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(Research Article)

Expert system for improving and controlling insulation system of service transformers using fuzzy logic controller

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Abstract

Implementation of the smart transformer concept is critical for the deployment of IOT-based smart grids. Top manufacturers of power electrics develop and adopt online monitoring systems. Such systems become part of high-voltage grid and unit transformers. However, furnace transformers are a broad category that this change does not affect yet. At the same time, adoption of diagnostic systems for furnace transformers is relevant because they are a heavy-duty application with no redundancy. Creating any such system requires a well-founded mathematical analysis of the facility's condition, carefully selected diagnostic parameters, and set points thereof, which serve as the condition categories. The goal hereof was to create an expert system to detect insulation breach and its expansion as well as to evaluate the risk it poses to the system; the core mechanism is mathematical processing of trends in partial discharge (PD). This research work examined the acidity of distribution transformer oil in service through laboratory tests using a case study of installed distribution transformers at Abuja metropolis network comprising ten Feeders. The result shows the minimum breakdown voltage of 40KV/mm and maximum breakdown voltage of 58KV/mm. The maximum transformer oil Acidity is 0.1143mgKOH/g and the minimum transformer oil Acidity level is 0.0954mgKOH/g. The transformer efficiency without fuzzy is 82.89% and transformer efficiency with fuzzy controller is 98.10%.

Keywords: Transformer Oil Acidicity; Fuzzy Controller; Breakdown Voltage

1. Introduction

The power transformer is one of the most essential components of a power system network that must be properly and highly effective in terms of its efficiency and also steady in its reliability in operation at all times. As it plays a major role in voltage level transformation in power networks, its workability, efficiency, and safety depends not solely on external protective devices or components but rather it depends more on itself insulation system design [1].

Insulation system design in service transformers is a sacrosanct factor for determining the reliability and size of transformers; hence the quality of the insulation system within the transformer reflects the health status of the asset. The service transformer insulation system can be categorized into two; i.e. the Major insulation and the Minor insulation respectively. The major insulation consists of the insulation between the windings, between windings and the limb/yoke, and also the insulation between the high voltage leads and the ground. While minor insulation system includes external insulation within the windings that is the inter-turn and the inter-disk insulation. The end insulation design of a transformer is one of the factors deciding the window height of transformers; hence optimization of the insulation will permit a reduction in the clearances to the core and thus reducing the amount of steel and transformer oil [2,3]

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The objective of the course is to improve the insulation system strength of the service transformers, an important assessment index in-service transformers of the insulation properties, the planning, construction, and maintenance (PC&M) unit of the power distribution companies (DISCOs) measures the insulation levels and properties of the service transformers for some electrical and chemical parameters measured from the transformers to evaluate their state of health (SOH) [4,5].

Researcher [6] notes that high-voltage equipment is a special category of complex equipment subject to continuous diagnosis. In that category, it is power transformers that require most attention and regular checkups. The reason is that they are critical for uninterrupted electricity delivery to consumers [7]. Researcher [8] states that power transformers are significant and valuable units, and that this is why condition monitoring is crucial in their case. Should a critical transformer fail in a transmission grid, energy security might be jeopardized. Unscheduled shutdown of a furnace transformer disrupts the process cycle of the steelworks facility. Such disruption will result in undersupply and multimillion losses. Worse than that, furnace transformers have no redundancy, unlike their grid or unit counterparts. The service life of a power transformer depends on the condition of its insulation, which is degraded by loads of various physical natures. These include thermal, electrical, mechanical, and environmental loads [9]. The adoption of smart grid technologies [10,11] and the advancement of IoT-based smart grids [12] have brought attention to the condition monitoring of power transformers.

This study proposes an algorithm to measure and evaluate the insulation level of service transformers using Fuzzy Logic (FL). The study will formulate a training-set from data obtained from real and historical data collated from Abuja Electricity Distribution Company (AED) covering some part of Abuja metropolis on their service transformers, some of the data will be reserved for validation while simulation will be done using Fuzzy Logic (FL) tools available in the MATLAB optimization software.

