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Analysis of Transformer Loadings and Failure Rate in Onitsha Electricity Distribution Network

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Abstract This study investigated transformer loadings and failure rate in the Onitsha Electricity Distribution Network by using the Electrical Transient Analysis Program (ETAP) software 12.6 and the Statistical Package for the Social Sciences (SPSS) software 16.0. Data collected over the period 2011-2015 on the distribution network were simulated on ETAP software using the Newton-Raphson (N-R) technique to determine the transformer loadings while responses to 350 copies of questionnaire distributed among the technical staff were statistically analysed on the SPSS software to ascertain the failure rate among transformers in the network. The findings of the study show that during the 5 years period covered by the study, the sampled substations recorded transformer average failure rate of 11.7 %. It was further revealed that besides insulation issues which accounted for 24.2% of all the failures, overload (22.5%) was the next major cause of transformer breakdowns in the distribution network. The study recommends installation of more transformer units, use of high quality transformers, balanced loading of the transformers and proactive inspection and maintenance program of transformers units within the network. The outcome of this work would help electricity utilities provide more reliable and cost effective services to customers.

Keywords: *distribution network, electricity supply failures, failure rate, transformer failure, transformer loading*

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1. Introduction

The recent reforms in the Nigerian power sector pose fresh challenges to the nation’s electricity industry such that most electricity utilities now resort to increased equipment utilization, deferred capital expenditures and reduced maintenance expenditure in the provision of electricity to the consumers. Transformers, for instance, are now frequently operated beyond the nameplate rating in order to meet increases in energy demand either on short term emergency such as the loss of another transformer in a substation or on a long term basis [1]. This happens because it is considered a more economic strategy to overload an existing transformer than to install a new transformer unit [2]. Consequently, while load on each transformer continues to grow at about 2 % per year, installation of new transformer unit keeps declining [3]. Certain factors such as the hot spot temperature, the top oil temperature and the ratings of the ancillary equipment: the bushings and the load tap changers (LTCs) determine how much load the transformer can support beyond the nameplate rating [1]. However, utilities now overlook these factors and the safety of the transformer thereby leading to increased cases of transformer failures and cutting off of power supply to the service areas concerned. According to ref [4], an average failure rate of approximately 0.5 % is often designated to European substation transformers while the U.S. Department of Energy (DOE) estimate gives transformer constant failure rate of 0.5 %/year due to lightning and other random failures unrelated to transformer age [5]. Researches have also put the failure rate of transformers in India and many developing economies in the range 12% -15% as against less than 1% in developed countries [6].

Power system experts had declared that given “ideal conditions”, a transformer can last 30 to 40 years. Recent studies, however, have found this claim not to be completely true. A study carried out by Hartford Steam Boiler (HSB) in 1975, for instance, revealed that transformer average age at time of failure was 9.4 years. A further research by HSB in 1985 indicated the average age of a transformer as 11.4 years. Another related study spanning a 10-year period from 1988-1997 still by HSB put the transformer average age at 14.9 years [3]. These statistics underscore the need to undertake periodic checks on transformers to ascertain the operational condition and proactively avert possible sudden breakdowns.

Recent researches have also pinpointed electrical disturbances, lightning, insulation degradation, loose connections and overload among the chief causes of transformer failures in electrical distribution networks [3,7,8]. According to ref [9], however, overload, insulation oil degradation, thermal stress, humidity in oil/paper and bushing defective are the major causes of transformer problems. The term “Overload” describes a situation whereby a transformer is subjected to voltages and/or currents that exceed its nameplate rating such that excess heat is generated which causes the insulation system to break down resulting in decreased life expectancy of the transformer unit [10]. Transformer overload in industries has always been traced to rapid plant expansion without adequate capacity improvement. Inadequate planning coupled with the presence of low power factor and high harmonic currents generated by inductive loads cause a transformer to become heavily overloaded. It is widely acknowledged also that overloaded transformers hinder future plant expansion while the resulting excessive heat pose a potential fire hazard [11]. Overloading leads to accelerated aging and increased losses in transformers [12].

