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ORIGINAL RESEARCH ARTICLE

Analysis of power distribution transformers' failure in rural electrification projects in Kenya.

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Abstract
Reliable, safe and stable power distribution network is pivotal for realization of a steady economic growth in a country. Power distribution transformers play an important role to enhance this stability and efficiency in national grid networks and power distribution companies. To enhance sustainability and reliability in these grid-lines performance, customer satisfaction and profitability of the grid services should be optimally maintained and in sound state. Typically, the distribution transformers used in Kenya are Oil-immersed type which has a general lifespan of 25 to 30 years; this notwithstanding, they fail in large numbers, within the first 3 years of operation or even during commissioning, due to various reasons causing enormous economic and service impact on the distribution utilities as well as the power consumers. In this study, a detailed discourse on the causes of failure in distribution transformers and possible recommendations to mitigate these challenges have been discussed with reference to data collected from Rural electrification and renewable energy corporation transformer stores and field project reports. The results show a clear indication that both power line factors and manufacturers' defects have great impact on these failures. The conclusion and recommendations will be crucial to inform future grid line designs and policies' formulations for the optimal functionality of these transformers.

Keywords— Distribution transformers, reliability, transformer failure, grid extension.

1.0 Introduction
As the Kenya's utility company grapples with system losses beyond what it is allowed to recover from consumers in a general financial year, technical losses cannot be overlooked as a major contributor. The firm's system losses rose 23.46 per cent Vis a Vis low distribution percentages in the range of 4% recorded in other economies in that period(World Bank Open Data, 2016). The Utility alluded that the high system losses were due to technical and commercial factors arising from the expanded transmission and distribution network as well as increased electricity pilferages. Technical losses occur as electrical energy is dissipated in the process of transmission, transformation and distribution while commercial losses are mainly attributed to pilferages, faulty meters and meter tampering. As the firm looks to slash its system losses to 19.9 percent by 2025('KAWI HUB', 2022), riding on a raft of measures such as riding on modern technology to curb electricity theft and reduce technical losses "Improving system efficiency is a top priority as the rising system losses are of great concern.

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This can only be attained by ensuring efficient transmission and distribution components are installed on the grid during construction.

Distribution transformers are key static electronic devices that provides final voltage transformation in the electric power distribution system. It steps down voltage from medium voltage level of 6-36kV to consumer voltages of 110V- 433V suitable for use with electrical appliances(Singh and Singh, 2016).

Frequent malfunctionality and failure of transformers increase the system down time and eventually lead to massive system losses to the grid network. It's these failures of transformers in the distribution network installed during grid-extension and reticulation projects that raised major concerns to both the customers and the utility leading to a keen investigation and surveys on the main causes.

During repair of the transformers, most of them are found to have short circuit fault and open circuits mainly on the High Voltage (HV) coils, black insulating oils, broken ceramic terminals, and damaged connecting rods(Singh and Singh, 2016). Short circuit fault mainly occur due to improper winding terminations and poor insulations of the coils. Transformer insulating oils are always clear and gold in colour. Black oil is a sign of aged oil or oil with impurities. Contaminated oil lead to improper insulation; a recipe for short-circuiting within the windings. Open circuits are as a result of open points along the windings due to poor fastening and loose connections. Broken ceramics and damaged connecting rods are as a result of careless handling.

To enhance effective and durable power line construction services, high voltage test bench system for transformers are set up in utility yards under which various routine tests are conducted on sampled transformers sourced from suppliers. The samples are selected randomly ranging from 15% – 50%, depending to the quantity delivered, desired confidence levels, margin of error and population variability. Ideally, all the transformers in the selected sample should pass the tests, any that fails is rejected. A failure of more than 2% of the sample leads to testing of the whole delivery. Most failures recorded indicate open circuit on HV winding, poor insulation and short circuit of the LV windings to the transformer tank. To ensure a more stringent approach, the technical inspection team established a requirement that each transformer delivered to the utility yards be accompanied with routine test results certificate during delivery or delivery of shipment documents. The routine test results should be detailed including the transformers' serial numbers, date of manufacture and results of each test carried out. Test of the oil used as insulations should also be done at the manufacturers' premises during the Factory Acceptance Tests.