2. Materials and Method

This research work examined the acidity of distribution transformer oil in service through laboratory tests using a case study of installed distribution transformers at Abuja metropolis network comprising ten Feeders. The study covers part of the commercial place in the city where regular and continuous supply of electricity is desired.

Prior testing of distribution transformer insulation oil, a detailed sampling was carried out on installed distribution transformers at Abuja metropolis distribution network to arrive at the selected transformers. Samples were not taken from energized transformers. The transformers have no external sampling valve, hence, the units were first de-energized and the samples were taken internally. The adopted method of obtaining liquid samples follows ASTM D 923 standard. Oil samples were taken from the bottom of the transformers, since less-flammable liquid samples were the ones recommended to be taken from the top. The samples were allowed to stand in tightly sealed containers for 24 hours prior testing. Five oil samples each from ten distribution transformers making a total of fifty samples were taken from different installed distribution transformers all from the Abuja metropolis distribution network, cross-rivers state. The acid neutralization number is a measure of the amount of acid materials present in the oil. As the transformer ages, the oil will oxidize and increase in acidity. An automatic potentiometric titration system Titrino SM 702 was used to measure the acidity of the oil samples. The system involves determination of the Total Acid Number TAN by a volumetric titration with potash to neutralize the carboxylic acids. Ten gramme (10 g) of the oil sample were dissolved in 40 ml of solvent ethanol in a ratio of 5 to 4. Then 0.1mol/litre of Potasium hydroxide (KOH) was added as titre with volume increments of 0.001 ml. The system detects, when the acid-base equivalence-point EP is reached by a voltage measurement in the solution. The acidity test for each sample was carried out four times and the average total acid number recorded. From the volume of potassium hydroxide at the equivalence point for each experimental run, the total acid number was calculated from equation (1):

$$T_A = \frac{(E_X - C_Y)N_{KOH}M_{KOH}}{W} \quad \text{………………….. (1)}$$

T_A is the total acid number, E_x is the equivalent point, C_y is the blind value of solvent ethanol.

N_{KOH} is the concentration of the titre (mol/L), M_{KOH} is the molar mass of titre =56,106g/mol and W is the weight of the oil sample.

Test Methods by the American Society for Testing of Materials (ASTM) provides that the acidity of oil in a transformer should never be allowed to exceed 0.2mg KOH/g oil. This is the Critical Acid Number and deterioration increases rapidly once this level is exceeded.

2.1. Transformer Design Model

$$V_t = C\sqrt{KVA} \quad \text{.....................} (2)$$

Where V_t is volts per turn and C is 0.45 for core type transformer

$$V_t = 4.44 f\Phi = 4.44 fB_m A_i \quad \text{.....................} (3)$$

A_i is core area

Coil length =1.015 x (turns/layer+1) x (covered width of each turn) .... (4)

Leg length, L= (length of HV. Winding)+(total end clearance) .... (5)

Centre, C=(O/D of H.V winding) + (total end clearance) .... (6)

[O/D]=external diameter]

Weight of legs = $3LA_i 7.55 x 10^{-3}$kg .... (7)

Weight of yoke= 4x(C – width of max. punching) x A_i x $7.55x10^{-3}$kg .... (8)

Weight of corners = 6.18 x (width of max. punching) x A_i x $7.55x10^{-3}$kg..................... (9)

Where L is the leg length in cm, C is the core centres in cm and A_i is the net core area in cm^2.

The total iron loss= (wt. of legs and yoke above window in kg) x (watt loss per kg along rolling direction) + (wt. of corners in kg)x(watt loss per kg across rolling direction).

$$\text{Percentage impedance (\%R)} = \frac{I_1 R_{equivalent}}{V_1} \times 100 \quad \text{.....................} (10)$$

$$(\%R) = \frac{I_1^{\,2} R_{equivalent}}{V_1 \times I_1} \times 100 = \frac{Total\ load\ loss}{KVA\ x\ 10} \quad \text{.....................} (11)$$

$$\text{Hence } \%Z = \sqrt{(\%R)^2 + (\%X_1)^2} \quad \text{.....................} (12)$$

Transformer efficiency at power factor $Cos\phi$ and load x(KVA) can be determine by:

$$\eta = \frac{Output}{Input} \quad \text{.....................} (13)$$

$$\eta = \frac{Output}{Input + Losses} \quad \text{.....................} (14)$$

$$\eta = \frac{x(KVA)\cos\phi}{x(KVA)\cos\phi + ironloss + x^2(loadlossorfullload)} \quad \text{.....................} (15)$$

Where
KVA = total KVA rating of the transformer
x = fraction of full load KVA at which efficiency is calculated.