In this paper, the failure rate among transformers in the Onitsha Electricity Distribution Network was investigated and the loading on each transformer evaluated. Though featured among vulnerable Nigerian Cities which are susceptible to perennial flooding [13], Onitsha is an economic hub for commerce and industry in Anambra state; a major centre for trade between the coastal regions and the north, as well as between eastern and western Nigeria and across the West African region. The metropolitan and high density areas of Onitsha include Awada, Woliwo and 3-3. This strategic nature of the town thus makes it imperative to carry out this research in order to determine predominant factors that could contribute to transformer failures and consequent sudden blackouts thereby preventing unnecessary financial losses to both utility and electricity customers within the network.

1.1. Overview of Transformers

Transformers perform the function of stepping up or stepping down electrical voltages and are therefore a vital, essential and one of the most expensive components in any electrical network. Its cost varies between thousands and millions of dollars depending on the design and size of the unit [14]. Any failure of the transformer before expiration of its designed lifespan results in unplanned outage, production loss, unavailability of critical services and in most cases huge financial losses to both utilities and customers.

Transformer winding insulation deteriorates as aging sets in. Heat is a major cause of winding insulation breakdowns. Overloading the transformer causes its temperature to rise due to the resistive (I^2R) losses, stray, and eddy current losses. Temperature is widely noted as the main parameter affecting transformer insulation failure. Hence, the heat produced through the process called pyrolysis in the transformer as a result of loading and the effect of ambient temperature is the important factor affecting the life of the transformer [15]. Any increase in temperature adversely influences the properties of the winding insulation and the oil surrounding it. In other words, overloading of transformer leads to increase in the winding temperature, leading to deterioration of the insulation material and subsequent reduction in the transformer life span.

Routine testing and performing diagnostics can minimize loss and down time of transformers. According ref [16], the three categories of testing and diagnostics required in determining transformer electrical, thermal, and mechanical characteristics include:

(i) Performing acceptance test after installation and commissioning of the transformer;

(ii) Predictive maintenance test during normal operation of the transformer to ascertain that electrical properties have not changed from design specifications;

(iii) Failure test to identify breakdown cause of the transformer.

Owing to limited data on transformer cycle, however, statistical analysis only evaluates transformer failure rate based on the operational experience. IEEE C57.125 is considered an excellent guide for transformer failure investigations [17].

The U.S. Department of Energy (DOE) defines distribution transformer life as the age at which the transformer retires from service, while the IEEE defines a transformer failure as “The termination of the ability of a transformer to perform its specific function” [17].

A transformer hardly fails as its insulation withstand strength is usually higher than the normal operating or the fault stress. But as the transformer ages, however, the insulation withstand strength gradually reduces due to its normal degradation and the cumulative effects from transient events. This continues till a point where the insulation withstand strength can no longer sustain the high operational stress thus resulting to failure of the transformer as illustrated in Figure 1. The impulses in the actual stress curve indicate the sudden increased stresses from transient events and because these events occur randomly during transformer operation, there is often likelihood of reduction in the insulation withstand strength of the transformer [18]. Each step change in the insulation withstand curve therefore indicates a slight reduction of insulation withstand strength. It follows that as the load increases, and/or a transient event occurs, the insulation withstand strength reduces. The crossover point of insulation withstand curve and operation stress curve in Figure 1 shows the expected operation lifetime of a transformer [18].

Every transformer is designed to withstand the expected growing load and the system transient fault events [18]. However, given a rapidly growing load demand that is faster than envisaged in Figure 1, or the more frequently occurring transient event, or given that the fault stress exceeds the insulation withstand strength, the transformer fails before the designed age of 40. A transformer, which failure occurred due to the significant effect from a transient event before the designed life, is shown in Figure 2.

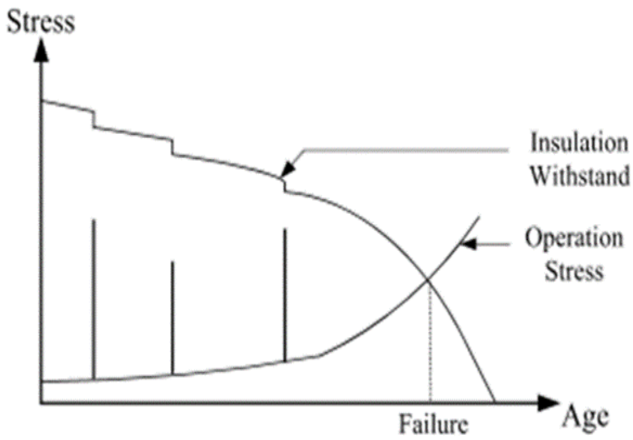

Figure 1. Transformer failure illustration [18]