1.1 The Transformer

1.1.1 Distribution transformer

Service transformers are used on grid networks to provide the final voltage transformation in the electric power distribution system, stepping down the high transmission line voltages

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to the consumable level used by the customer. They are normally rated up to 500KVA although on some special cases, they may be rated up to 1MVA. Distribution transformers are classified into different categories based on certain factors such as: Mounting location – pole, pad/ground, underground vault, type of insulation – liquid-immersed (oil) or dry-type, number of Phases – single-phase or three-phase, voltage class- 11KV or 33KV for instance, basic impulse insulation level (BIL).

Transformer works on the principle of mutual induction of two coils or Faraday Law's of Electromagnetic induction. When current in the primary coil is changed the flux linked to the secondary coil also changes. Consequently, an EMF is induced in the secondary coil due to Faraday laws of electromagnetic induction(Institute of Electrical and Electronics Engineers and IEEE-SA Standards Board, 2010). A transformer has a soft iron or silicon steel core and windings placed on it (iron core). Both the core and the windings are insulated from each other using oil and impregnated resin paper.

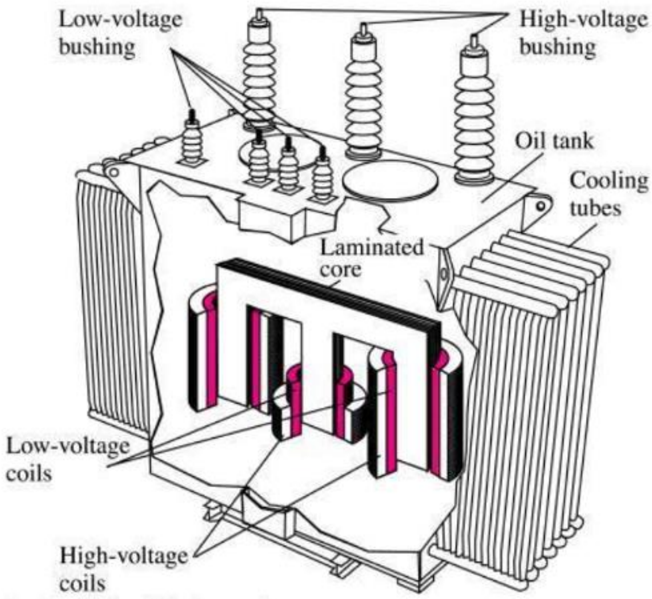

Figure 1: Sectional Layout of a Distribution Transformer (source)(Amadi and Izuegbunam, 2016)

1.1.2 Transformer insulation

To attain pure induction in a transformer, proper insulation should be maintained between the coils. This is enhanced using two materials such as; transformer oil for oil immersed transformers and insulating paper that offers insulation between the copper winding. The insulation paper is made from 100% wood pulp and is required to be of class K as per IEC standards 60554-2 and 60243-1 Hermetically Sealed Oil Type Distribution Transformer. Transformer oil besides being an insulation medium is also used for cooling the winding coils. The transformer tank is sealed hermetically to prevent air coming into contact with the

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transformer oil hence preventing moisture contamination which may result to oil deterioration. This helps to maintain the insulation property of the transformer oil, lengthening the transformer functionality hence reducing on the transformer losses and the cost of maintenance as well(Institute of Electrical and Electronics Engineers and IEEE-SA Standards Board, 2010). Generally, this is the type of transformer used by utility companies in Kenya.

The insulation oil used in the transformer insulation should have;

i. Minimum breakdown voltage or dielectric strength of 30 KV.
ii. Minimum standard specific resistance of 35 × 1012 ohm–cm at 90°C and 1500 × 1012 ohm–cm at 27°C.
iii. Low viscosity to offers less resistance to the convectional flow thereby not affecting the cooling of transformer.
iv. Very high flash point is required.
v. No cloudiness or sediments indicating free of water, insoluble sludge or dirt particles(Institute of Electrical and Electronics Engineers and IEEE-SA Standards Board, 2010).

1.1.3 Transformer Faults

Power distribution transformers generally suffer the following faults; internal faults or external failures. Under the internal faults some of the common triggers are over currents stress due to overloads and external short circuits, terminal faults, winding faults, and incipient faults. These transformer faults cause mechanical and thermal stresses inside the transformer winding and its connecting terminals. Thermal stresses lead to overheating and pressurization which ultimately affects the insulation system of transformer. Deterioration of insulation leads to winding faults and bursts which eventually cause fires and pollution.
External faults on the other hand are caused by factors such as high ambient temperatures, Mechanical stresses due to vibrations, load fluctuations, and other external impacts stressing the transformer structure and oil contaminations. Breakages on the transformer exteriors are also a greater contributor to these external failures(Al-Arainy, Malik and Qureshi, 2012).

