The Impact Of Transformer Failure On Electricity Distribution Network: A Case Study Of Aba Area Network

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Abstract*— *This research assessed the effects of transformer failure on the electrical distribution system in Aba, Nigeria. Various transformer-related faults that hinder the effective distribution of electricity to Aba's residents and the environs were analyzed holistically. Using SAIDI, SAIFI, CAIDI, and ASAI reliability indices, data on distribution transformer failures, daily load forecasts, and delivery systems gathered from 2016 to 2020 were evaluated to determine transformer reliability, failure frequency, and overall network availability. The study's findings indicate that, over the course of the five years under evaluation, the sampled distribution substations saw an average rate of 18.4% transformer failures, with substations in rural regions suffering the greatest losses. According to the study's classification of faults based on causes, overloading, insulation failure, and vandalism/theft activities accounted for 16.6%, 15.9%, 13.7%, and 11.6% of all faults, respectively. It also showed that the bulk of transformer failures was found in rural regions, with the feeders serving Uvoji and Aba/Umuahia leading the list with 34% and 20.7%, respectively. The greatest failure rates, 19.6%, and 28.3% were found for the operational years 2019 and 2020 respectively. The analysis gave a power availability gap of 58.6% between the expected demand and the actual supply, which is much low for an industrial or commercial region. As a measure to improve the reliability, availability, operational performance, and overall efficiency of the distribution network, the research identified the need for additional transformer installation with strict adherence to relevant standards, increased daily load allocation, a balanced loading system, and effective monitoring system based on the technology of GSM and Internet of Things (IoT).

Keywords—Transformer; Power Distribution; Failure Frequency; Reliability; Availability

INTRODUCTION:

Components including power/distribution transformers, circuit breakers, cables (overhead and underground), surge arresters, insulators, and bushings are essential for an efficient service delivery system in electric power generating, transmission, and distribution systems. With a life expectancy of 25 to 30 years, transformers play a crucial role in controlling supply voltage from the site of power generation through the transmission network to the ultimate consumer point [1]. They are not designed to require as much care as most electrical equipment, but it is important to remember that the care and maintenance requirements are crucial and must be rigorously followed by the manufacturer's instructions [2]. According to [1], the unit's difficult nature leads to routine maintenance being neglected, which lowers life expectancy dramatically and increases the risk of outright transformer failure and consequent damage. The electricity demand has been on the rise due to the multiple applications for it in contemporary society that affect people's everyday lives either directly or indirectly. The efficiency of the system components mentioned earlier heavily influences the supply and distribution of energy, which are essential for any country's significant economic and social progress.

As in other emerging economies worldwide, Nigeria's energy demand exceeds its supply, making it impossible to continue expanding with the existing generation, transmission, and distribution infrastructure. Numerous reasons, including a lack of infrastructure, a poor maintenance culture, inconsistent application of energy legislation, sabotage by vandals, regular or rare breakdown of crucial power distribution equipment like transformers and switchgear, and a host of others, have limited this. Since the first power plant was erected in Lagos in 1896, the Nigerian electrical supply system may best be characterized as a significant instrument as well as a restriction to the expansion of the national economy [3]. The operators of Discos have made it a habit to use more equipment, with little to no capital investment and lower maintenance costs, to offer energy to their clients ever since the Nigerian electric power sector was privatized. For example, distribution transformers are now regularly used over their rated capabilities to handle load demand increases, whether temporary emergencies or long-term trends [4]. Although the utility operators viewed these actions as a cost-effective way to install new transformer units, they harmed the network's overall availability, stability, and reliability of the electricity supply, and they may even be to blame for the frequent system failures.

Understanding the many transformer components, including the magnetic circuit, the electrical circuit, the conservator, the tank, the breather, bushings, oil, and the fins that are prone to breakdown, is crucial to preventing ongoing system failure caused by transformer problems and the resulting downtime. The three main causes of transformer failure—electrical, mechanical, and thermal—can occur on any of the identified parts, and it is frequently challenging to distinguish between the three because most transformer failures are due to insulation failure [6, 2], which can be linked to any of the three causes.

Recent studies have identified several external electrical conditions that contribute to transformer failure, including partial discharge between windings, transient over-voltages from lightning and switching surges, unbalanced loads, and excessive harmonics [4, 5]. The mechanical issues can include obvious damage to the transformer's windings, rupturing of the solid insulation, the collapse of the coil support structures, displacement of the transformer's leads and coils, failure of the tap-changer, and loose connections as a result of protracted vibrations [2]. Electromagnetic forces, improper handling of the equipment during shipment, subpar manufacturing techniques, etc. may all contribute to some of these issues. Thermal variables play a key role in the deterioration of the insulating medium owing to excessive heat generation during normal transformer operation, which leads to the rupture of solid insulation and the degradation of the mineral oil or dielectric failure [5]. Transformer failure is mostly caused by thermal agitation brought on by prolonged over-loading of the transformer, failure of the cooling system or obstruction of the oil ducts, and operation of the transformer in an overexcited state.