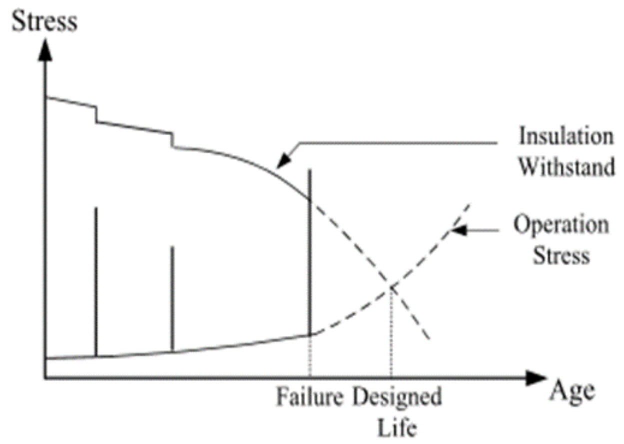

Figure 2. Transformer failure before expiration of designed life span [18]

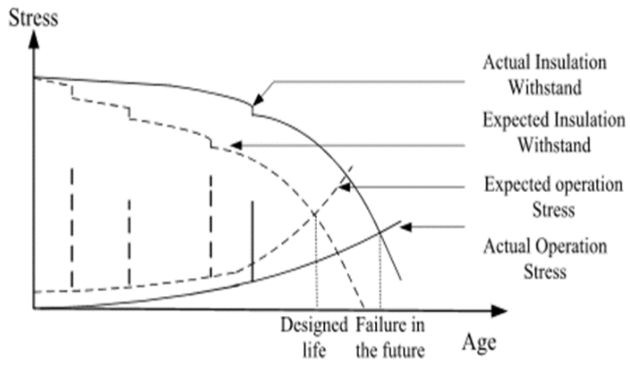

Figure 3. Transformer failure beyond designed life span [18]

Operation experiences also show that given slower increases in load and less frequent occurrences of transient events, every transformer has insulation withstand strength capable of sustaining the actual operation and fault stress beyond the 40 years expected life-span [18, 19]. This is because under such condition, the insulation strength reduces less than expected thereby making it possible for the transformer to survive beyond the 40 years. A transformer post-lifespan failure caused by less loaded condition is illustrated by solid curves in Figure 3. The dash curves represent the expected operation condition and the expected reduction of insulation withstand strength [18].

Generally, therefore, transformer failure is determined by individual design, loading experience, maintenance culture and the environment in which it is installed and operated and not on whether or not the transformer has attained the designed life-span of 40 years [18].

1.2. Onitsha Electricity Distribution Network

Figure 4 shows Onitsha Electricity distribution network in ETAP environment. The network consists of 45MVA; 132/33/11KV Transmission substation feeding seven (7) Injection stations with variant capacities. Table 1 shows the Injection Substations, their capacities and 11KV feeders radiating from them. In addition to Table 1, there are other feeders namely PPI/Enamel, IUNIT and Inland 11KV feeders which radiated directly from the 11KV bus of the transmission substation located at the Onitsha Works Centre.

