Development of a Hybridized Model for Determining the Degree of Polymerization of Power Transformers

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Abstract

Power transformers have been described as an important equipment of electrical switchyard in which its failure results in long hours of outage. Some of the existing models for determining the Degree of Polymerization (DP) of power transformers were based on singular parameter which is not sufficient for the assessment of power transformers' lifespan. This research paper therefore developed a hybridized model for determining the degree of polymerization of power transformers. The study employed the use 2-Furaldehyde (2FAL) content values of 0.5 ppm to 10ppm in determining the DP value and simulation was carried out using MATLAB. The result was compared with existing DP model for effectiveness of the Hybridized DP model. The developed model yielded a DP range of $247 \leq DP \leq 1184$ based on a constant hotspot temperature of 110^0C and the values of activation energy and pre-exponential factors used. The results from this research presented a better method of determining the Degree of Polymerization of power transformer compared to the existing method. Therefore, the Hybridized DP model developed is more sufficient for the evaluation of lifespan of power transformers.

Keywords: Power Transformers, Electrical Switchyard, Lifespan, Degree of Polymerization, Statistical Tools, Power Failure, Outages.
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I. Introduction

Generation of electrical power is usually at low voltage level due to the cost effectiveness associated with generating at low voltages. This low voltage level power can be transmitted to the receiving end. If the transmission voltage level is low, the current is high which causes high power losses. When the voltage is stepped up, the current of the power system is reduced which causes reduction in power losses in the system, reduction in cross sectional area of the conductor, reduction in capital cost of the system and improvement in the voltage regulation of the system [2]. As a result, low level power must be stepped up for efficient electrical power transmission. This is done by step-up power transformer at the sending end of the power system network. As this high voltage power may not be distributed to the consumers directly, this must be stepped down to the desired level at the receiving end with the help of a step-down power transformer [1, 2, 11].

[17] described power transformer as comprising all transformers of large size (250 kVA and above) used in generating stations and transmission substations for transforming the voltage at each end of a power transmission line. They are used in distribution systems wherever there is the need to interface between different voltage levels i.e. to step up and step down voltages. They also defined distribution transformer as a transformer that provides the final voltage transformation in the electric power distribution system, stepping down the voltage used in the distribution lines to the level used by the customer. Power transformers generally operate at full load. Hence, it is designed such that copper losses are minimal. However, a distribution transformer is always online and operated at loads lesser than full load. Hence, it is designed such that core losses are minimal [4, 8].

Transformers with power ratings above 10 MVA are key elements in the supply of large regions or industrial areas. Such transformers have to comply with specific requirements on safety and reliability and also have to provide a very high efficiency and low sound level [16]. When the transmitted power is about 10 MVA, special designs are required to cope with the mechanical forces of short circuit currents, higher insulation levels, increased temperature and its attendant cooling requirements, etc. Hence, liquid-filled transformers are usually employed. The insulation between the windings also becomes more and more demanding at higher voltages in addition to the resonance effects inside the winding itself which have to be considered to avoid insulation failures during highly dynamic impulse stresses such as lightning strikes which may reach amplitudes of one to two thousands kilovolt with a 1μs rise time [4, 6].

The process of the transformer operation causes gradual deterioration of the transformer. Most transformers are designed to accommodate load growth [19]. Components which experience deterioration mostly include the insulation system dielectric properties, the transformer windings, among others. While deterioration may lead to the eventual failure of the transformer, the detection of the initial failure may prevent further development of the total transformer failure. Qualitative documentation of the technological production process and available knowledge of lifetime and degradation processes are of great importance in terms of the device lifetime. During the pre-production technological process therefore, accelerated lifetime tests are used. The aim of the accelerated lifetime tests is to determine the lifetime of a selected group of materials, components, products or equipment at the given significance level in a technically feasible time interval [1, 4].

In typical use, transformers last more than 20 to 30 years with a transformer life expectancy generally related to its average operating temperature (which is proportional to its average loading conditions). Most transformer designs operate at 150 ºC temperature rise upon fully loaded conditions, but do not operate at fully loaded conditions continuously. Given light loads, most transformers never operate at maximum design conditions and, in reality, run much cooler than conditions for which they were designed. Consequently, life expectancies can increase many times and most transformers last much longer than 40 years [19, 20].

In the case of transformers, the accelerated lifetime tests with respect to their financial demands are mainly carried out before the introduction of a new insulation system of transformer. The accelerated lifetime tests are not often performed after partial changes in the transformer insulation system [4, 20]. However, the interaction between the newly used insulation materials may be significant, especially in oil-filled transformers and similar devices. Influence of the different materials of the insulation system can theoretically have positive or negative effect in terms of lifetime. Due to the diffusion processes in the insulation systems containing electro-insulating oils and various insulation materials, more significant degradation may occur than in the dry insulation systems. Intercourse of a material not yet used and tested with oil may activate a significant degradation process [3, 7].

The life span of any transformer depends upon the Degree of Polymerization (DP) and on the fault conditions it encounters in its life time. However, established statistical tools and reliability theories have been insufficiently used to determine the Degree of Polymerization and estimate the overall life cycle of power transformers because the standard real time working condition of one or more parameters may have been compromised [7]. Hence, the use of the engineering tools to determine the DP and estimate overall life span of power transformer is a very difficult task. This is largely due to the complex nature of the equipment [9].

It is therefore important to break down the complete transformer unit into major individual components and consider the parameters affecting them separately. However, the use of models considering singular parameters may not be sufficiently effective in solving this problem. While several works have considered some of the singular factors that affect the ageing of the transformer such as (temperature, loading, insulation etc) separately, not much have been done to hybridize some of the results [1]. This forms the basis of this research paper.

A. Transformer Rating and Classifications

Transformer rating is based on life expectancy, which in turn is based on insulation loss of life. It is also based on "usual" service conditions, as prescribed by standards. Most times, transformers are rated based on the power output they are capable of delivering continuously at a specified rated voltage and frequency under "usual" operating conditions without exceeding prescribed internal temperature limits. The internal temperature becomes very important because it determines to a large extent the lifespan of the transformer [11, 18].

[15] described deterioration of insulation as a time function of temperature. He further described natural ageing or deterioration of insulation as a time function of temperature, moisture content and oxygen content. Hence insulation used in transformers is based on how long it can be expected to last by limiting operating temperatures. The temperature that insulation is allowed to attain under standard operating conditions determines the output rating of the transformer, otherwise referred to as the kVA rating. Standardization has led to temperatures within a transformer being expressed in terms of the rise above ambient temperature, since the ambient temperature can vary under operating or test conditions. Transformers are designed to limit the temperature based on the desired load, including the average temperature rise of a winding, the hottest spot temperature rise of a winding, and, in the case of liquid-filled units, the top liquid temperature rise [14, 17].