When considering the expenses of repair or replacement as well as the operation of alternative electric power supply systems, transformer failure results in a significant loss of income for both the customer and the utility operator [6]. As a result of frequent transformer failure and extended outages caused by faults, the network's dependability and availability are significantly reduced.

The condition of the distribution transformers in Aba, Nigeria, will be examined in this study to determine the frequency of failures, the load distribution and allocation system, and the overall dependability of the distribution system as well as potential mitigation measures.

THEORETICAL FRAMEWORK:

Transformer Types and Ratings Applicable to Nigerian Network:

The transformer is a static electrical machine designed with high efficiency and rugged construction comprising two or more windings with the primary function of transforming input voltage to either low or high depending on its configuration. Distribution transformers are designed to service the final consumers of electricity, taking supplies from the distribution network.

For effective transmission and distribution of electrical power, transformers of various types and capacity ratings are usually employed at various stages of the supply network from generation to utilization point. In Nigeria as applicable to other nations, transformer types and ratings can be classified based on the nature of duties performed in step-up transformers (increasing the input voltage to very high transmission values of up to 330 kV) with transformer sizes usually of MVA capacities and step-down or distribution transformers (reducing the supply voltage to consumer levels of 33 kV, 11 kV, 6.6 kV, and 415 V) with ratings ranging from pole mounted 50 KVA to 15 MVA Injection Substation type transformers.

Most of the transformer units as applied in Nigeria's electricity supply system are oil immersed which are either of the conservator type or hermetic type and are generally of Dyn11 vector group, with impedance values of 3.5% to 6.2% and ONAN (Oil Natural Air Natural) cooled except for the MVA transformers with additional cooling systems such as ONAF (Oil Natural Air Forced) (Danelec, 2015). Table 1 is a table showing 33/11 kV Injection Substations under Aba District of EEDC and their respective ratings and associated number of outgoing feeders.

The table (table 1) depicts what is obtainable in Nigeria's typical distribution network system. It is from the Injection substations that power is fed to the various consumer (final) substations with common capacities ranging from 50 KVA to 500 KVA except for specialized designs and applications with ratings from 750 KVA to 1200 KVA. The voltage class for the Injection Substations is usually 33 kV input and 11 kV output, however, it is a common practice to have several consumer substations (not directly linked to any industry) connected from the 33 kV network lines, but this practice is being discouraged by regulatory bodies, especially in urban centres.

Table 1 Injection Substations and their capacities in Aba District Electricity Distribution Network

S/N	INJECTION SUBSTATION	CAPACITY (MVA)	NO. OF FEEDERS
1	Ogbor-Hill by Omoba Road	7.5 x 1	2
2	Power Station by Nigeria Breweries	15 x 2	5
3	ECN	15 x 2	5
4	Omoba	7.5 x 1	2
5	Ovom by Opobo Road	7.5 x 1	1
6	Uratta*	7.5 x 1	

Source: personal visit to the stations.

Note the marked (*) station is no longer in operation due to power transformer faults.

Major Transformer Fault Conditions:

Fault in any electrical equipment may be generally defined as a defect, imperfection, or deviation from the original circuit design due to which current is diverted from the intended path [7]. This implies any abnormal condition resulting in a drop in the basic insulation or dielectric strength of the electrical equipment such as the transformer thereby reducing impedance values between windings or windings and the ground. Transformer fault conditions which are inevitable occurrences in a power system network are classified into internal and external.

Internal Faults:

This involves fault conditions that originate from the inside of a transformer. As the name implies, they usually manifest in the form of earth, transformer core faults due to insulation breakdown resulting in the high flow of eddy currents accompanied by overheating and subsequent damage of windings; inter-turn faults due to winding flashovers caused by line surges, phase-to-phase fault resulting in a flow of high current due insulation failure, mechanical failure of On-load Tap Changer and tank faults leading to loss of oil [8].

External Faults:

These are faults caused by external activities in the operation of a power system network that results in stresses on the transformer. These fault conditions are but are not limited to Overloading, System faults, Over-voltages, and Under-frequency (over-fluxing) operations [8].

Loading a transformer beyond its rate capacity is a common practice, especially in the Nigerian electricity supply system where some units are operating far above their capacity for profit maximization by the Discos [4]. The implications of this practice result in thermal agitation and subsequent deterioration of solid insulation and a drastic reduction in the lifespan of the transformer.