For maximum efficiency

$$\text{Iron loss} = x^2 \text{ (load loss on full load)} \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Thus, maximum efficiency occurs at x(full load KVA), where x is found from the relation $x = \sqrt{\frac{iron\ Loss}{Load\ loss\ on\ full\ load}}$ ………………… (17)

Oil calculations of the transformer can be calculated below

$$oil\ in\ tank = \frac{(Lenght\ in\ cm)(Width\ in\ cm)(Height\ in\ cm)}{1000}\ litres \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

3. Result and Discussion

The rules state that if the Breakdown voltage less than 30KV/mm the condition is poor, if the breakdown voltage is between 30KV/mm to 40KV/mm the condition is fair and if breakdown voltage greater than 40KV/mm the condition is good. Also, if Acidity is between 0 to 0.1 the condition of acidity is good, if Acidity is between 0.11 to 0.2mg the condition is fair and if Acidity is greater than 0.2mg the condition is poor. If the temperature is 25^0C the condition is good, if Temperature is between 30^0C to 40^0C the condition is fair and if Temperature greater than 40^0C then the condition is poor. The stability of oil level indicates the transformer insulation output condition. The breakdown of insulating material is mainly affected by the maximum value of the voltage waveform. The fuzzy logic controller was applied for the improvement of transformer health condition. There are three inputs which are Breakdown Voltage(BDV), oil acidity and Temperature with one output which indicate the stability level of transformer insulation.

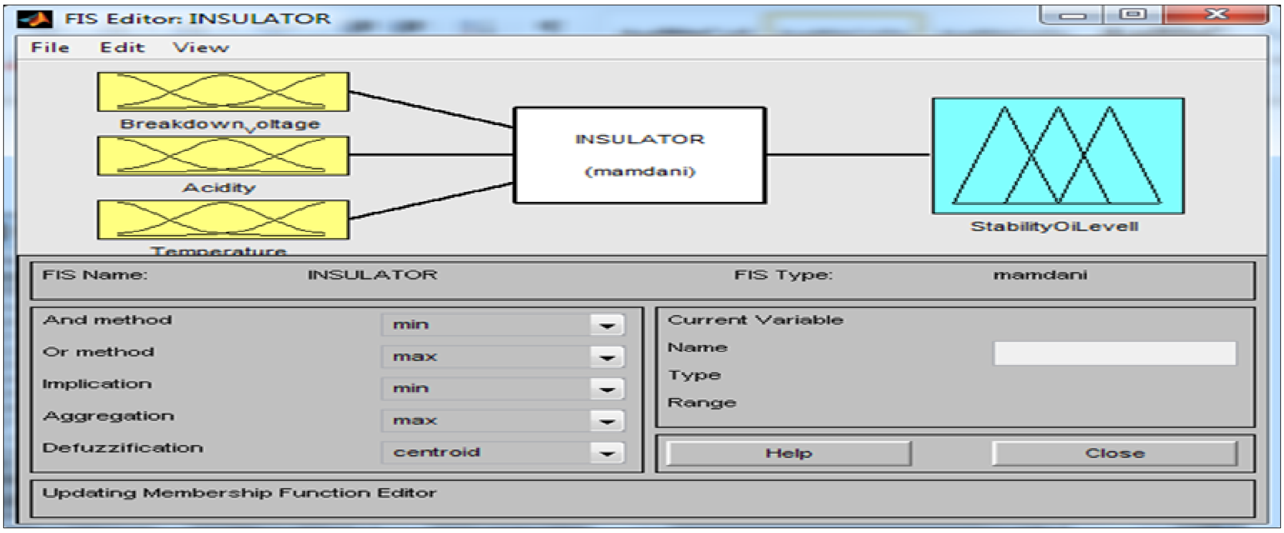

Figure 1 Fuzzy controller of transformer oil

The figure 1 shows the three input which are: Breakdown Voltage, Oil Acidity and Temperature. Also the stability in oil level which shows output of the system. The rules are program in oil dialogue box which shows the controller of the system.