The normal life expectancy of power transformers is generally assumed to be about 30 years of service when operated within their ratings [18]. However, they may be operated beyond their ratings, overloaded under certain conditions with moderately predictable "loss of life". Situations that may involve operation beyond rating are emergency re-routing of load or through-faults prior to clearing. When transformers are operated beyond their normal rating, it could lessen the lifespan or life expectancy of the transformer. On the other hand, effective usage on the transformer below the rating may attract more life. Based on some standards, the kVA rating may refer to the power that can be input to a transformer, the rated output being equal to the input minus the transformer losses [5, 11, 16, 19].

B. Functions of a Power Transformer

The purpose of a power transformer is to transfer power efficiently and instantaneously from an external electrical source to an external load. In doing so, the transformer also provides important additional capabilities [16, 18, 20]:

i. The primary to secondary turns' ratio can be established to efficiently accommodate widely different input/output voltage levels.
ii. Multiple secondary terminals with different number of turns can be used to achieve multiple outputs at

different voltage levels.

iii. Separate primary and secondary windings facilitate high voltage input/output isolation, especially important for safety in off-line applications.

C.Furanics

Furaldehydes (Furans) are chemicals formed when cellulose paper degrade due to overheating. They are the major degradation product of insulating paper in transformer oil. Hence their concentration in oil can be used as a good indicator of paper deterioration [1]. The status of solid insulation can be measured using liquid oil insulation. This is an alternative method for estimating the Degree of Polymerisation (DP) value of the paper insulation. Furans are one of the most important age-related by-products of cellulose paper ageing. It has been shown by ageing experiments that no furan is produced in a blank oil sample (i.e. oil with no paper insulation). When a cellulose chain breaks down during paper ageing, the chain liberates a glucose monomer, which undergoes a further chemical reaction to form furanic compounds. Therefore, furan concentration is directly related to insulation paper degradation [2, 5].

Furans are rapidly produced during paper pyrolysis at very high temperatures. At typical transformer operating temperatures, the primary mechanism of furan formation is paper hydrolysis. Studies by [5] have shown that Furanic compounds are generated if the cellulose is subjected to electrical discharges, but in very small quantities. During thermal ageing, large quantities of Furanic compounds can be generated when cellulosic materials are exposed to very high temperatures (typically above 120°C). Once formed, the Furanic compounds can still survive for prolonged periods of time in bulk oil, which is at a much lower temperature than the hottest spot in the insulation (winding) [7].

Five main Furanic compounds have been identified in transformer insulating oil, namely 2-Furaldehyde (2FAL), 2-Acetylfuran (2ACF), 5-Methyl-2-Furaldehyde (5MEF), 2-Furfuryl alcohol or 2-Furfurol (2FOL) and 5-hydroxymethyl-2-furaldehyde (5HMF) [7]. However, the stability of the Furanic compounds is very essential. Compounds which are not stable for a long period of time will lead to inaccurate conclusion drawn from the analysis. Some of the above mentioned Furanic compounds are formed during ageing but are very unstable under a number of conditions. These, therefore, cannot be used or are not useful for diagnostics [1. 5, 12, 15].

D.The Degree of Polymerisation (DP) of oil

The solid insulation in a transformer is cellulose based, consisting of long chains of glucose rings. When degradation of the cellulose occurs these chains get shorter. The Degree of polymerization (DP) is the average number of these rings in the chain and indicates the condition of the paper [9]. The Degree of Polymerization (DP) is a test done on the paper to reveal its mechanical strength. According to [9], new paper has an average DP value of 1200-1400. A DP less than 200 means that the paper has reached a poor mechanical strength that it can no longer fulfilled its function.

An inverse relationship exists between the DP (paper test) and the Furans (oil test); the higher the Furans in the oil, the lower the DP of the cellulose paper. This relationship holds however, only when paper or oil is degrading evenly. The DP of the paper usually varies with the solid insulation. Furan analysis in the insulating oil can indirectly reveal the status of the solid insulation. During ageing, some by-products are formed. These get dissolved in oil and hence the oil can therefore be analyzed for furan content [7, 12, 16].

In addition, the removal of paper from a transformer is extremely difficult, especially if the transformer is still expected to continue in service and may lead to the failure of the unit if not done with appropriate skill [12]. The ability to estimate the condition of the paper without exposing the transformer to such a risk is therefore desirable. It has been found that indirect testing can be done by analyzing the oil for the concentration of the Furanic compounds, which are formed during the ageing process. After their formation during the ageing process, the Furanic compounds migrate from the paper into the oil and hence by analyzing the oil, the DP value can be estimated [7].

Although the measurement of Furanic compounds from an oil sample is relatively simple, the interpretation is complex and more than one mechanism is involved in the ageing process. At low temperatures, moisture and carbon-oxide gasses are the more dominant products of the ageing process. The Furanic compounds are dominant at intermediate temperatures and are unstable at high temperatures [12, 16, 19]

Mathematical models have been developed for the observed relationship between the DP value and the Furanic compound (2FAL) concentration. The Arrhenius transformer loss of life model by [13] is well known. It is based on the concept that temperature is the only ageing parameter. According to this model, transformer ageing is dictated by the ageing of the most thermally stressed location i.e. the hottest spot usually referred to as just the hot spot as shown in equation (1).

$$LoL\% = 100 \times \Delta t \times 10^{-\left[A + \frac{B}{\phi + 273}\right]} \tag{1}$$

Where:

LoL% = Loss of life

A, B = ANSI standard parameters

Φ = Hot spot temperature in degrees Celsius
Δt = Transformer operating time in hours, with hot spot temperature of Φ

The DP value can be calculated as a function of the amount of CO, CO_2 and furfurals in the oil. According to [16], the elapsed life in years is:

$$ElapsedLife = 20.5 \times \ln\left(\frac{1100}{DPValue}\right) \tag{2}$$

Where it has been assumed that unaged transformer cellulose insulation has a DP value of about 1100.