Similarly, system faults are faults originating from the generating systems, transmission lines, and other connected equipment (synchronous motors/condenser and induction motors) on a power system network [7]. They may be faults like single phase to ground, phase to phase, two phases to ground, all three phases to the ground and all three phases short-circuited. System faults could also be from operational errors, transient voltages from switching operations, and general equipment failure, especially from protective gears. Overvoltage tends to stress the insulation of the electrical equipment andise likely to cause damage to them when it occurs frequently. Overvoltage caused by surges can result in spark over and flash over between phase and ground at the weakest point in the network, breakdown of gaseous/solid/ liquid insulation, and eventual failure of transformers [2].

As explained, these fault conditions could be grouped into electrical, mechanical, and thermal faults as identified by previous research works in the literature [4, 6].

RELATED WORKS:

In analyzing the impact of transformer failure and mitigation methods on the overall reliability and availability of the electricity supply system, different approaches have been adopted by researchers over the years. The efforts of these researchers have reviled the implications and possible remedial measures to improve the life expectancy and performance of this costly equipment.

Transformer Failure Causes, Types and Impacts:

Transformers can fail as a result of any or a combination of electrical, mechanical, or thermal factors [9, 6], however, it is not always easy to pinpoint a particular factor responsible for the failure as most transformers fail due to failure of insulation which can be caused by either of the three as noted by [9]. This implies that faults may occur from any of the component parts of the transformer and therefore, a better understanding of the failure cause requires knowledge of the associated parts of the transformer. However, most transformer failures are traceable to gradually developing faults [10] such that any type of fault might occur due to more than one cause [9]. It is noted by different researchers [1, 6,11] that some transformer problems occur mainly due to oil contamination, which is generally caused by insulation oil degradation, overload, thermal stress, humidity in oil or impregnated paper (solid insulation materials) and defects on the bushings. According to [1], the greatest cause of failure of a transformer is insulation failure followed by design material, and workmanship-related issues as summed in Table 2 with associated costs implications.

Thermal aging, which is the gradual deterioration of transformer insulation with respect to time and temperature has also been observed as a major cause of failure [12]. This is common in oil-immersed transformers where the insulation system is composed of mineral oil and pressed paper which loses its mechanical and electrical strength over time, even when the unit is operated under or a little above rated capacity [12].

Effects of Harmonics on Transformer Failure:

According to [5], harmonics are voltages or currents with frequencies usually an integer multiple of the fundamental power frequency occasioned by the non-linearity of today's applied electrical loads which draw currents of high amplitude short pulses thereby creating distortions in voltage/current waveform as measured in terms of total harmonics distortion (THD). Transformers by design, are meant to operate on power frequency with linear loads, incidentally, the network has been characterized by non-linear loads from sensitive electrical and electronic appliances such as variable frequency drives (VFDs), electric arc furnaces, uninterrupted power supplies (UPS), florescent lights, computers, Switched Mode Power Supply (SMPS) etc [5]. This change in load profile is responsible for most power quality problems as noted by [5]. Power quality-related issues usually manifest in form of deviations in voltage, current, and frequency resulting in malfunction, failure, and consequent damage of connected electrical loads and devices as noted by [6 and 13]. However, the biggest impact is that harmonic distortions generate additional heating in transformer components which give rise to higher losses (I^2R and Eddy currents), transformer insulation degradation, and the resultant reduction in the life expectancy of the transformer and consequent premature failure [5] and power outage that follows.

The impacts of harmonics on the transformer are usually not observed until a failure occurs, however, reducing the impact on the power distribution network, [5] noted the integration of active harmonic filters to produce harmonic components of the fundamental current waveform to cancel the harmonic components generated from the nonlinear loads. Passive filters are made up of static and linear components like inductors, capacitors, and resistors arranged in such a manner to either attenuate the flow of harmonic currents through them or to shunt the harmonic component into the filter circuit would mitigate the impacts.

Transformer Fault Diagnostic Techniques:

In addressing the rate of failure of distribution transformers, an attempt has been made by several researchers in the literature. Dissolved Gas Analysis (DGA) and measurement of partial discharge (PD) level, (though associated with very low energy cannot be overlooked) has been identified as integral tool for evaluating the insulation status of a transformer [14]. This is a major indicator to assess the healthiness of a transformer and therefore, can help in preventing the total failure of the transformer.