The general faults in transformer windings are either earthing faults or inter-turns faults. Phase to phase winding faults in transformers are rare. The phase faults in an electrical transformer occur due to bushing flash over and faults in tap changer terminations. Whatever may be the cause of faults, the transformer must be isolated instantly during fault otherwise major breakdown may occur in the electrical power system (Muriuki *et al.*, 2018). Incipient faults are internal faults that constitute no immediate hazards. But if these faults are over looked and not taken care of, they may lead to major faults. The faults in this group are mainly inter-lamination short circuit due to insulation failure between core lamination, lowering the oil level due to oil leakage and blockage of oil flow paths. All these faults lead to overheating and loss of phase voltages. Efficient transformer protection scheme are desirable to curb these incipient faults. The earth fault that occurs near to the neutral point of transformer star winding may also be considered as an incipient fault.

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There are mainly two conditions for earth fault current to flow during winding to earth faults,

i. A current must exist for the current to flow into and out of the winding.
ii. Ampere-turns balance is maintained between the windings.

The value of winding earth fault current depends upon position of the fault on the winding, method of winding connection and method of earthing. The star point of the windings may be earthed either solidly or via a resistor. On delta side of the transformer the system is earthed through an earthing transformer. Grounding or earthing transformer provides low impedance path to the zero sequence current and high impedance to the positive and negative sequence currents(Muriuki *et al.*, 2018).

The short circuit current of an electrical transformer is normally limited by its reactance and for low reactance; the value of short circuit current may be excessively high. The duration of external short circuits which a transformer can sustain without damage as given in BSS 171:1936.

Transformer % reactance	Permitted fault duration in seconds
4 %	2
5 %	3
6 %	4
7 % and over	5

Figure 2; Transformer Fault Duration Ratings(Institute of Electrical and Electronics Engineers and IEEE-SA Standards Board, 2010)

Owing to exaggerated failure rate of power distribution transformers both in operation and upon pre-commissioning tests, the then, rural electrification authority (REA) set-out to undertake a detailed research and analysis to establish the main causes of these failures through laboratory tests and workshop work-downs to device ways on how to curb and mitigate them. Of the 24,188 transformers procured by the authority by the year 2020, 2,187 had failed either in the operation or before commissioning to the project sites. This informs a 9% failure rate compared to the 2-3% failure rate in the developed world(Singh and Singh, 2016).

2.0 Methodology: Transformer Inspection and Testing.

By principle, when power line construction materials are procured, they are first tested and inspected before dispatching for installation. In the utility yards, all the delivered materials and transformers are inspected and samples identified for testing besides being tested during the factory acceptance inspection at the factory.

These notwithstanding, there had been an incessant failure of utility transformers during project powering/commissioning or shortly afterwards within first three years of functionality. This insighted a team of technical staff to undertake a keen survey on the failed

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transformers to establish the root causes of the uncalled-for failures and consequential repair costs.

Out of the total 24,188 nos procured transformers by the corporation in less than a decade, 2,187 nos had failed. The failed transformers were all issued to local and regional contractors for repairs under contracts. During the repair, corporation's technical team would visit the repairing firms for pre-repair and after-repair testing and inspection.

In the endeavour to establish the common causes of failure a census of the 2,187 nos. faulty transformers was inspected, tested and analysed. Physical inspections, electrical testing and field report reviews were the adopted approaches in this survey.

Various tests were carried out on routine measurement of transformers according to the standards(Institute of Electrical and Electronics Engineers and IEEE-SA Standards Board, 2010). These included the following categories; Type test tests, Routine tests and Special tests. Other tests carried out on site include; Pre-commissioning tests, Periodic/condition monitoring tests and Emergency tests.