E. Loading Transformers beyond Nameplate Rating

Power Transformers may be overloaded unintentionally or intentionally by the utility providers beyond their nameplate ratings. This may occur when the load demand has surpassed the transformer capacity and additional capacity is needed. It can also be to accommodate emergency or contingency conditions. The operation of transformers usually fit into one of the following categories [6, 9, 11, 13]

i. Normal life expectancy loading – Here, the transformer is operated at constant 30^0C ambient condition while the continuous hotspot conductor temperature of 110^0C is maintained.
ii. Planned loading beyond nameplate – This results in the conductor hottest-spot or top-oil temperature exceeding the limits of the normal life expectancy. The hottest spot temperature in the range 120^0C – 130^0C is usually associated with this loading requirement.
iii. Long Time Emergency Loading – This results from the prolonged outage of a system component which causes transformer loading that results in hottest spot conductors' temperatures in the range of 120^0C – 140^0C. This type of operation causes accelerated ageing of the transformer insulation system and may have other associated risks.
iv. Short Time Emergency Loading – This loading condition is unusually high, caused by one or more events which disturb normal operation loading. The loading condition can cause hottest-spot temperatures as high as 180^0C for short period of time.

Due to the complexity and exposure of the power system, no matter how well it is designed, transformer failures are bound to occur. While it is the primary function of protective equipment to recognize such faults and isolate the faulted element from the rest of the system, the system will cause the power flow to find alternative routes to meet the load demand. Transformers that will be involved in this might experience overloads beyond their normal capacity [4]. Understanding the ageing of the insulation and how to calculate the hottest-spot winding temperature are of vital importance in order to know how much a transformer can be safely overloaded. [18] suggested thermal limits of temperature and loading for the particular case of loading above nameplate rating for a power transformer with 65°C rise as

i. Top-oil temperature 110°C
ii. Hotspot conductor temperature 180°C
iii. Maximum loading 200%

Table 1 shows the recommended temperature limits for each type of loading for power transformers with an average winding rise of 65 °C, as per test reports or nameplate information [12].

Table 1: Suggested Maximum Temperature Limits for Types of Loadings IEEE versus IEC

		Normal Loading	Planned Loading	Long-Term Emergency Loading (1-3 months)	Short-Term Emergency Loading (½- 2 Hrs)
Hottest-Spot Winding/Insulation Temperature In °C	IEEE	120	130	140	180
	IEC	120	N/A	130	160
Top-Oil Temperature In °C	IEEE	105	110	110	110
	IEC	105	N/A	115	115
Other Metallic (Supports, Core, etc)	IEEE	140	150	160	200
	IEC	N/A	N/A	N/A	N/A
Maximum Loading in %	IEEE	200	200	200	200
	IEC	200	200	200	200

F. Degree of Polymerization

This method measures the remaining life in terms of the Degree of Polymerization (DP) value. Several researchers have worked on this. A few of the researchers came up with some models, while others justified the models. The DP value indicated the number of monomer units in the polymer as the cellulose is a linear polymer composed of individual anhydrous glucose units linked by glucosidic bonds [8]. The DP value is currently used by utilities as a diagnostic tool to determine the condition of the solid material (particularly paper). One way of determining the DP value without taking the transformer out of service, involve analyzing the insulating oil for furanic compounds, which are produced during the ageing of the cellulose insulation. This method is referred to as the indirect method. Studies have been done which correlated the DP value with the furan content in the oil. Mathematical models showing this correlation have been developed. Some of these are [10, 13, 17, 19, 20]:

G. Existing Models.

Some of the existing models are:

i. The Chendong Model

$$DP = \frac{\log(2FAL) - 1.51}{-0.0035} \tag{3}$$

Where the concentration of 2FAL is in ppm

This equation was developed based on the data collected from transformers that have normal Kraft paper and free breathing conservators [10, 13]

ii. Stebbins Model

Stebbins proposed a modified Chendong equation to be used for thermally upgraded paper. Stebbins's equation is given by [13]:

$$DP = \frac{\log(2FAL \times 0.08) - 4.51}{-0.0035} \tag{4}$$

The concentration of 2FAL here is expressed in parts per billion (ppb).

Both the Chendong's and Stebbins's models are limited to certain transformers. This is dependent on the type of paper used for insulation. The model calculated the prevailing DP value by considering the concentration of the furans in oil. The use of furans is better than using purely hot spot gradient, because the former is based on the by-product of the ageing process, which may be due to even the other factors [11].

iii. De Pablo Model

The De Pablo model is given by [13]:

$$DP = \frac{7100}{8.8 + 2FAL} \tag{5}$$

where; 2FAL is in ppm, and the equation is linear.

The De Pablo model was also modified by [14] in order to take into consideration that paper ageing is not uniform and the assumption that 20% of the inner paper layers in the winding degrade twice as fast as the rest of the insulation paper. The modified De Pablo's equation referred to as Pahlavanpour model is

$$DP = \frac{800}{[0.186 \times 2FAL] + 1} \tag{6}$$

[10] also gave another modified De-Pablo Model which would thereafter be referred to as Leibfried model as:

$$DP = \frac{1850}{2FAL + 2.3} \tag{7}$$

iv. Heisler and Banzer Model

As given by [10], the Heisler and Banzer method is related as:

$$DP = 325 \times \left(\frac{19}{13} - \log(2FAL) \right) \tag{8}$$

One major setback common with these models is where the oil has been replaced or regenerated, which may vary the concentration of the furans. However, with the assumption that the mineral oil would not be changed, the second setback is based on the range of the values based on the 2FAL content range of 0.01ppm (for a virgin transformer/oil) and 10ppm (for a transformer/oil at end of its useful life). With the established models and their DP values, an upper DP level and a lower DP level, representing the expected beginning of life and end of life is expected to be chosen. Typically, values of 1200 and 250 may be chosen for virgin transformers and for transformers with the end of useful lifespan respectively for simulations and analysis.

II. Materials and Method

This research paper hybridized Vuarchex model and the Burton model for the determination of the Degree of Polymerization of a power transformer. This developed model is based on the existence of a relationship between the Degree of Polymerizations and the Furan content of power transformer oil. Furan content of

0.01ppm to 10ppm corresponding to a DP value of about 1200 and 250 respectively was established to approximately represent the end of transformer life. The two models and their DP range of values are given as:
The relationship between the DP and the 2FAL according to Vuarchex and Burton is:

$$DP = \frac{2.6 - \log[2FAL]}{0.0049} \tag{9}$$

Approximate Range: $940 \le DP \le 320$
And

$$DP = \frac{2.5 - \log[2FAL]}{0.005} \tag{10}$$

Approximate Range: $900 \le DP \le 300$

A hybridised model was thereafter developed with these two models. The developed model is a linear system of equation.

The linear system of equation of DP range is given as:

$$DP = \frac{x_1 - \log[2FAL]}{x_2} \tag{11}$$

Where;

$$x_1 = 250x_2 + 1 \tag{12}$$

$$x_2 = \frac{x_1 + 2}{1200} \tag{13}$$

Therefore equation (13) becomes:

$$DP = \frac{(250x_2 + 1) - \log[2FAL]}{x_1 + 2 \big/ 1200} \tag{14}$$

Equation (14) is the developed Degree of Polymerization (DP) model of the power transformer. The iterations x_1 and x_2 were solved using both Gauss Seidel of numerical analysis.