Table 2 Causes of Transformer Failures

Cause of Failure	No.	Cost Implications ($)
Insulation Failure	24	149,967,277
Design/material/workmanship	22	64,969,051
Unknown	15	29,776,245
Oil contamination	4	11,839,367
Over-loading	5	8,568,768
Fire/explosion	3	8,045,771
Line surge	4	4,959,691
Improper maintenance and Operation	5	3,518,783
Flood	2	2,240,189
Loose connections	6	2,186,725
Lightning	3	657,935
Moisture	1	175,000

Source: Corbin, 2013.

[15] identified three techniques of transformer failure analysis for monitoring the condition of distribution transformers. One is based on the Conventional Oil Test Analysis where oil samples are collected and subjected to various tests such as Colour/visual analysis to check its turbidity, cloudiness, suspended particles; moisture content in the oil (<= 40ppm); Dielectric strength or Breakdown Voltage (>= 40 kV); Neutralization or acidic number (<= 0.3); Power Factor to determine the leakage current that passes through the oil; and Dissolved Gas Analysis to determine the quantity of Hydrogen, Methane, Ethane, Acetylene, Ethylene in the oil [15]. The second technique employs the Furan Derivative test to check the extent of degradation of the cellulose (pressed) paper used for the insulation whereby a number of furans in the oil are computed using High-Performance Liquid and finally the third technique which computer-based is Markov Models criteria for the determination of fault probability of the transformer [15].

In failure rate prediction of the transformer, [16] proposed a condition-based assessment centered on monitoring operating conditions such as level and type of oil, winding, insulation, and physical conditions of the transformer as a base for ascertaining the operational life service of a transformer and its failure rate.

Fault Tree Analysis (FTA) and Statistical Package for Social Sciences (SPSS) have been identified as veritable tools for the qualitative analysis of power transformer faults [3]]. This according to Onuh can effectively be used to improve transformer failure assessment and thus increase the reliability and availability of the electricity supply system. However, [17] employed FTA for transformer fault analysis using the fuzzy logic controller technique which was more efficient than FTA thereby overcoming the inherent disadvantages of the fault tree analysis method.

Of recent, Sweep Frequency Response Analysis (SFRA) has been used to analyze power transformer failure rates [18]. This is an advanced electrical test technique with the ability to accommodate a comprehensive evaluation of the mechanical conditions of a transformer. It is an advanced management tool with an inherent problem of result interpretation. However, the SFRA test technique is a quick diagnostic tool for assessing transformer integrity after failure has been recorded especially in low voltage networks as it has the ability to investigate a number of defects in a transformer using one technique and also capable of localizing the fault point [18].

Apart from the conventional SCADA (Supervisory Control and Data Acquisition) system widely used in monitoring power system installations, the most recent transformer fault diagnostic tool employs the technology of Internet of Things (IoT) for gathering information on the unit condition [19]. However, a major drawback of this technology is the unavailability of internet services, especially for unit installations in rural communities.

However, for effective failure analysis of distribution transformers, international standards such as the Institute of Electrical and Electronic Engineers (IEEE standard C57-125) are essential guides for failure investigation and diagnostics as noted by [6] which is a comprehensive guide for failure investigation, documentation, and analysis for Power Transformers and Shunt Reactors.

GSM Based Transformer Monitoring:

The use of GSM to monitor the operating conditions of power distribution facilities is viewed as an improvement over the conventional SCADA system, Power carrier communication system, and physical checks conducted by utility operators on units in service [20]. It is defined by [20] as an online monitoring of key parameters of power distribution transformers with a view of sending information on the health status of a transformer to utility operators for necessary remedial actions to forestall total collapse. In his design, the LM35 precise integrated circuit was used to monitor the temperature and voltage of the transformer unit been monitored.

Similarly, [21] achieved a monitoring system using GSM technology with increased capacity to monitor and record key parameters such as load current, overvoltage, oil level, winding, and ambient temperature associated with a given transformer substation employing AT89C52 high-performance CMOS together with Atmega16 and a GSM modem. The operation requires that any deviation from the programmed parameter values would be seen as an abnormality and hence a short message service (SMS) would be sent to the programmed GSM line notifying the operator of an upcoming fault.

Overload, over temperature, high excitation, and oil level faults as major faults that can lead to a drastic reduction of life expectancy of power distribution transformers, and their eventual total damage was monitored by [22] using the GSM module to improve on the fault reporting system. This resulted to a significant time reduction in response by the maintenance crew compared to when the units were monitored by traditional physical monitoring.