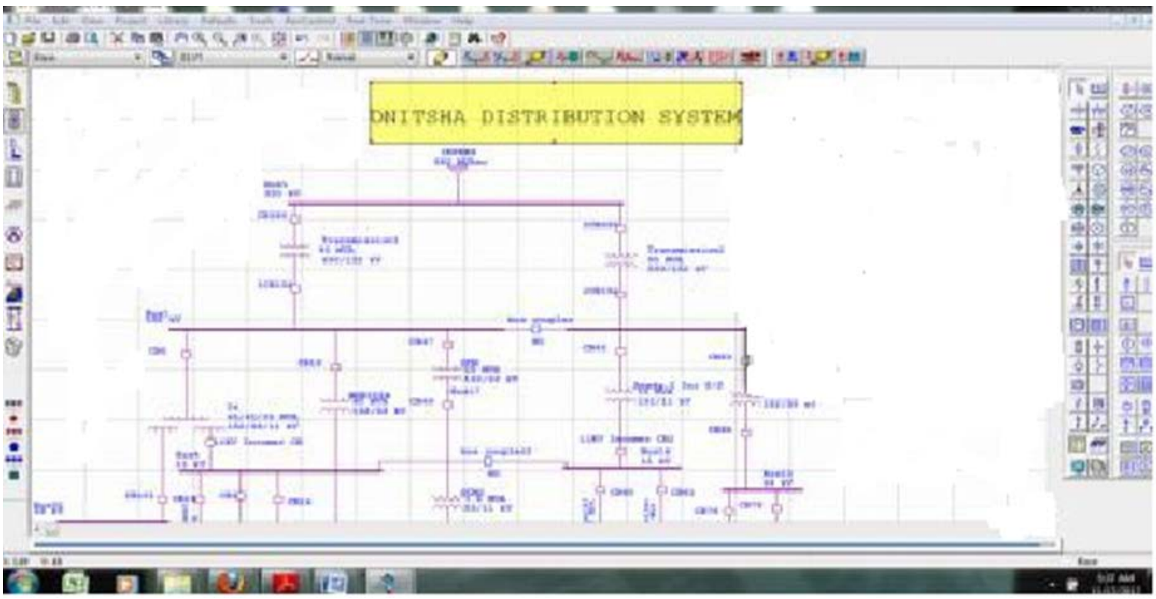

Figure 4. ETAP Single line representation of Onitsha Electricity Distribution Network

Table 1. Onitsha Electricity Distribution Network Injection Substations, Capacities and Feeders

S/N	Injection Substations	Rating/Capacity	11KV Feeders
1.	Ugwunwanosike	15 MVA, 33/11KV	Toll gate, Mkpor and Ogidi
2.	Army Baracks	15MVA, 33/11KV	Omagba, Minaj, GRA and Army
3.	Atani	2X15MVA, 33/11KV	Market, Iweka, Water works, Uga, Industrial and Premier
4.	GCM	7.5 MVA, 33/11KV	Habour, Golden oil, GCM and Dozzy
5.	Awada I	15 MVA, 33/11KV	Woliwo and Nwaziki
6.	Awada II	15 MVA, 33/11KV	Ugwuagba and Mgbemena
7.	3-3	7.5 MVA, 33/11KV	Housing and Nsugbe

2. Materials and Methods

The study employed the qualitative and quantitative approaches to investigate transformer failures in the network using the Electrical Transient Analysis Program (ETAP) software 12.6 and the Statistical Package for the Social Sciences (SPSS) 16.0. Transformer reports from 2011 to 2015 on the seven injection substations in the Onitsha Electricity Distribution network were accessed from the Enugu Electricity Distribution Company (EEDC).

The Injection substations are Ugwunwanosike, Army Barracks, Atani, GCM, 3-3, Awada I and Awada II (See Table 1). The collected data include list of all transformers rated 200KVA - 1.5MVA connected to each of the injection substations, monthly maximum loadings on the injection station feeders, number of transformers units that failed, age of the failed transformers, cause of failure, the number of outages caused by transformers failure, the outage duration, voltage level etc. for the study period covering 2011-2015. Additional data were collected through 350 copies of a well structure questionnaire which were served on the technical staff of the electricity distribution companies. The network data and transformer parameters were used in power flow simulation using ETAP 12.6 software. The simulation results obtained were used to evaluate the loadings on the transformers within each of the injection substations, whereas the responses to the questionnaire were statistically analysed on the SPSS 16.0 software to determine the failure rate and actual causes of failure of the transformer units.

To determine the transformer failure rate, the following formula was used [4,20]:

$$\lambda = \frac{\sum_{1}^{i} n_i}{\sum_{1}^{i} N_i} .100\% \qquad (1)$$

Where:

$\lambda =$ Failure rate per annum (p.a) in percentage

n_i =Number of transformers that failed in the ith year.

N_i = Number of transformers in service during the ith year

For the calculation of failure rates a constant transformer population of 4500 was assumed for the investigated failure time period.

3. Results and Discussion

The calculated transformer failure rates among the injection substations are given in Table 2. The findings show that out of a sampled 4,500 units of transformers that were installed and in use within the Onitsha distribution network during the 2011-2015 period of study, a total of 525 units of the total transformer units (See Table 2) failed owing to several cause factors (See Table 3). This represents an average failure rate of 11.7% and is close to failure rate of transformers in India which according to ref [6] is in the range 12% - 15% but much higher than 0.5 percent obtainable in the European countries [5].