Having obtained the DP from the model above, the operating temperature of the power transformer was considered. The DP value was simulated, relating it to the ageing rate constant *k* at chosen transformer operational temperature. The operating temperature typically ranges from 85 ^{0}C to 120 ^{0}C, but a standard loading hotspot temperature is assumed for the development of this model.

The ageing rate *k* is related to the temperature *T* by the Arrhenius relationship as:

$$k = A \times e^{\frac{Ea}{R \cdot T}} \tag{15}$$

where; k is rate constant, Ea is activation energy (J/mol), A is pre-exponential factor (h^{-1}), R is molar constant (8.314 J/molK) and T is temperature (K).

The remaining life *t*, is given as:

$$t = -\frac{1}{k_2} In\left\{1 - \left[\frac{k_2}{k_{10}} \times \left(\frac{1}{DP_t} - \frac{1}{DP_0}\right)\right]\right\} \tag{16}$$

where; k_{10} is initial rate at which bond breaks, k_2 is rate at which k_{10} changes, DP_t is insulation DP value, DP_0 is initial insulation DP value and t is remaining life time in hours.

Thus, the lifespan of the transformer is determined as:

$$LIFESPAN\ (hours) = ServiceAge + RemainingLifetime \tag{17}$$

where "Service Age" is the total time (in hours) to which the transformer has been operational. The service age may be taken as zero for a virgin transformer.

III. Discussion of Results

The simulation results of hybridized model of the Degree of Polymerization (DP) of a power transformer are presented in Figures 1 to 10. The simulation was done with Furan content of 0.01ppm to 10 ppm corresponding to a DP value of about 1200 and 250 respectively to represent the end of transformer life and the iterations were solved using Gauss Seidel method of numerical analysis.

With the Gauss Seidel method of numerical analysis, the result shows that both x_1 and x_2 converged at the 13th iteration at an error value of 0.00. Hence, the values of x_1 and x_2 are 1.789 and 0.0032 respectively. Thus, the developed mathematical DP model in this research paper is therefore given as:

$$DP = \frac{1.789 - \log[2FAL]}{0.0032} \tag{18}$$

with approximate Range of $1184 \le DP \le 247$

This range is a closer approximation to the established range of 1200 ≤ DP ≤ 250 by Abu-Siada and Islam, (2014).

Figure 1 shows a comparison of the average values of DP obtained for the existing models to that obtained from the developed model. The graph shows a close range of results from the average values and the developed model. This validates the result of the model developed. Figure 2 shows the same graph plotted with greater precision of values but with graph truncated as it progresses. From both Figures 1 and 2, it is clearly shown that the gradient of the two curves is similar, especially from the 2FAL value of the ranges between 1ppm to 10ppm. This is a clear validation of the developed model. However, the sharp difference between the DP values equivalent to the 2FAL content of between 0.01ppm to about 1ppm shown in Figure 1 is gave a better view in Figure 2 which was plotted with better precision of values.

Two major observations were distinctly noticeable. Firstly, the DP value has taken its range from 1216, which is closer to the value given by practical measurements. This is an important result which gives credence to the result. Secondly, the shape of the curve still correlates, despite the variation in the DP range for the early part of the graph. The variation however is as a result of the range derived from the average of the other DP models.

Figures 3 to 9 show the comparison of the individual existing models to the developed model based on the modifications made to the existing models. The graphs also show the deviations of the existing models from the developed model.

Figure 3 shows a comparison of the developed model with the Chendong model. It is observed that the slopes of the graphs are similar, but the values of the DP corresponding to each 2FAL value vary completely.

Figure 4 compares De-Pablo Model with the developed model. The graph shows a relatively similar slope between the two models. The graph shows that the DP values are equal at a 2FAL value of 0.2 corresponding to a DP of 777.

Figure 5 also compares the developed model with Vuarchex Model. The DP values are equal at 465 corresponding to a 2FAL value of 2.

Figure 6 compares Burton Model with the developed model. The DP values are equal at 389 corresponding to a 2FAL value of 3.5.

Figure 7 is a comparison of the developed model with the Heisler and Banzer Model. The graph shows that the Heisler and Banzer Model and the Chendong model are similar. It is observed that the slopes of the graphs are similar, but the values of the DP corresponding to each 2FAL value vary completely.

From the results, it was concluded that all models generally follow a curve pattern, representative of the logarithmic nature of the models. However, a closer look at the developed model shows clearly, a trend in the evaluation of the DP values using the values of the 2FAL content. In addition, the Chendong model and the Heisler and Banzer model almost follow the same pattern like the developed model. The major differences lie in the range covered by the DP values. However, the other models discussed clearly reveal a meeting point on the graph where a 2FAL value produced approximately the same DP value. Vuarchex and Burton Models gave clear deviations from the developed models on both sides of the curve. This justifies why it was important to have developed the hybrid model from the two models.

Figure 8 shows the comparison of the remaining life of a virgin transformer obtained from the developed DP model (DP_0 and DP_t as 1184 and 247 respectively) with that from the standard DP_0 and DP_t as 1200 and 250 respectively. This is a deviation of about 166.5 days representing about 1.48% deviation from the 1200 – 250 DP boundary. However, observing the trend of the curve in Figure 10 shows that as the transformer gets to the end of its useful life, the changes in the DP value becomes less significant. In other words, as the DP value approaches the end of its useful life, a unit change (decrease) in the DP value takes a longer time to occur. Hence, the number of days may be quite insignificant. Note that from a DP of about 500, the curve gradually approaches less steepness while at 400, the steepness becomes more significant.