Transformer Reliability Assessment:

Reliability considers the capacity or ability of a transformer unit to perform certain desired duties under load for a given time period [3]. Assessment of a transformer's performance from time to time would be necessary for evaluating the integrity and reliability in delivering optimal services of voltage transformation. This could be achieved by utilizing basic or advanced engineering softwares. [3] used a combination of Statistical Packages for Social Sciences (SPSS) and Fault Tree Analysis (FTA) in analyzing power transformer failure frequency for transformers in Abuja Transmission Sub-region and were able to identify weaknesses in the overall system reliability mostly on the core and coil sub-systems respectively. He noted that this combination technique is not only limited to an existing system but can also be used to analyze a system under design and therefore suggested the adoption of this combination technique as an easy approach to analyze power transformer reliability to Discos for distribution transformers analysis.

Similarly, [23] observed the devastating impact of the power outages on the overall network reliability of Lakya feeder in India with an average availability of 0.68 and failure rates of 15%, 18%, and 13% for a three-year review period. It was suggested that minimizing outages remains the best option for improving distribution network reliability.

MATERIALS AND METHODS:

The materials employed in this research comprised of surveys of the Injection Substations and the available facilities which helped to correlate the obtained transformer outage data covering a period of five years, from 2016 to 2020. Personal interviews of the substation personnel bordering on operating system and challenges formed the background of the equipment performance and their reliability evaluations. Materials of interest were mainly distribution transformers that are installed to service the final consumers with capacities ranging from 50 to 500KVA ratings for both 11kV and 33kV feeders.

The adopted methods are as summed in the flowchart (figure 3) describing the stepwise flow in analyzing power distribution system failures associated with transformer units in the Aba District of EEDC. The design considers the evaluation of the reliability indices and failure frequency analysis to determine the overall rate of failure as well as network reliability and availability.

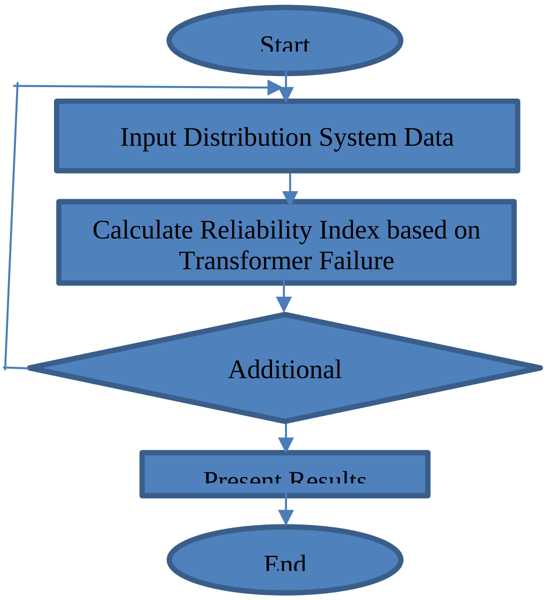

Fig.1 Research Flowchart Diagram

Reliability Analysis Models:

System Average Interruption Duration Index (SAIDI): Defines the total number of interruption duration in hours due to transformer faults experienced by an average customer.

$$\text{SAIDI} = \frac{Total\ Consumer\ Interruption\ Duration}{Total\ Number\ of\ consumers}$$

$$= \frac{Customer\ Hours}{No\ of\ Customers} \qquad 1$$

$$= \frac{\sum(Df * Ni)}{Nt} \qquad 2$$

System Average Interruption Frequency Index (SAIFI): Measures how often an average customer would experience power supply interruption due to a transformer outage at fault.

$$\text{SAIFI} = \frac{Total\ Number\ of\ Consumers\ Interrupted}{Total\ Number\ of\ consumers}$$

$$= \frac{Customer\ Frequency}{No\ of\ Customers} \qquad 3$$

$$= \frac{\sum(\lambda f * Ni)}{Nt} \qquad 4$$

Customer Average Interruption Duration Index (CAIDI): Determines the average time required to restore power supply to a feeder or transformer substation after an outage or fault is observed on a substation.

$$\text{CAIDI} = \frac{SAIDI}{SAIFI} \qquad 5$$

$$= \frac{\sum Df}{\sum \lambda f} \qquad 6$$

Average Service Availability Index (ASAI): Measures the ratio of customer service availability to customer service demand, and it is usually expressed as a percentage.

$$\text{ASAI} = \frac{\sum Ni\ x\ 8760 - \sum UiNi}{\sum Ni\ x\ 8760} \qquad 7$$

$$= 1 - \frac{\text{SAIDI}}{8760} \qquad 8$$

Where,

Ni = number of customers connected to a particular feeder

λf = number of outages occasioned by transformer-related faults

Df = duration of outage resulting from transformer-related faults

Nt = total number of customers connected to an Injection Substation

Ui = restoration time of supply in hours

8,760 = the number of hours in a calendar year.