During this survey, only routine tests category was adopted for the verification and validation of the findings. Under routine tests the following tests were conducted at both the repairer's and REA test benches;

- Physical Inspection on the transformer tanks and its peripherals
- Winding resistance and continuity test
- Insulation tests or megger test
- Turns ratio tests
- Open circuit test
- Short-circuit test

3.0 Results and Discussions

3.1 Findings

Power distribution transformers fail in a variety of ways and from a variety of reasons. Some of the important factors are design weaknesses, abnormal system conditions, aged condition, pre-existing faults and timescales for fault development. Most transformers in medium voltage network as the case in Kenyan power utilities are paper/oil insulated. In addition to the stresses caused by persistent operational voltages, the insulations get older due to high temperatures caused by loads, humidity and mechanical stresses caused by fault currents. Small discharges in the insulations weaken the paper insulations and produce gases in oil. According to these literature, the general causes of transformer failures as established from existing studies (Al-Arainy, Malik and Qureshi, 2012; Singh and Singh, 2016; Muriuki *et al.*, 2018; Amadi and Izuegbunam, 2016) can be categorized as either utility side or manufacturer side defects;

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3.1.1 Utility side

i. Unbalance Loading: During the commissioning time, most of these transformers in the rural areas are not optimally loaded basically due to the nature of settlement around the project. Consequently, by the electrification of the area, more populace and constructions tend to crop up in the region causing increase in the loading level. Unfortunately, most of this extensions do not follow a distributed loading pattern but extend the line/phase in their proximity. This ends up loading a particular phase more compared to the others hence a high susceptibility to failure in the event of any power fluctuation.

ii. Prolonged Overloading: The overloading is mostly observed in transformers installed in town areas due to increasing population and unconsidered connections during design/unauthorized loads. The Distribution Transformers are not recommended for continuous overloading as it affects the winding insulation strength causing the failure.

iii. Improper LT and HT Protection: overhead line protection system installed in the Kenyan grid especially in the distribution level were not sufficient to cushion these substations from power surges and faults. The installed surge arrestors would easily fail leaving the transformer exposed to high fault currents which leads to ultimate failure of the transformers.

iv. Faulty terminations: In several occasions, transformers are observed to be sparking from the bushing termination joints especially on HT connections. This is due to loose contacts terminations during the course of installation or else have been loosen due to bad service conditions. Once spark Occurs at the cable termination, it causes breaking of the bushing sealing gaskets, eventually causing oil leakage from the bushing top, which later on results to transformer failure.

v. Power Theft and Hooking of Mains: This is a more prevalent issue in the Kenyan rural regions where customers hire unlicensed technicians to connect them to power illegally. Since such hooking make the transformers to run in overload/unbalance load they end up causing transformer failure in due course. This is one of the major causes of failure of distribution transformers for which the repairers have accounted for all the time. To minimize this, regular monitoring, stringent actions against theft cases, energy audits, initiating stringent actions etc. should be taken up.

vi. Faulty ground/Earth Connection: Some of the transformers when not keenly installed and tested for ground resistance end up failing due to ground faults in the network.

vii. Surge arresters not placed across the transformer bushings. In many cases with too long connections from bushing to the surge arresters.

viii. Other causes categorized under the utility defects include low transformer oil levels caused by lack of regular maintenance and servicing, low break down value (BDV) of the transformer oil and poor insulation resistance (IR) values, lightning, external short circuit (through faults), flash over, and vandalism.

3.1.2 Manufacturer side

The failures due to manufacturers' defects are majorly due to: Improper/Faulty design with limited clearances for the live parts, Use of poor quality of raw material for the core lamination

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and Poor workmanship on the transformer terminals. Contaminated oil due to insufficient drying during manufacture and Poor insulation covering on windings conductor.

These are due to the low entry barriers in the distribution transformer market leading to unorganized vendors entering the market, and competing on the price factor.

From the inspected census of distribution transformers in REA and failure reports from field engineers, there was a clear indication that the transformers either failed during commissioning or shortly after commissioning within a short period of operation. Vandalism under contractors' custody was also common as per the reported occurrences.

However, these reports did not indicate neither the nature of the fault nor the type of vandalism done on the transformer e.g., copper windings stolen or transformer oil siphoned. In addition, some reports indicated that a sample of transformers failed insulation test at the stores upon delivery before dispatch to the contractors.

A report from a contracted repair company, on the repairs of the transformers highlighted only the nature of defects repaired stating them only as transformer faults. The mentioned faults included, "contaminated black oil", "black oil mixed with water", "broken ceramic insulator", "short circuiting on the high voltage windings", "damaged tank", "damage on the conductive rods on both HV and LV sides", "Siphoned transformer oil", and "replacement of fasteners and seals" as indicated in the table below.

Table 1: Common fault indicators on failed transformers.