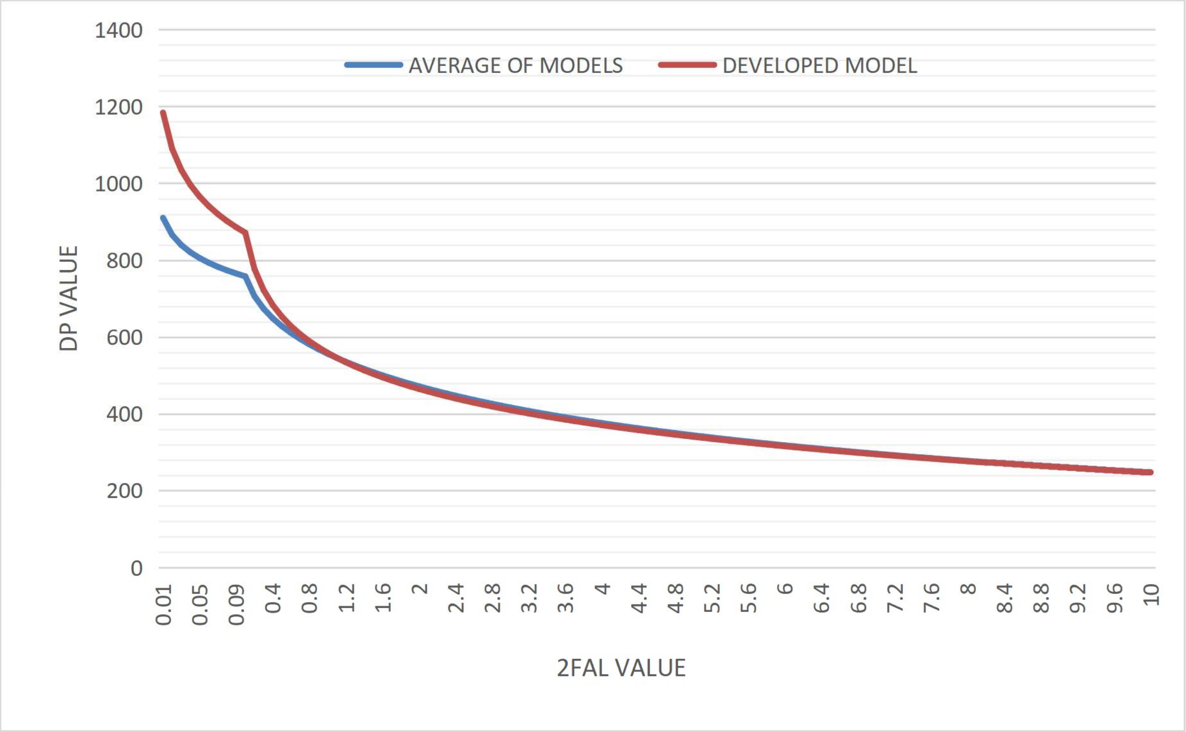

Figure 1: Average Value of Existing 'DP' Models against '2FAL' Values

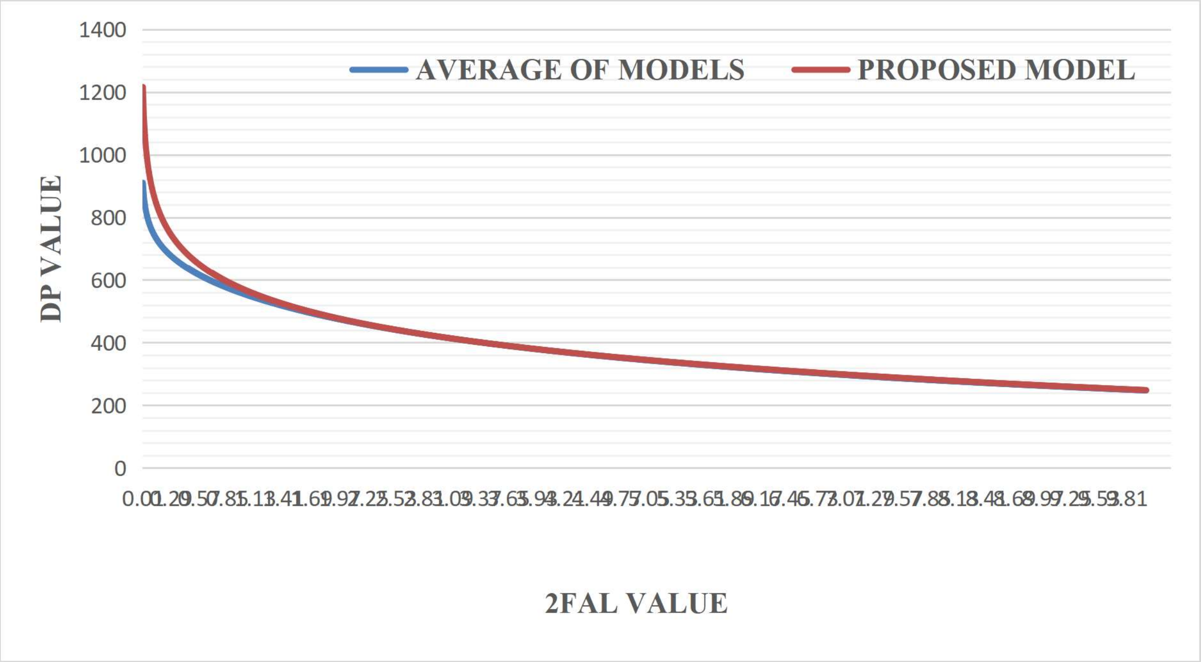

Figure 2: Average Value of Existing 'DP' Models Against '2FAL' Values Using 0.01ppm Range