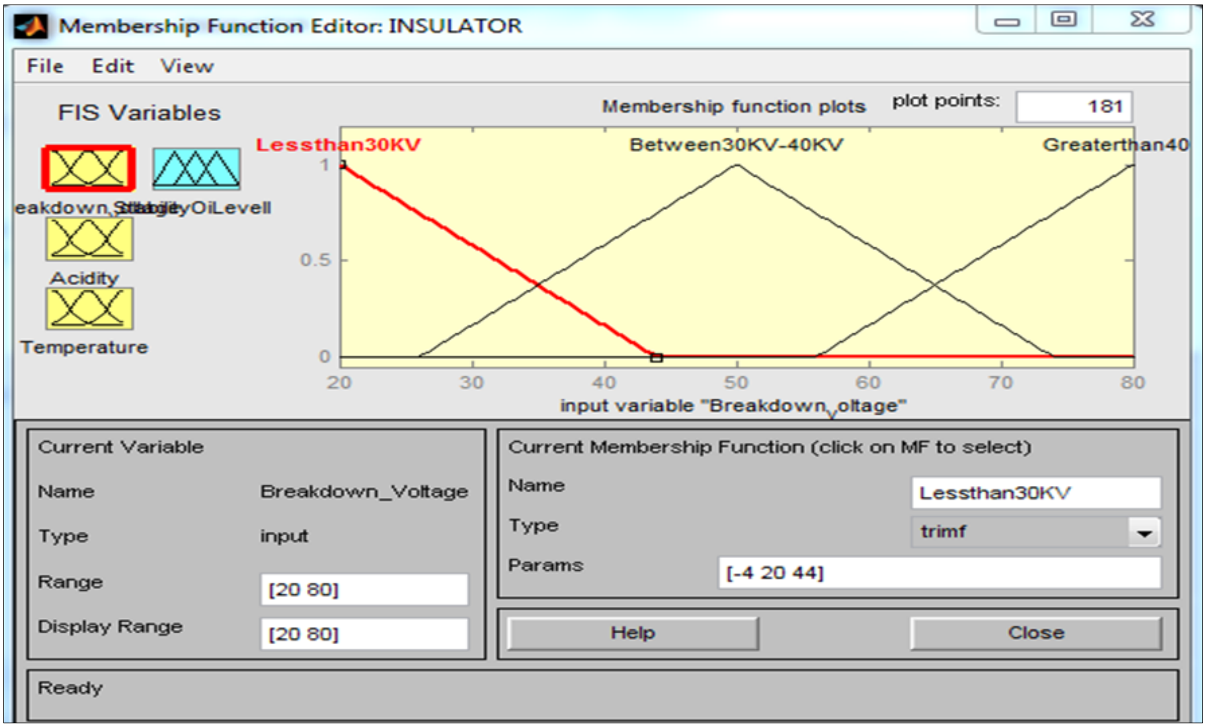

Figure 2 Membership function of transformer insulation

The result in figure 2 shows the membership function of insulation Breakdown voltage. This insinuate that if Breakdown voltage less than 30KV/mm the condition is poor, if Breakdown voltage falls between 30-40KV/mm the condition is fairly good and if Breakdown voltage greater than 40KV/mm the condition is good.