Failure Frequency: To determine the failure rate of the distribution transformers for the period under review, [24] defines failure as the ratio of the number of observed failures to the number of units in service for a specific time period usually expressed in percentage.

$$\lambda = \frac{\sum ni}{\sum Ni}\ x\ 100\% \qquad 9$$

Where,

$\lambda =$ Transformer failure rate per annum

ni = Number of failed transformers in the ith year

Ni = Number of transformers in operation during the ith year.

RESULTS AND DISCUSSION:

Transformer Failure Frequency: The results indicate that out of the 885 units of distribution transformers installed and in operation within the period under review, a total of about 597 units had one fault or the other that caused interruption of power supply to customers. Poor maintenance, excessive loads, failure of insulation, activities of vandals, and poor workmanship/network issues contributed immensely to transformer failure frequency in the order of 16.6%, 15.9%, 13.7%, 11.6%, and 9.5% respectively.

Load allocation and delivery system: There was a progressive increase in both forecast and the actual load delivery with ECN taking the lead followed by Power Station while Omoba is the least. The increment may be justified by load demand and substantial increase in generation capacity over the years. However, the calculated 58.6% power availability with respect to load projection and delivery statistics for the period under review shows how poor and unreliable the entire supply system is in sustaining industrial, commercial and domestic needs for meaningful development. The available power also shows the poor state of the national grid system and need for urgent and immediate increase to boost the capacity. The detailed illustration of power allocation and delivery system are as contained in figures 2 and 3 below.

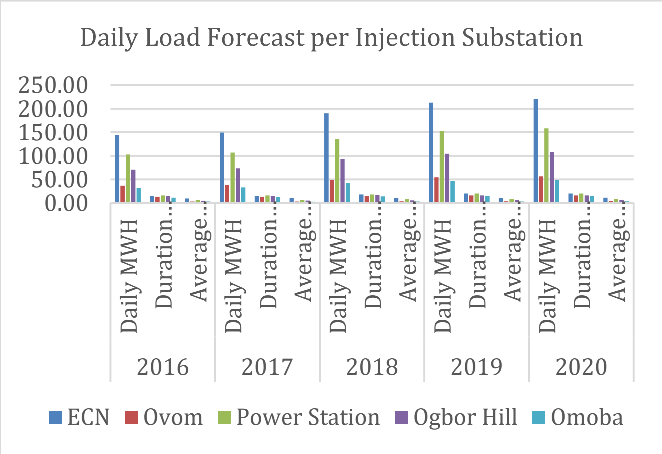

Figure 2 Average Daily Load Allocation

Year	2016	2017	2018	2019	2020
Failure Rate (λ) *in* %	15.4	15.0	13.9	19.6	28.3

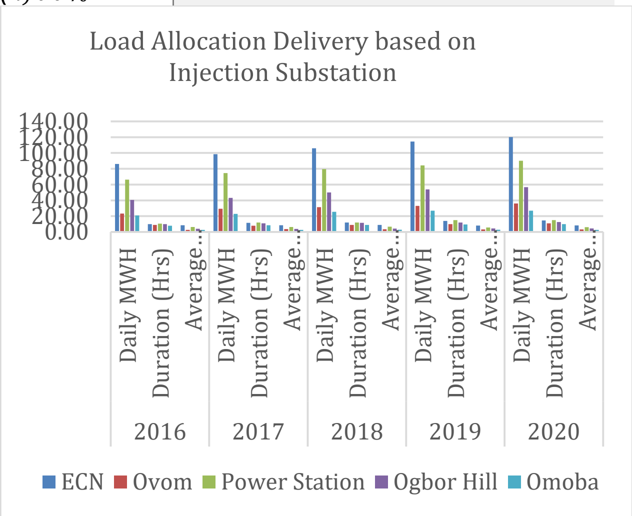

Figure 3 Average Daily Load Received per Injection Substation.

Table 3 Summary of Failure Frequency of Transformers Year wise.

From Table 3, the failure frequency for the period under review is determined as the average of the values, which is approximately 18.4%. This is very high in comparison with the 0.5% average value designated to European Substation transformers [24]; 12 to 15% range in India and 11.7% obtained at the Onitsha area distribution network of the same EEDC, within 2011 to 2015 operations years [4].

On the basis of transformer classification (fig.4), 50KVA/11kV units failed mostly due to poor workmanship with the highest recorded in the 2016 operation year. These categories of transformers were the NIPP federal government intervention project according to Ossai (personal interview, October, 2021).