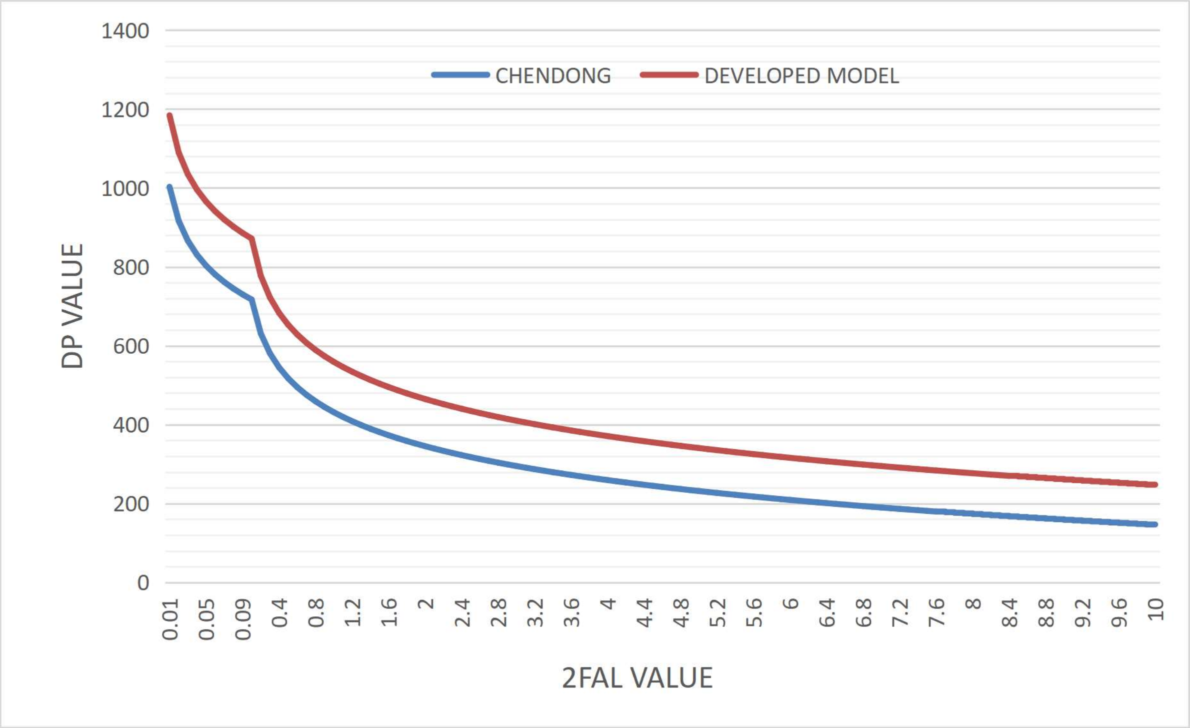

Figure 3: Comparison of the Chendong Model with the Developed Model

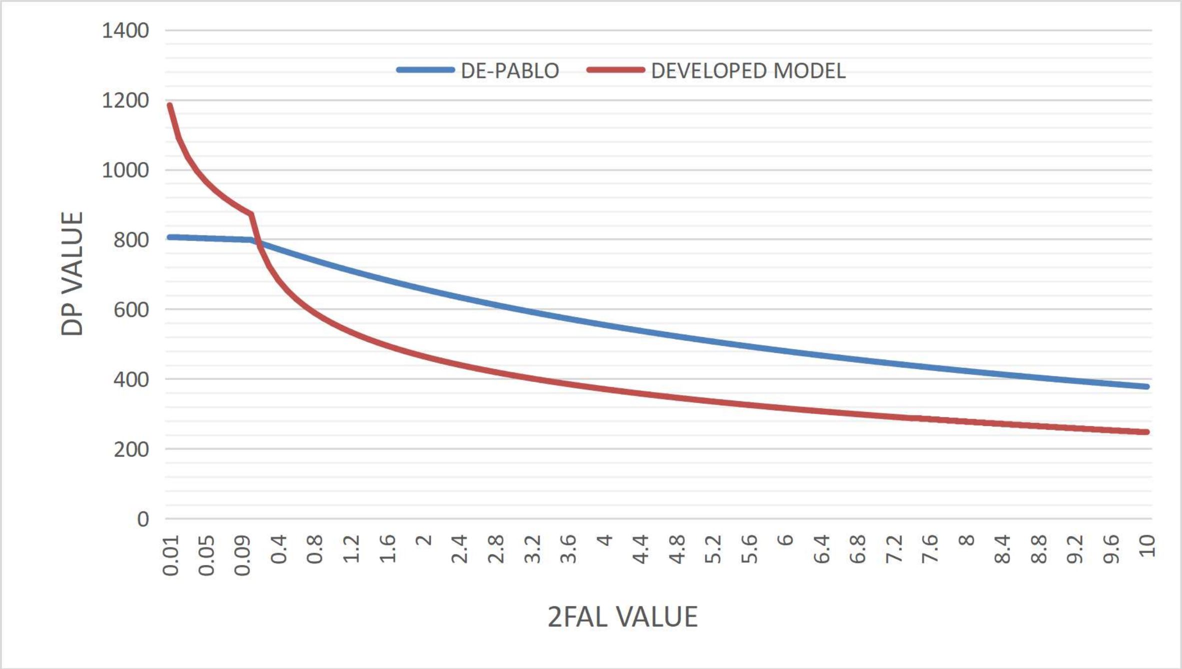

Figure 4: Comparison of the De-Pablo Model with the Developed Model

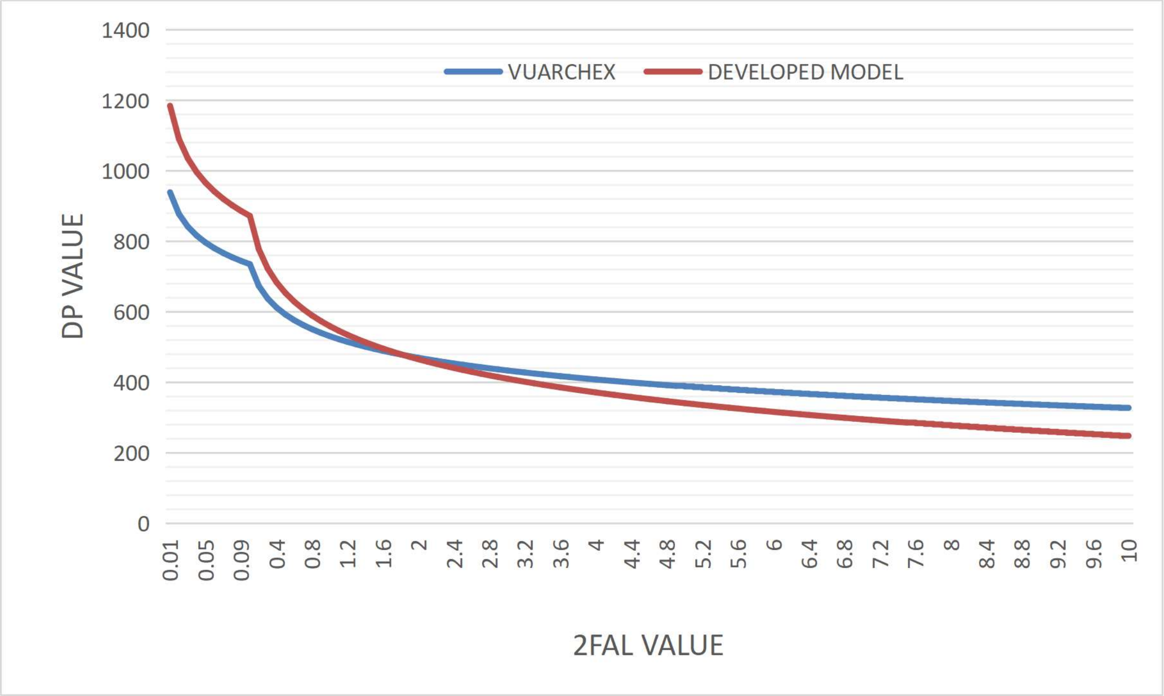

Figure 5: Comparison of the Vuarchex Model with the Developed Model

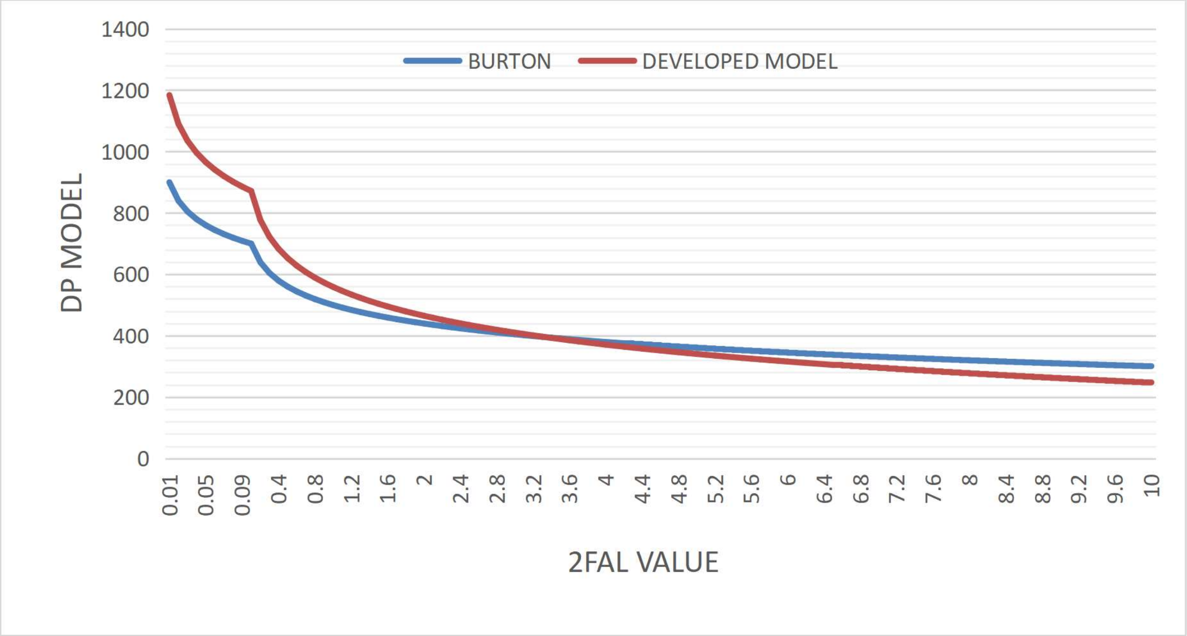

Figure 6: Comparison of the Burton Model with the Developed Model

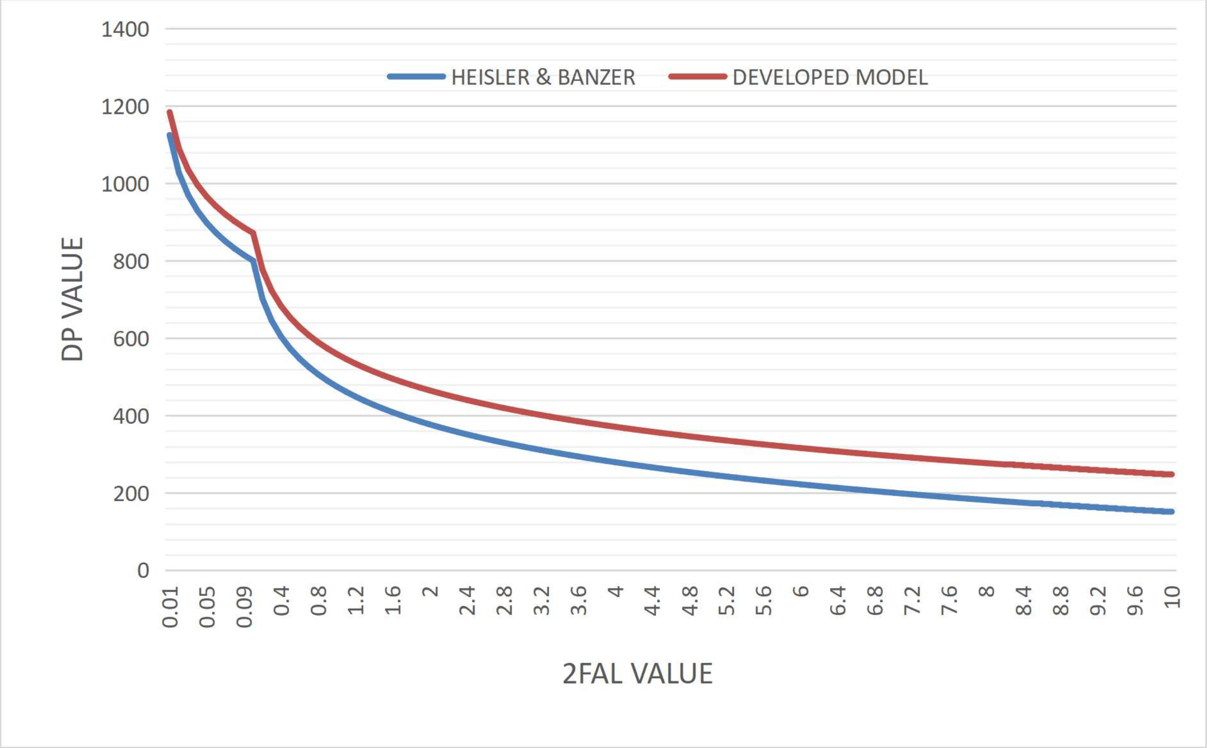

Figure.7: Comparison of the Heisler and Banzer Model with the Developed Model

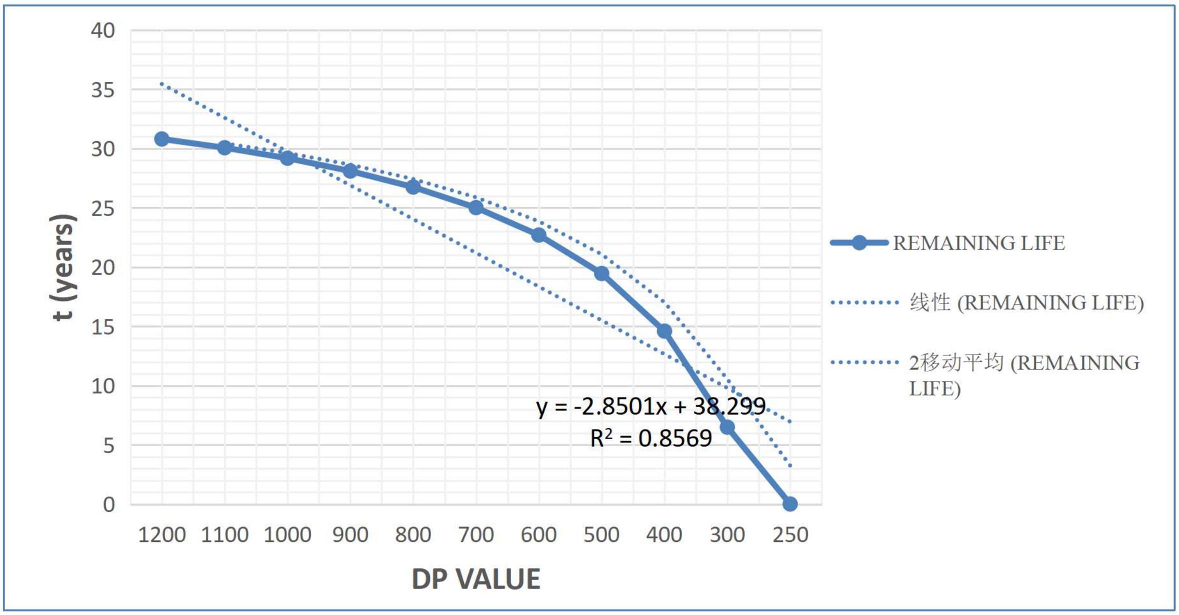

Figure 8: Variation of Remaining Life with DP Value

IV. Conclusion

The study developed a hybrid model for the determination of the Degree of Polymerization of a power transformer in order to predict the lifespan of power transformers. The model development is based on the degree of polymerization which considered the level of furan (2FAL) content and the loading of the transformer which is a function of the hotspot temperature among other parameters. The developed DP model was compared with existing DP method for the effectiveness of the model. The results indicated that all the models generally followed a curve pattern, representative of the logarithmic nature of the models. However, the developed model showed clearly, a trend in the evaluation of the DP values with the 2FAL content. This justifies why it was important to have developed the hybrid model from the two models. This study will therefore help to monitor the major parameters, to determine the remaining life and the lifespan of power transformers. Therefore, the developed model is recommended to utility companies that make use of power transformers.

V. References

[1] Abu-Siada, A. and Islam S. (2014): "A New Technique to Estimate Concentration through Spectral Response of Transformer Oil"**.** Doble Engineering Company – 81st International Conference of Doble Clients, Pp 1-10.