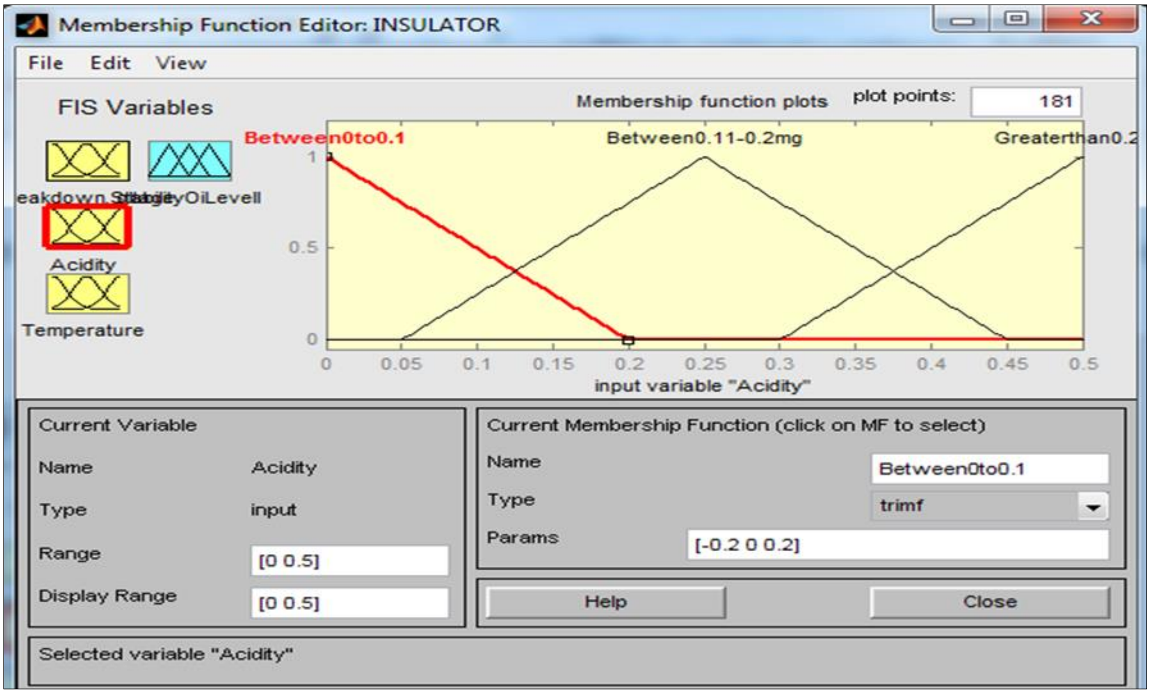

Figure 3 Membership function of oil Acidity of transformer

The result in figure 3 shows that if oil Acidity greater than 0.2mg the condition is poor, if oil Acidity falls between 0.11 to 0.2mg the condition is fairly good and if oil Acidity falls between 0 to 0.1 the condition is good.

