paper.

Declaration

Competing interests
The authors declare that they have no competing interests.

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Publisher's Note

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