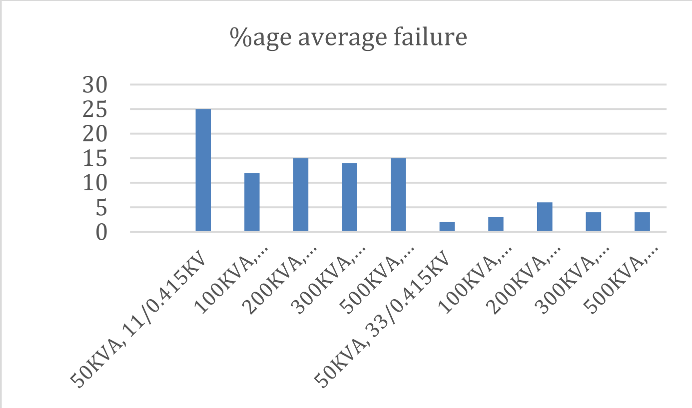

Figure 4 Failure Rate based on Transformer Rating

System Average Interruption Frequency Index (SAIFI): The frequency of interruption was observed mostly in rural areas and heavily overloaded units at the city centres of the coverage area of this study. This is evidently seen on Aba/Umuahia 33kV feeder topping the list with 15.81 followed by Ovuoji feeder (under Omoba 7.5MVA Injection Substation) with a frequency of 12.2 for feeders supplying rural communities. However, IGI and 7Up feeders are on the lead for overloaded areas with interruption frequencies of 5.73 and 5.32 respectively. Generally, utility operators would want to improve the overall SAIFI index for better profit. Reduced outage frequencies translate to more energy for consumers and more money for the utility. It also improves the quality of supply services, for instance, if in a given day the planned availability is for 12 hours to a given area, a good SAIFI index ensures that such areas get the supply as at when due and are not affected by an unreliable equipment/system.

System Average Interruption Duration Index (SAIDI): The interruption duration in hours was more in the 2020 operation year followed by 2016 with a total of 4,975.33 and 4,156.35 hours respectively which amounts to an average of approximately 237 and 244 hours for the period of five years. Considering the year 2020, feeders feeding rural communities registered very long hours of outage duration when faults occurred on the respective substations as compared to those near the city centres. Uvoji feeder topped the chart with an approximate value of 1,946 hours (as seen from table 4) followed by Aba/Umuahia and 7Up feeders with respectively 732 and 615 hours approximately.

Improvement in response time to transformer failures/outages remains the most direct approach to improving this reliability matrix. As the rate of power interruption due to fault is reduced SAIDI will automatically appreciate and interruption duration will gradually varnish. Improved monitoring and a well-coordinated maintenance system will result in a significant boost to the reduction in system interruptions and their durations.

Customer Average Interruption Duration Index (CAIDI): The average time required to restore power supply to a feeder or transformer substation after an outage/fault or its clearing time can be more related to the operational dynamics of a utility (measures adopted to clear system faults and improve service delivery) company. From table 4, Uvoji feeder recorded the highest duration time to restore service (159.5 hours) followed by ECN feeder 4 with 122.86 hours. The least on the table are the IGI 33kV feeder, Waterside feeder, and PS feeder 1 with respectively 19.64, 24.00, and 25.63 hours of restoration time. Improvement of this reliability index would require faster resolution of unit failure issues through effective communication and troubleshooting skills to reduce system downtime.

Table 4 Reliability Index for 2020 Operation Year

S/No	Feeder Name	SAIDI (Hrs)	SAIFI	CAIDI (Hrs)	ASAI (%)
1	PS FDR-1	34.31	1.34	25.63	99.6083
2	PS FDR-2	82.82	3.16	26.18	99.0546
3	PS FDR-3	23.18	0.86	27.00	99.7354
4	PS FDR-4	51.76	1.29	40.20	99.4091
5	PS FDR-5	34.25	0.54	63.33	99.6090
6	ECN FDR-1	15.48	0.16	96.00	99.8232
7	ECN FDR-2	304.84	5.23	58.33	96.5201
8	ECN FDR-3	113.86	1.21	93.88	98.7002
9	ECN FDR-4	160.90	1.31	122.86	98.1632
10	ECN FDR-5	46.45	0.87	53.33	99.4697
11	7UP FDR	615.05	5.34	115.20	92.9789
12	WATERSIDE	78.31	3.26	24.00	99.1061
13	IGI FDR	112.52	5.73	19.64	98.7155
14	ABA/UMUAHIA	732.00	15.81	46.30	91.6438
15	OVOM FDR	503.00	5.00	100.60	94.2580
16	OMOBA FDR	120.92	2.34	51.67	98.6196
17	OVUOJI FDR	1,945.67	12.20	159.50	77.7891
	AVERAGE	292.67	3.86	66.10	96.6591

Figure 4 is the summary of year-wise average reliability indices covering the period under review.