[2] Cheim, L., Platts, D., Prevost, T. and Xu, S., (2012): "Furan Analysis for Liquid Power Transformers," IEEE Electrical Insulation, Vol. 28. Pp. 8–21.

[3] Esmaeilinasab, A. and Vahidi, B. (2014): "Prediction of Power Transformer Insulation Length of Life Using Thermal Model and Pareto Distribution". Sci.Int (Lahore), 26(5), ISSN 1013-5316; CODEN: SINTE 8. Pp 1953-1957.

[4] Fassbinder S. (2013): "Efficiency and Loss Evaluation of Large Power Transformers". European Copper Institute, Copper Alliance, Leonardo Energy. ECI Publication No Cu0144. Pp 1 – 21.

[5] Franzén, A. and Bertling, L. (2007): "State of the Art - Life Time Modelling and Management of Transformers". Royal Institute of Technology, KTH School of Electrical Engineering RCAM Stockholm, Sweden. Pp 1 – 33.

[6] Hashmi M., Lehtonen M. and Hänninen S. (2013): "Effect of Climate Change on Transformers Loading Conditions in the Future Smart Grid Environment". Open Journal of Applied Sciences, (3), pp 24 – 29.

[7] Hohlein I. and Kachler A. J. (2005): "Aging of Cellulose at Transformer Service Temperatures. Part 1: Influence of Type of Oil and Air on the Degree of Polymerization of Pressboard, Dissolved Gases, and Furanic Compounds in Oil", IEEE Electrical Insulation Magazine, (21), pp. 15-21.

[8] Kalogerakis S. (2009): "Distribution Transformers and Maintenance". Central Ostrobothnia University of Applied Sciences Ylivieska. Pp 1 – 50.

[9] Karlsson, S. (2007). A Review of Lifetime Assessment of Transformers and the use of Dissolved Gas Analysis.An unpublished Msc Thesis.KTH School of Electrical Engineering. Pp 1 – 51.

[10] Leibfried T., Jaya M., Majer N., Schäfer M., Stach M. and Voss S. (2011): "Post-Mortem Investigation of Power Transformers – Profile of Degree of Polymerization and Correlation with Furan Concentration in the Oil"