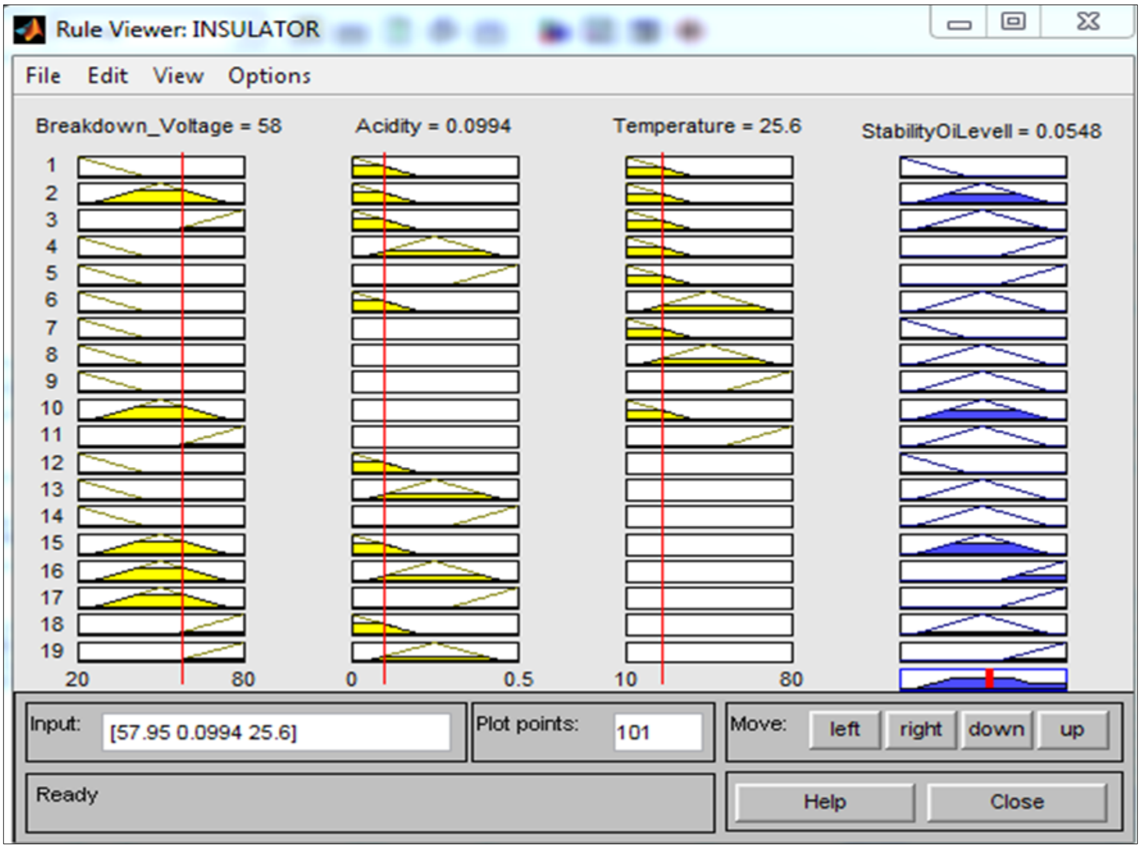

Figure 4 Transformer insulator Rule Viewer

The figure4 shows the three inputs which are breakdown voltage, Acidity and Temperature with output which is stability Oil level. The result shows that when breakdown voltage is 58KV/mm, oil acidity is 0.0994mg and Temperature is 25.6^{0}C then the stability oil level 0.0548mg. Therefore the rule shows the stability of insulation system of the transformer.

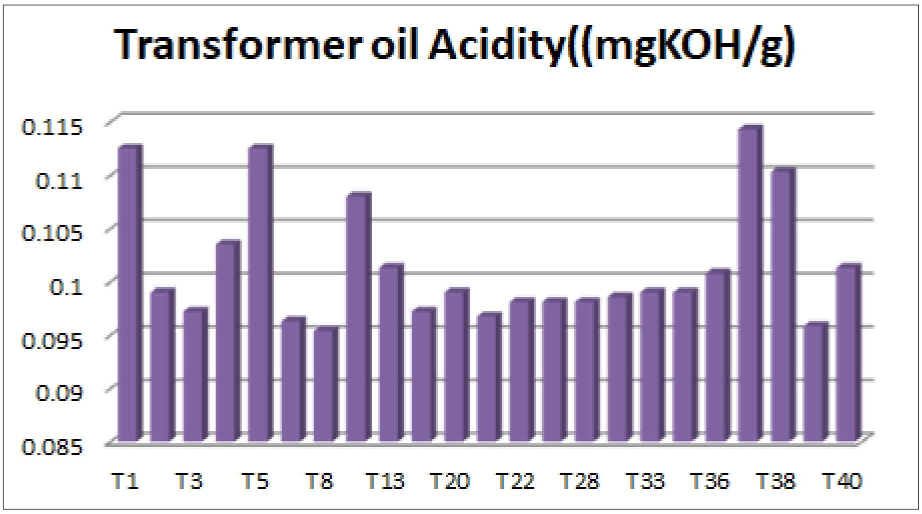

Figure 5 Corrected Transformer oil Acidity Level with Fuzzy logic

The figure 5 shows the corrected transformer oil acidity level when fuzzy logic controller is incorporated. The results correct the fail transformer due to oil acidity level and also stabilize the level of oil. The corrected transformers are T1, T2, T3, T4, T5, T7, T8, T9, T13, T14, T20, T21, T22, T25, T28, T30, T33, T34, T36, T37, T38, T39, T40 and oil acidity level are 0.1125, 0.099, 0.0972, 0.1035, 0.1125, 0.0963, 0.0954, 0.108, 0.1013, 0.0972, 0.099, 0.09675, 0.0981, 0.0981, 0.0981, 0.09856, 0.099, 0.099, 0.1008, 0.1143, 0.1103, 0.09585, 0.1013 respectively. According to Test Methods by the American Society for Testing of Materials (ASTM) provides that the acidity of oil in a transformer should never be allowed to exceed 0.2mg KOH/g oil. Therefore from the result achieved, it was shows that the acidity level of transformer did not exceed 0.2mgKOH/g.