Observed Faults Major indicators of failures	Total
Open circuit in windings, soot in oil, soot in the bushings, burnt terminations	365
Burst HV coils, soot in the oil, burst tanks	307
No oil, Low level oil, no coils and also open tanks	584
Rusty cores, Contaminated oil, shorting windings, sooty coils	827
Loose delta terminations, open circuits, broken terminal rods, broken bushings	104

Source; REA Test Results and Observations

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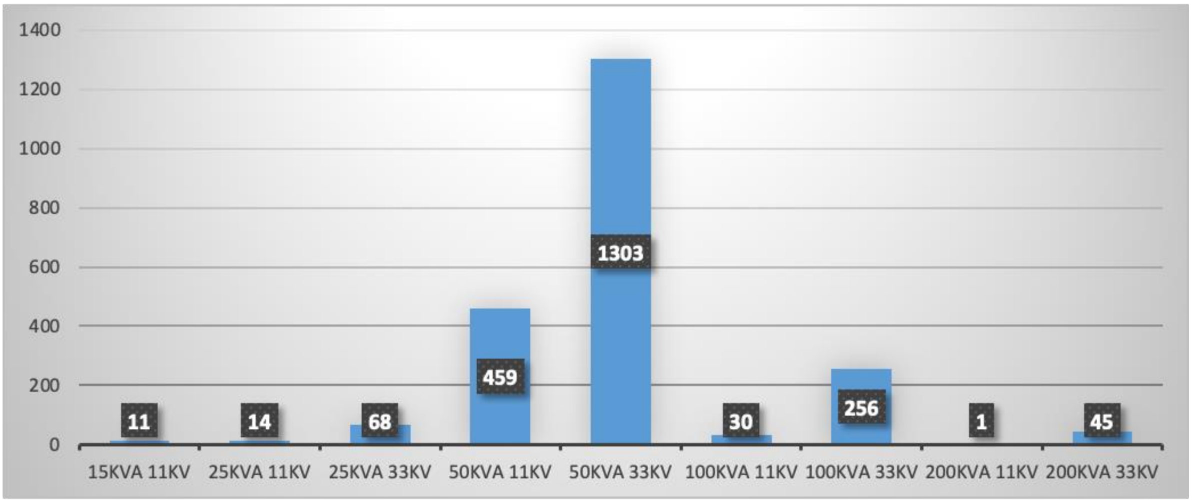

Figure 3: Bar graph on Transformer Failure Rate per Size

Further, categorizing the analysed sample into ratings, the 33kV distribution lines were the most affected juxtaposed to the 11kV lines as indicated by the majority of failed transformers rating at 50KVA/33kV followed by 100KVA/33kV as shown in figure 3. From figure 4, it is also indicative that most of the transformers were procured from India as compared to other nations and thus the high failure rate.