Table 2 indicates also that the Army Barracks Injection Substation had the highest transformer failure rate of 23.8%. This was followed by GCM and Atani Injection Substations with 22.7% and 20.6% failure rates respectively.

Results of the analysis presented in Table 3 shows that Insulation Issues topped the list of failure causes in the distribution network with 24.2%. This was followed by Overloading and Inadequate Maintenance with 22.5% and 16.4% respectively. The study thus established the following causes of transformer failures in the Onitsha electricity distribution network (See Table 3 and Figure 5):

1. Moisture - The moisture category includes failures caused by leaky pipes, leaking roofs, water entering the tanks through leaking bushings or fittings, and confirmed presence of moisture in the insulating oil. Moisture could be included in the inadequate maintenance or the insulation failure category, but it is reported separately here [7].

2. Overloading - This category includes failure arising from established cases of overload and includes basically transformers that experienced a small but sustained annual increases in load (See Table 4) that exceeded the nameplate capacity over time such that failure occurs [7]. Excessive load on a transformer can lead to increase in temperature and deterioration of the winding insulation, which if unchecked, can result in transformer failure after a sustained period of time.

3. Flood – This category of causes are due to the flooding of substation transformers sites such that there is breakdown of the transformer. Onitsha is among vulnerable Nigerian Cities which are susceptible to perennial flooding [13].

Table 2. Transformer failure rate according to Injection Substations during 2011-2015

S/N	Injection Substations	No. of Transformer Units Installed	Failures	
			Frequency	Percentage
1.	Ugwunwanosike	717	97	18.5
2.	Army Barracks	574	125	23.8
3.	Atani	620	108	20.6
4.	GCM	659	119	22.7
5.	Awada I	673	37	7.1
6.	Awada II	624	15	2.9
7.	3-3	533	24	4.6
Total		4500	525	100

Table 3. Classification of failure causes, frequency and percentage during 2011-2015

Failure Cause	Failures	
	Frequency	Percentage
Moisture	16	3.1
Overloading	118	22.5
Flood	4	0.76
Poor workmanship/ Loose Connections	17	3.24
Overheating	6	1.14
Insulation Issues	127	24.2
Lightning surges	43	8.2
Line surges/External short circuit	74	14.1
Inadequate maintenance	86	16.4
Vandalism	14	2.7
Others	20	3.81
Total	525	100

Table 4. Transformer MVA Loadings (%) during 2011-2015

Injection Substation	Transformer Annual MVA Loadings (%)					Average MVA Loading (%)
	2011	2012	2013	2014	2015	
Ugwunwanosike	104.2	110.3	115.7	120.9	127.3	115.68
Army Barracks	137.5	138.2	140.4	145.7	149.8	142.32
Atani	125.6	127.4	130.3	138.1	141.6	132.6
GCM	130.9	133.5	136.8	140.4	144.1	137.14
Awada I	85	87.1	88.2	89.9	93.3	88.7
Awada II	23.5	25.7	28.9	34.6	39.5	30.44
3-3	56.1	58.2	60.1	66.4	70.2	62.2

4. Poor workmanship/ Loose connections – This category though somewhat similar to Inadequate Maintenance /Operation includes workmanship errors in making electrical connections, for instance, the improper use of dissimilar metals together or poor tightening of bolted connections. Ordinarily, loose connections should have been placed in the inadequate maintenance/operation category, but this study had chosen to report it alongside poor workmanship for purpose of emphasis.

5. Overheating -These are failure causes due to excessive heating of the transformer which increases transformer losses, weakens the insulation and finally results in reduced transformer life. Due to abnormal operation conditions such as excessive loads, transformer windings could become overheated resulting in sudden breakdown of the transformer unit.

6. Insulation Failures – These were the leading causes of failure as affirmed by this study. This category excludes those failures where there was evidence of a lightning or a line surge. There are actually four factors that are responsible for insulation deterioration: pyrolosis (heat), oxidation, acidity, and moisture. But moisture is reported separately. The average age of the transformers that failed due to insulation Issues was 18 years. In this study, insulation breakdown has been found to be the major cause of transformer failures in the Onitsha electricity distribution network followed closely by overload.

7. Lightning surges - are transformer failures due to surges arising from a lightning strike. It is normal to first confirm that there was a lightning strike before attributing such transformer failure to lightning surges.