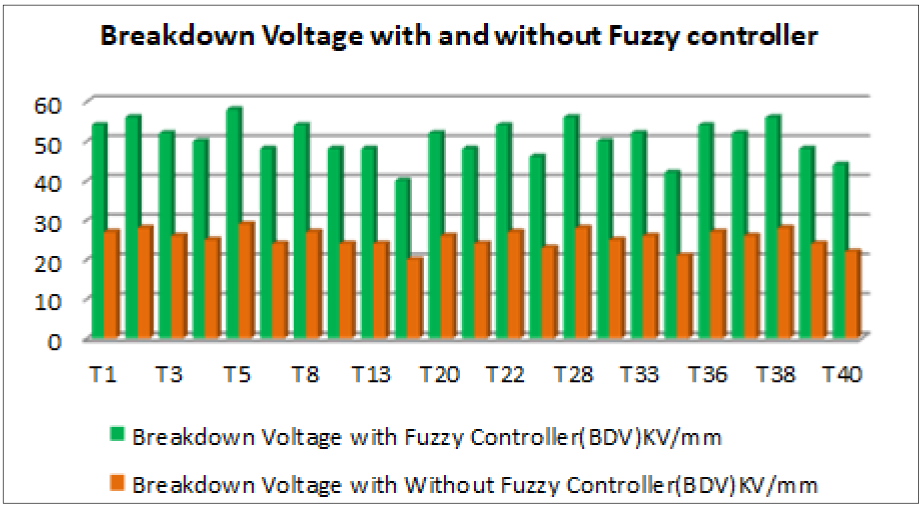

Figure 6 Comparison of Insulation Breakdown voltage with and without fuzzy controller

The figure 6 shows the insulation Breakdown voltage without fuzzy and with fuzzy controller. The Breakdown voltage without fuzzy are 27, 28, 26, 25, 29, 24, 27, 24, 24, 20, 26, 24, 27, 23, 28, 25, 26, 21, 27, 26, 28, 24, 22kV and Breakdown with fuzzy are 54, 56, 52, 50, 58, 48, 54, 48, 48, 40, 52, 48, 54, 46, 56, 50, 52, 42, 54, 52, 56, 48, 44kV respectively. The type C transformer was used in this research work. According to the standard IEC 60422. The Breakdown voltage of type C transformer is good when is greater than 30KV/mm. The result shows that the minimum Breakdown voltage with fuzzy logic is 40KV/mm and maximum Breakdown voltage with fuzzy logic is 56KV/mm