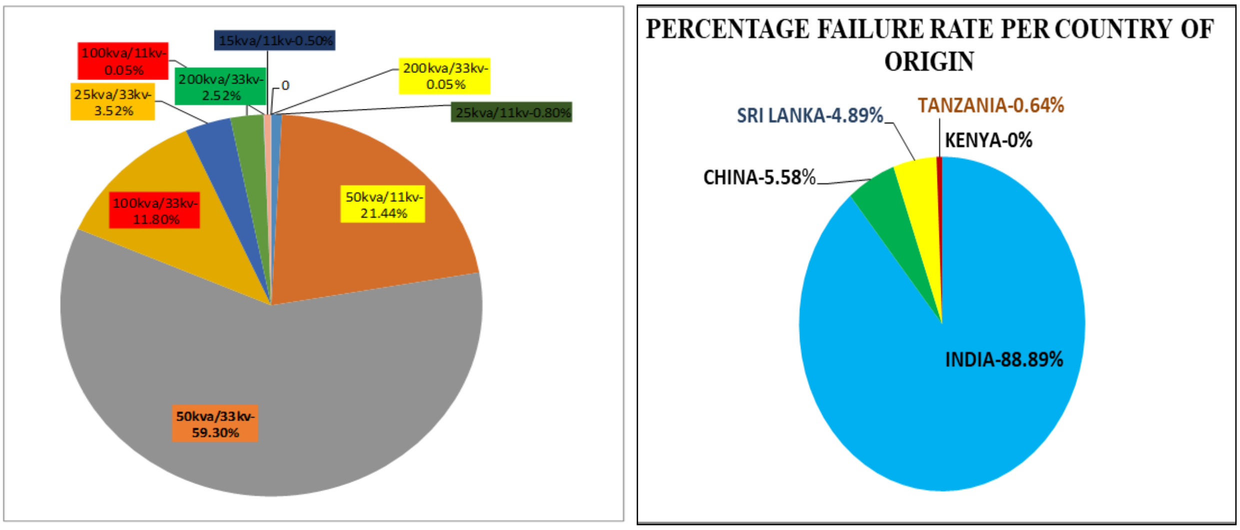

Figure 4: Failure rates per transformer ratings and Country of origin

The main cause of transformer failures highlighted above was observed to be due to improper insulation of the windings. Since the transformer insulation is by oil and paper; poor quality or contaminated oil appeared to be a major contributing factor to these failures.

As it was clearly observed, from every transformer that was repaired, the problem was either blackened oil, oil mixed with water or no oil at all with other transformers having oil levels at 30%-50% of the tank level.

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Improper handling of transformers while on transit from REA stores to projected sites for installation lead to damages of the transformer especially the bushings and the arcing horns. Damage on the bushes affects the insulation and exposes the transformer internal assemblies thereby rendering the transformer defective. Table 2 below highlights the observed/recorded failure indicators matched with the corresponding probable cause of failure and the percentage of the total number of failed transformers.

Table 2: Established Causes of Transformer Failure

Faults and their Probable causes		
Major indicators of failures	Possible cause of the failure	Percentage of total failure
Open circuit in windings, soot in oil, soot in the bushings, burnt terminations	Power surges either by lightning strikes or line faults.	37.8%
Burst HV coils, soot in the oil, burst tanks	Unbalanced loading especially overloading one phase of a 3phase transformer	26.7%
No oil, Low level oil, no coils and also open tanks	Vandalism	14.0%
Rusty cores, Contaminated oil, shorting windings, sooty coils	Manufacturers Defects (Poor core lamination & Poor Insulation)	4.8%
Loose delta terminations, open circuits, broken terminal rods, broken bushings	Mishandling and poor transportation system to remote areas	16.7%

4.0 Discussions

As it can be deduced from the above observations, power surges either from lightning strikes, short-circuit faults or grounding faults have been the greatest contributor to transformer failures which could be due to insufficient protection systems in the grid. Power surges either due to natural impulses like lightning or technical impulses during switching, causes undue stress on the transformer insulation consequently weakening the insulation cover of the windings and flashovers between ground and weakest point of the phase windings(Al-Arainy, Malik and

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Qureshi, 2012). This causes broken circuits in the HV windings, bursts of the windings and tanks, soot in the oil and burnt terminations. Reliable grid line and substation protection systems such as overhead surge arrestors should be installed appropriately to arrest these power surges and ground faults when they occur(Predota, Benesova and Koudela, 2012). To increase the reliability of these protection systems, transformers are currently installed with on-transformer-mounted surge arrestor in addition to the conventional one span protection system(*IEEE Guide for the Application of Surge-Protective Devices for Use on the Load Side of Service Equipment in Low-Voltage (1000 V or Less, 50 Hz or 60 Hz) AC Power Circuits*, 2016). Also good securing of the transformers cuts on the vandalism of grounding systems which protects the transformers against surges.

Unbalanced loading on three phased transformers have a detrimental impact on the devices as the leaden phase strains more electrically causes issues of overheating and insulation breaks. This will be implied by burst coils, soot in the oil, burst tanks and short-circuited windings. Three phase distribution system always faces unbalancing in the load because of overloading of one phase compared to the other phases. To solve this problem equal sharing of load on each phase of the distribution system is followed. Current flow in the neutral wire, energy losses can be reduced by equal sharing of load. During the project development, effective forecasting of terminal customers should be done so as to avoid unbalanced loading(Nancy *et al.*, 2020).

Cases of transformer theft and vandalism are still rampant in local areas exacerbating the rates of transformer failures as implied by transformers with no oil, no coils and damaged core assemblies. Transformers are also damaged during transportation in the rough roads servicing rural areas. If they are not well handled, the delicate windings configurations tend to shift which strains the terminals of the transformer coils leading to open circuits.