[11] Lucas J. R. (2000): "Historical Development of the Transformer". The Institution of Electrical Engineers, Sri Lanka Centre. Pp 1 – 16.

[12] Mehta, D. and Jariwala, H. (2012): "Predication of Life of Transformer Insulation by Developing Relationship between Degree of Polymerization and 2- Furfural". International Journal of Scientific and Engineering Research, Volume 3, Issue 7.

[13] Mtetwa N. S. (2008): "Accuracy of Furan Analysis in Estimating the Degree of Polymerization in Power Transformers".MSc Thesis, University of the Witwatersrand

[14] Pahlavanpour, B, Martins, M.A and De Pablo, A. (2002): "Experimental Investigation into the Thermal-Ageing of Kraft Paper and Mineral Insulating Oil". IEEE International Symposium on Electrical Insulation.pp. 341- 345.

[15] Penny, B. (2010): "Best Practices For Maintaining Power Transformers"Aappa Fall Professional Development Conference Halifax, N. S.

[16] Pradhan. M. K, and Ramu, T. S. (2004): "Diagnostic Testing of Oil Impregnated Paper Insulation in Prorated Power Transformers under Accelerated Stress". Conference Record of the 2004 IEEE International Symposium of Electrical Insulation, Indianapolis, USA, 19-22 September.

[17] Pranjal. D, Deepchand K., Saddam H., and Sachin B. (2014): "Comparison between Power and Distribution Transformers". Int. Journal of Electrical, Electronics and Computer Research & Development. Vol. 1, Issue 2. ISSN: 2394-3246. Pp 21-25

[18] Rosenlind J. (2013): "Lifetime Modelling and Management of Transformers". Ph.D Thesis Kth Royal Institute of Technology. Pp 1 – 60.

[19] Sim, J. H. and Digby, S. H. (2001): "Power Transformers". Electrical Power Engineering Handbook Series. University of California, Davis.Pp. 94 – 111.

[20] Zhou, D. (2013): "Transformer Lifetime Modelling Based On Condition Monitoring Data" International Journal of Advances in Engineering & Technology, Vol. 6, Issue 2, pp. 613-619.