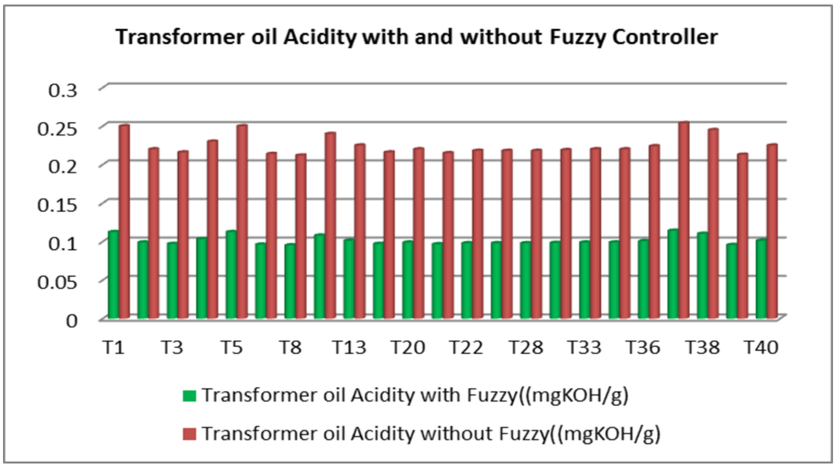

Figure 7 The transformer oil Acidity with and without fuzzy controller

The figure 7 shows that the transformer oil Acidity without fuzzy are 0.25, 0.22, 0.216, 0.23, 0.25, 0.214, 0.212, 0.24, 0.225, 0.216, 0.22, 0.215, 0.218, 0.218, 0.218, 0.219, 0.22, 0.22, 0.224, 0.254, 0.245, 0.213, 0.225 and transformer oil Acidity with fuzzy are 0.1125, 0.099, 0.0972, 0.1035, 0.1125, 0.0963, 0.954, 0.108, 0.1013, 0.0972, 0.099, 0.09675, 0.0981, 0.0981, 0.0981, 0.09856, 0.099, 0.099, 0.1008, 0.1143, 0.1103, 0.09585, 0.1013 respectively. The maximum transformer oil Acidity is 0.104mgKOH/g and the minimum transformer oil Acidity level is 0.0945mgKOH/g.

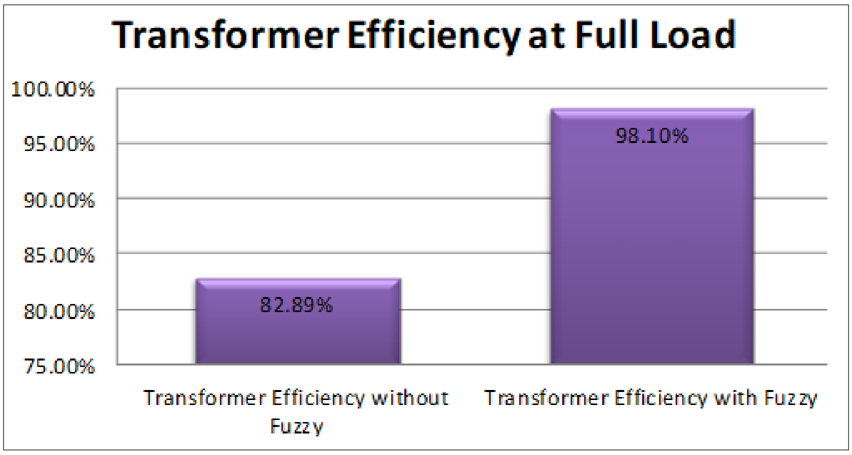

Figure 8 Transformer Efficiency at full Load

The figure 8 shows the efficiency of transformer without fuzzy controller and with fuzzy controller. The transformer efficiency without fuzzy is 82.89% and transformer efficiency with fuzzy controller is 98.10%. The result shows that the fuzzy controller gives better performance of transformer insulation compare to transformer insulation without fuzzy controller. Therefore, the transformer health is improved and stabilizes at full load.

4. Conclusion

The research work analyzes forty transformer sample of Abuja metropolis. The result shows that seventeen test samples of transformer insulating oil passed acidity test and twenty three test samples of transformer insulating oil fail acidity test. This indicates that the transformer insulating oil from distribution transformers T1, T2, T3, T4, T5, T7, T8, T9, T13, T14, T20, T21, T22, T25, T28, T30, T33, T34, T36, T37, T38, T39 and T40 are in failed condition, which implies that oxidation leading to acidity of the oil has commenced in the transformers. The samples failed acidity test. This shows that contaminants, like sludge, were present in the oil from these transformers and reconditioning or replacement of the insulating oil is necessary for these sets of transformers. Therefore, the condition of oil in service, even, the new one should be checked regularly so that it will not result to transformer breakdown. The presence of acidic content beyond the prescribed minimum value in the transformer oil can lead to internal conduction, resulting to excessive heat and hence eventual explosion or fire outbreak in the transformer. Hence, the fuzzy logic controller is applied for control of oil acidity of transformer, Breakdown voltage and temperature. The poor transformer was simulated with 27 rules basically 3 input and 3 membership function each, in order to stabilizes the oil acidity of transformer below 0.2 mg IEC benchmark. The breakdown voltage was also stabilizes greater than 30KV/mm IEC benchmark. The result shows the minimum breakdown voltage of 40KV/mm and maximum breakdown voltage of 58KV/mm. The maximum transformer oil Acidity is 0.1143 mgKOH/g and the minimum transformer oil Acidity level is 0.0954 mgKOH/g. There is need for periodic tests on transformer insulating oil if a quality and continuous service are to be maintained.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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