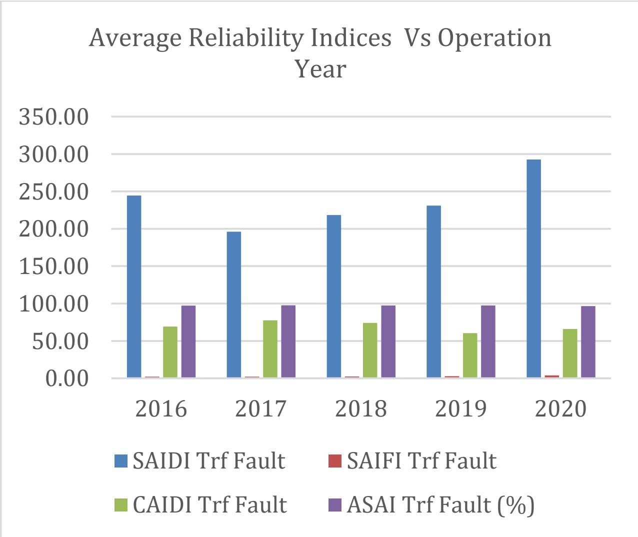

Figure 5 Year Wise Reliability Indices 2016 to 2020

CONCLUSIONS AND RECOMMENDATIONS:

This study investigated the impacts of transformer failure on the electricity distribution network with an emphasis on the Aba area distribution network and its environs. It analyzed various failure causes and mitigation measures to reduce associated downtime and hence, evaluated the reliability and availability of distribution transformers. It also analyzed daily load forecasts and delivery systems for the area. The study employed the use of statistical tools and reliability indices to analyze transformer failure frequency within the coverage area. Data on average daily load forecast and received power for the five Injection Substations and transformer failures were collected from the Aba District office of EEDC for a period of five years, from 2016 to 2020. The data were used to evaluate the system's reliability and availability in a structured excel environment.

The findings show that during the five-year period of the study, injection substations in the Aba Electricity Distribution Network recorded an average failure rate of 18.44% with the Omoba Injection Substation leading with an average of 34% followed by the IGI-Aba/Umuahia Feeder with 20.7%, Power Station (15.82%) and Ovom (15.38%). This value is far from 11.7% obtained previously at the Onitsha area network [4] of the same EEDC. Within the period under review, Ogbor-Hill and ECN Injection Substations witnessed comparatively low failure rates of 11.56% and 13.16% in comparison with the others. The 2019 and 2020 operation years recorded the highest failure rates of respectively 19.6% and 28.3%. The study also revealed that poor maintenance systems topped the list of failure causes with 16.6% and were closely followed by transformer overloading (15.9%). Others are insulation related (13.7%), activities of vandals/theft (11.6%) with poor workmanship, and network disturbances accounting for 9.5% each.

The study proved that power availability concerning daily load forecast and the actual power delivery to Aba residents was 58.6% within the period under review.

It is further identified by this study that poor communication cum effective monitoring system was a major cause of prolonged downtime of distribution transformers as observed in delays in maintenance actions and time lag before a failed transformer is restored to service, especially for substations in remote areas of Aba.

The outcome of this study would help electricity utility companies in providing more reliable and cost-effective service delivery systems to their numerous customers. Therefore, it is recommended that a well-coordinated monitoring/inspection system utilize the technology of GSM and the Internet of Things (IoT). This would also serve as a cost-saving measure in that manpower requirement for the conventional physical monitoring and inspection of facilities will be effectively conducted electronically. regular testing of power distribution transformers at intervals especially during yearly turnaround maintenance should be encouraged. This would mitigate against total failure and improve the overall network reliability and equipment availability.

Installation of additional units to reduce loads on the existing transformers, especially within the fast-developing areas of Aba city is highly recommended. The study also suggests strict statutory legislation against vandalism, good workmanship, a balanced loading system, use of quality transformers such as Danelec transformers which are manufactured here in Nigeria with readily available spares and well-trained local professionals for yearly turnaround technical support. A proactive and well-equipped maintenance programme for transformers within the network would ensure improvement in transformer life expectancy and increased availability of electricity supply system.

Boosting the grid system through the construction of additional power generating plants putting into cognizance, renewable technologies with little or no environmental impacts, and integration of embedded generation would go a long way to increasing capacity availability for quality service delivery for sustainable industrial, commercial and domestic process development.

These measures would reduce the occurrence of both momentary and sustained transformer outage frequencies and thus interruption durations will varnish completely.

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