8. Line surges/External short circuit - This category of faults includes switching surges, voltage spikes, line faults/flashovers, and other transmission and distribution (T&D) abnormalities resulting from poor surge protection or inadequate coil clamping and short circuit strength.

9. Inadequate Maintenance /Operation - This category of failure causes include accumulation of dirt, foreign matters and oil, disconnected or improperly set controls, corrosion and loss of coolant, which should have been promptly identified and corrected. Early detection and correction of abnormal conditions in and around electrical equipment often help to prevent eventual breakdowns and loss of finances [7].

10. Vandalism - These are failures due to carting away by vandals of vital parts of the transformer such as the oil, copper and aluminium, etc. Electrical Infrastructure vandalisation is a common occurrence among electricity distribution networks in Nigeria including the Onitsha distribution network.

11. Others –These are unclassified failure causes and includes all transformer failure causes that are not easily ascertainable.

The identified causes of the transformer failures in the Onitsha electricity distribution network during the period 2011-2015 have been expressed in terms of percentages in Figure 5.

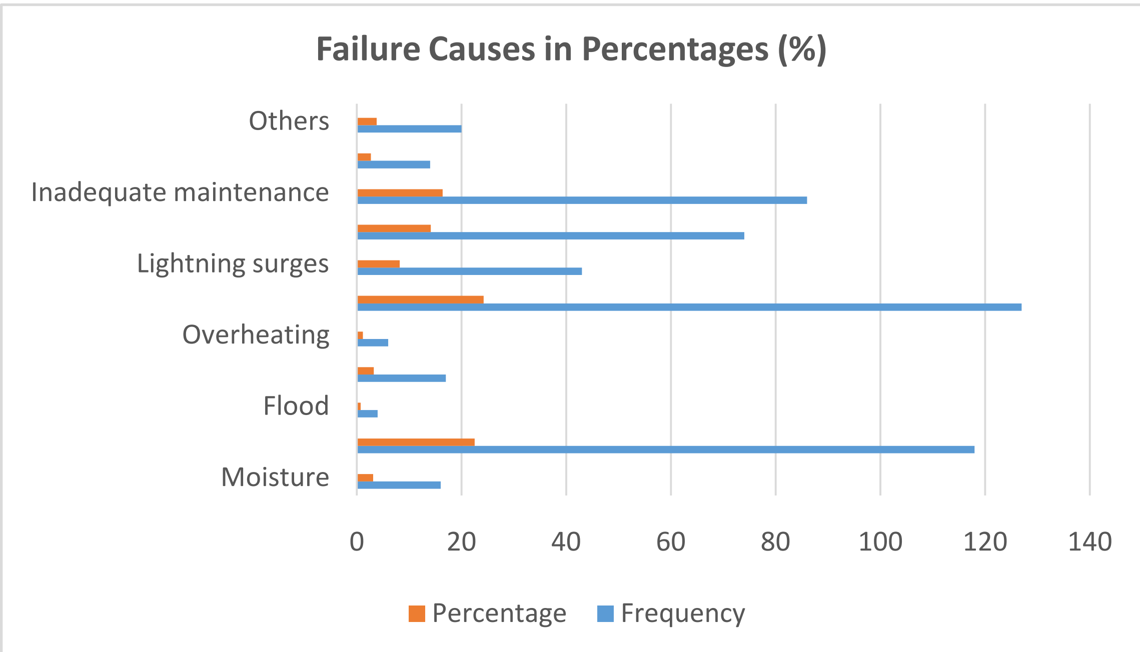

Figure 5. Classification of failure cause by percentage during 2011-2015

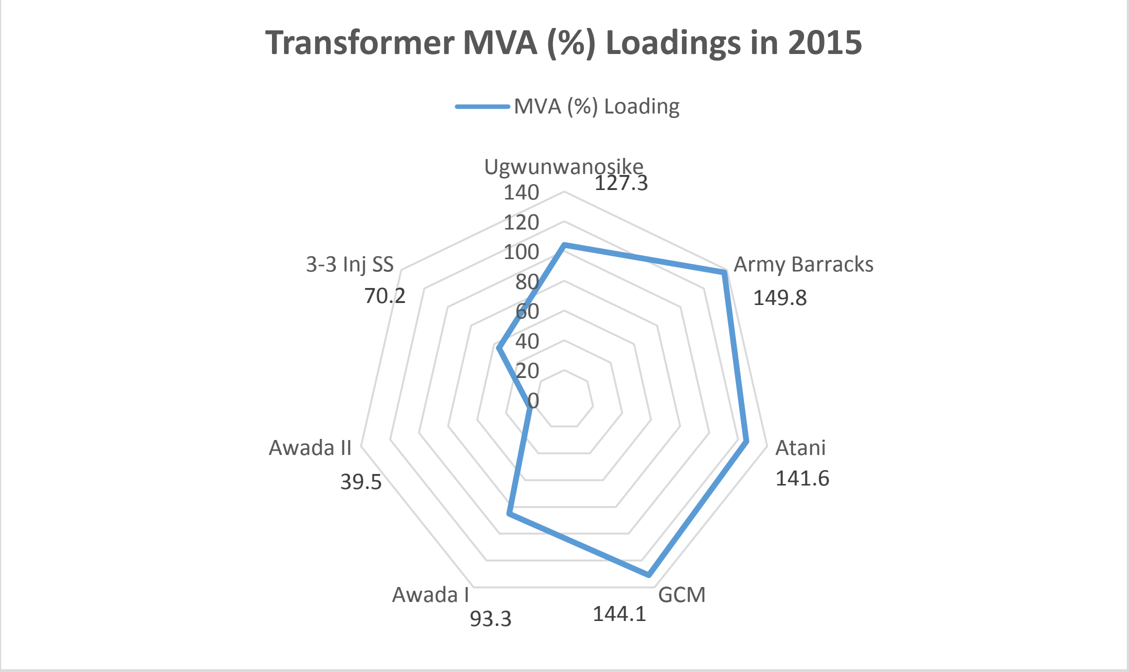

Figure 6. MVA Loading of transformers at the sampled Injection substations in Onitsha distribution network in 2015

The computed transformer MVA loadings in each of the injection substations studied during the period 2011-2015 are as presented in Table 4 while Figure 6 shows the loadings for the year 2015 only.

Observe that many of the transformers are loaded well above 100%. It is obvious also from Figure 6 that the loadings on the transformers increased steadily over the years as the power consumption increased leading eventually to the failure of the affected transformer units.

The findings of the study showed that during the period covered by the research, about 60% i.e. four out of the seven Injection substations in the distribution network had various transformer units loaded beyond the nameplate ratings.

It is obvious that this high percentage of overloaded transformers contributed significantly to the rapid deterioration of the transformers insulating materials and therefore the high rate of transformer failures as recorded in the study.