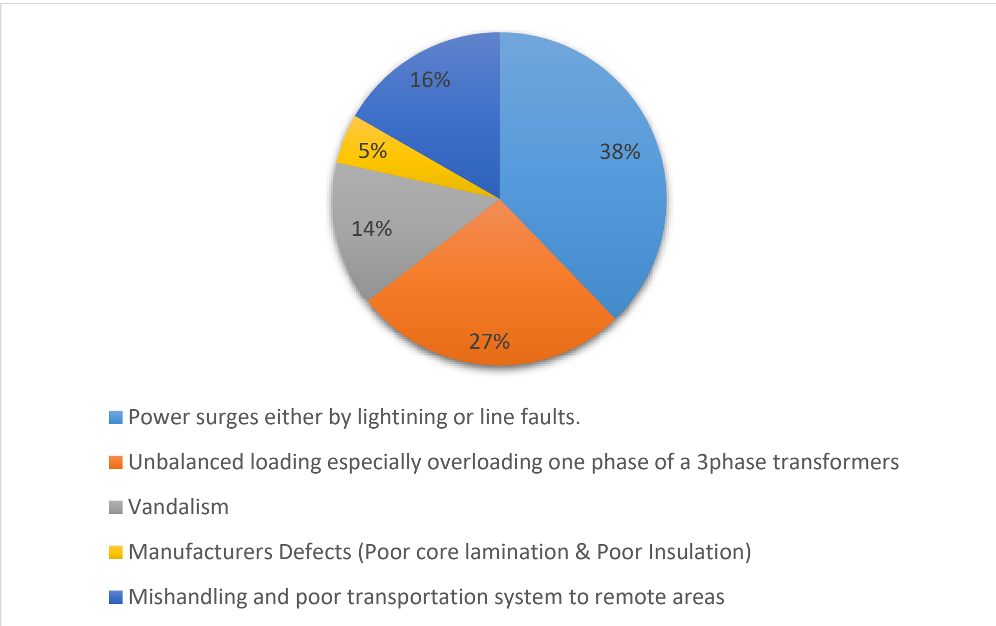

Figure 5: Main Causes of Transformer Failures

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5.0 Conclusions

Taking a transformer as an entity, the above failures may be segregated as Internal Cause and External Cause. Internal causes include but not limited to; Overloading, Lightning Surge, Deterioration, poor Insulation, Improper Cooling and Moisture contamination. External cause include; Extreme Weather conditions, Line Surges, Short Circuit, Poor Workmanship, High-voltage disturbance, malicious acts of vandalism and oil siphoning.

Power surges, unbalanced loading from the LV networks, vandalism, manufacturer defects and mishandling were established to be the main causes of the power distribution failures in the rural areas. Most of the failed transformers exhibited evidences of short circuit failure on the HV phases due to the poor insulation as a result of poor quality of insulation and/or absence of the oil. Open circuits found on the windings taps on HV and/or at the neutral connection on LV that were established to be due to improper terminations and defects caused by movement during shipment.

6.0 Recommendations

The following recommendations have been established to curb the above challenges;

i. Power distribution lines and substations should be constructed with reliable surge protection systems installed at the critical line points so as to address the impacts of power surges in the grid. Also low voltage distribution transformers should be installed with additional surge protector mounted directly across transformer bushings with as short leads as possible for additional protection in case of lightning strikes or switching impulses.

ii. Global earthing concept, where surge arresters/protectors, transformer tank/body, line hardware and network/system ground are bonded together and earthed, should be applied.

iii. Proper and comprehensive forecasting and predictive designs distributing the potential connections on the terminal transformers should be done to avert the effects of unbalanced loading on these distribution transformers. Continued inspection and maintenance surveys should also be deployed to ensure LV side load balancing on the transformers.

iv. Distribution transformers should be mounted in secured areas as opposed to secluded zones to mitigate cases vandalism and oil siphoning/theft.

v. All sourced transformers should be thoroughly inspected of defects and subjected under routine tests both at the manufacturer's location and the utility test points. Transformers with any physical defect on bushings, tanks or arching horns should not be issued for installations. In addition stringent factory assessment/acceptance tests to be implemented for every transformer.

vi. Qualified and licenced electrical contractors and technicians should always install, commission and maintain power distribution transformers with specialized transportation equipment being used for transformers transport.

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Factoring these recommendations at the utility level will see the transformers failure rates decrease to the expected 3% rate as stipulated by the standards(Institute of Electrical and Electronics Engineers and IEEE-SA Standards Board, 2010).

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7.3 Declaration of interest

None

7.4 Conflict of interest

The authors declare no conflict of interest in this work.

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