4. Conclusion and Recommendations

This study investigated transformer failure rates and failure causes in the Onitsha Electricity Distribution Network using both the Electrical Transient Analysis Program (ETAP) software 12.6 and the Statistical Package for the Social Sciences (SPSS) software 16.0. Network data and transformer parameters collected over the period 2011-2015 from substations within the distribution network were simulated on the ETAP software using the Newton-Raphson (N-R) technique to ascertain the transformer loadings while responses to the research questionnaire were statistically analysed on the SPSS software to determine the causes and rate of transformer failures. The findings of the study show that during the five years period of study, injection substations in the Onitsha Electricity Distribution Network recorded an average failure rate of 11.7 % among the installed and operational transformers. The study revealed also that besides Insulation Issues (24.2%), Overloading (22.5%) is the next major cause of transformer failures in the Onitsha Electricity Distribution Network. The study found also that the Army Barracks Injection Substation recorded the highest transformer failure rate of 23.8%. This is followed by GCM and Atani Injection substations with 22.7% and 20.6% failure rates respectively. It is obvious from the responses to the structured questionnaire by the technical staff of the distribution company that these high failure rates were due to inadequate number of transformers which necessitated the overloading of the available units. The study therefore recommends installation of additional transformer units in order to reduce the loads on the existing transformer units within the area. The study also suggests strict statutory legislation against vandalism, good workmanship, balanced loading of the transformers, use of quality transformers as well as proactive monitoring, inspection and maintenance program of the transformers within the network in order to ensure improvement in transformer life span and increased availability of electricity supply. The outcome of this work would help electricity utilities in providing more reliable and cost effective services to customers.

Statement of Competing Interests

The authors declare that no conflicting interests exist.

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