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Development of a Hybridized Model for Predicting the Life Span of Power Transformers

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ABSTRACT: Power transformers are important equipment of the electrical switchyard whose failure leads to long hours of outage. In this research, a two-stage hybridized model for determining the lifespan of power transformers is presented by using the furan content to determine the Degree of Polymerisation (DP) of transformer. For a 'virgin' transformer, the furan content was about 0.01ppm while a transformer with about 10ppm was within its end of useful life. 2-Furaldehyde (2FAL) content values of 0.01ppm and 10ppm correspond to DP values of approximately 1200 and 250, respectively. These parameters were used in developing a DP model using Jacobi and Gauss Seidel numerical analysis iterative techniques. The techniques were implemented in Matrix Laboratory 8.2 (R2013b) environment. The second stage involved the hybridisation of the developed DP model with another rate constant model adopted from Arrhenius. This stage was also implemented in Matrix Laboratory 8.2 (R2013b) environment. The life span of the transformer was determined by adding the service age at any point in time to the remaining lifetime at that point. A GUI of the hybridised model was developed using SIMULINK blocks. The developed model yielded a DP range of $247 \leq DP \leq 1184$. Factors such as the hotspot temperature, activation energy and pre-exponential factor were useful for the determination of lifespan.

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Power Transformer is a core ingredient for ensuring reliable and efficient electricity supply. Despite its usefulness, age is one of the factors that limit its efficiency. Currently, power system in Nigeria is working at its maximum capacity. Hence, the drastically decrease the margin between the installed power and the demand consumption. This has not only led to energy shortfall and the consequences are quite dominant in residential and commercial sectors that predominantly rely on energy for domestic and industrial use respectively but also propelled the migration of multi-national companies to neighborhood countries. In order to bridge the gap between energy supply and demand and also ensure optimal performance of the installed power transformers, there is need for regular assessment of insulation condition within high power transformers. (Hillary et al., 2017; Yuan et al., 2012) revealed that the lifetime of power transformer depends on the condition of paper-oil insulation and the dissipated heat as a result of temperature rise of the coolant. Studies conducted revealed that most power transformer installed in Nigeria had been in existence since 60's and this indicate that most transformers had been operating for more than 50 years. Although, this is in contrary to the expected lifetime of 20-40 years as stated by the manufacturers. However, the consequences are notably reflected in the quality of service delivered by the Power Holding Company of Nigeria (PHCN) coupled with erratic power supply, power outage, load shedding, black-out and these significantly affect the socioeconomic development of the country. Verman et al (Verma, Baral, Pradhan, & Chakravorti, 2017) proposed a time domain spectroscopy data to estimate activation energy of power transformer in order to assess their reaming life. Jayarathna et al (Hillary et al., 2017) presented a mathematical model based model to estimate the remaining life through assessment of furfural content in the oil and degree of polymerization of the insulated paper. Victor et al (Jimenez, Will, Gotay, & Rodríguez, 2018) modified the existing power transformer model by adjusting some parameters with stated conditions. Petru et al (Notingher et al., 2017) further proposed a novel model to estimate the remaining lifetime of an in-service power transformer based on monitoring of its oil resistivity. Laurentiu et al (Dumitran, Setnescu, Notingher, Badicu, & Setnescu, 2014) also developed a simpler model for a single ageing test that involve the usage of high

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temperature and the activation energy which are determined from non-isothermal Differential Scanning measurement. Furthermore, Dan Zhou (Zhou, Li, & Wang, 2012) proposed a baseline model integrated with Bayesian model in order to sequentially updating the model whenever new failure occurs , this allows the existing lifetime model to be improved. Recently, many literatures [8–10] have proposed mathematical model for predicting life time of power transformer with different insulation content and approach. In this paper, a hybrid mathematical models are formulated to predict the life span of power transformer.

MATERIALS AND METHODS

Identification of Parameters: Several parameters directly or indirectly affect the lifespan of power transformers. Such parameters include the insulation materials, insulation level, cooling system/network, humidity, loading (which directly affects the operating temperature), among others. However, this work has extensively explored the insulation and the temperature effect of the loading the transformer. The insulation model was developed with the Degree of Polymerisation of oil while for the temperature, the Arrhenius ageing rate constant model was adopted. The developed model is based on the existence of a relationship between the degree of polymerization and the level of Furan content in transformer oil. It has earlier been established (Islam, 2014) that at the commencement of operation of a new transformer, the Furan content is taken as about 0.01ppm which should correspond to a DP value of about 1200ppm. A furan content of about 10ppm which corresponds to a DP value of about 250 was also established to approximately represent the end of useful life of transformer (Islam, 2014)

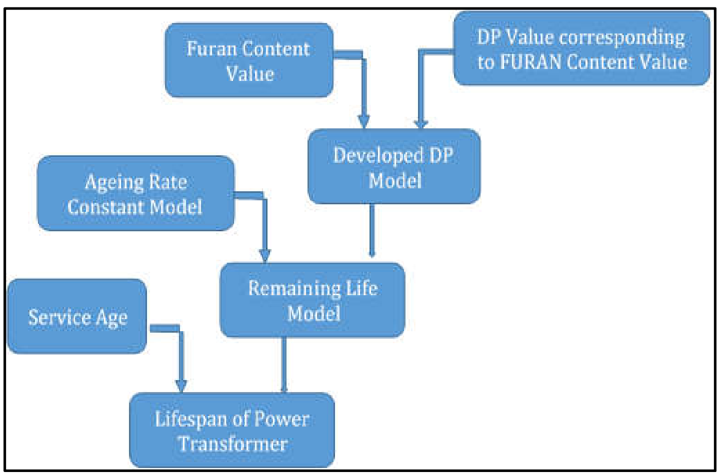

Fig 1: Model Development Block Diagram

Model Development: The DP Model: The established range of approximate correlation between DP value and 2FAL content value have been extensively discussed (Islam, 2014). This forms the basis for the major assumption in this work. From the correlation, a new transformer has a furan content of about 0.01ppm, corresponding to a DP value of about 1200 while a transformer in its end of useful life has a furan content of about 10ppm, corresponding to a DP value of about 250. This is a widely accepted condition. However, realities of experimental results under varied conditions which samples are taken and investigated over a long period of time have been largely responsible for the departure from this accepted result. This model still finds and considers this range as the standard range. In developing the hybridised model, two iterative techniques were utilised. The linear system of equation used in the model development is:

$$DP = \frac{x1 - \log[2FAL]}{x2} \quad 1$$

The iterative methods used are the Gauss-Seidel iterative technique and Jacobi iterative techniques. The two techniques were used to determine the consistency and the convergence point of the linear system. The implementation of the iteration was carried out in MATLAB 8.2 environment.

From equation 1,

$$DP \times x2 = x1 - \log[2FAL] \quad 2$$

$$x1 - (DP \times x2) = \log[2FAL] \quad 3$$

Meanwhile, for the 2FAL value of 0.01ppm

$$\log[2FAL] = LOG[0.01] = -2 \quad 4$$

Also,

$$\log[2FAL] = LOG[10] = 1 \quad 5$$

Substituting equations (4) and (5) in equation (3)

$$x1 - 250x2 = 1 \quad 6$$

$$x1 - 1200x2 = -2 \quad 7$$

From equations (6) and (7),

$$x1 = 250x2 + 1 \quad 8$$

$$x2 = \frac{1}{1200}x1 + \frac{2}{1200} \quad 9$$

Equations (8) and (9) form the basis of the numerical analysis.

Assuming initial values of (x1, x2) as (0, 0), the iterations were solved to determine the point of convergence to a tolerance level of 0.00 using both Gauss Seidel method and Jacobi method of numerical analysis

The Ageing Rate, K, Model: The ageing rate k is related to the Temperature T by the Arrhenius relationship below:

$$k = A * e^{\frac{Ea}{R*T}} \quad 10$$

Where: k = rate constant; Ea =activation energy (J/mol); A= pre-exponential factor (h^{-1}); R=molar constant (8.314 J/molK); T=temperature (K)

Relationship between the Degree of Polymerisation and Temperature: Having obtained the DP from the model above, the operating temperature of the power transformer will be considered. The DP values is expected to be simulated, relating it to the ageing rate constant K at chosen transformer operational temperature. At least three different temperature levels are usually considered in the operation of power transformers. They are: the ambient temperature, the top oil temperature and the hotspot temperature. Of these three, the hotspot temperature is of interest because it represents the aggregate of the entire temperature in the transformer. The operating temperature typically ranges from 85^0C to 120^0C, but a standard loading hotspot temperature is assumed for the development of this model. The equation for relating the DP model to the ageing rate constant is:

$$\frac{dDP}{dt} = -k \times DP^2 \quad 11$$

Assuming k_1 is a constant from the integration:

$$\frac{1}{DP_0} - \frac{1}{DP_t} = kt \quad 12$$

If ki changes with time with another rate constant k_j

$$\frac{dk_1}{dt} = -k_j \times k_i \quad 13$$

$$\int_0^t \frac{dk_i}{k_i} = \int_0^t -k_j \times dt$$

$$\ln[k_i]_0^t = -k_j \int_0^t dt$$

$$\ln[k_{it} - k_{i0}] = -k_j t \quad 14$$

Where 0 is the beginning of life, kj is a constant, and t is the time at any instant

Rearranging equation 14 gives

$$k_t = k_i \times e^{-k_j \times t} \quad 15$$

The Remaining Life, t: The remaining life t, is the time left for the transformer to be in useful operation. In relating the ageing rate constant "k" to the DP model at any instant,

Let DPt be the DP value at any time instant, and k_t be the k value at any time instant

By substituting equation 15 in equation 11,

$$\frac{dDP_t}{dt} = -DP_t^2 \times k_i \times e^{-k_j \times t}$$

$$\int \frac{dDP_t}{DP_t^2} = \int k_i \times e^{-k_j \times t} \times dt$$

$$-\left[\frac{1}{DP}\right]_{DP_0}^{DP_t} = \left[\frac{k_i}{k_j} \times e^{-k_j \times t}\right]_0^t$$

$$-\frac{1}{DP_t} + \frac{1}{DP_0} = \frac{k_i}{k_j} \times \left[e^{-k_j \times t} - 1\right]$$

$$\frac{1}{DP_t} - \frac{1}{DP_0} = \frac{k_i}{k_j} \times \left[1 - e^{-k_j \times t}\right]$$

$$\left[1 - e^{-k_i \times t}\right] = \frac{k_j}{k_i} \times \left(\frac{1}{DP_t} - \frac{1}{DP_0}\right)$$

$$e^{-k_j \times t} = 1 - \left[\frac{k_j}{k_i} \times \left(\frac{1}{DP_t} - \frac{1}{DP_0}\right)\right]$$

$$-k_j t = \ln\left\{1 - \left[\frac{k_j}{k_i} \times \left(\frac{1}{DP_t} - \frac{1}{DP_0}\right)\right]\right\} \quad 16$$

The Remaining Life will therefore be determined by:

$$t\ (\text{Remaining Life}) = -\frac{1}{k_j}\ln\left\{1 - \left[\frac{k_j}{k_i} \times \left(\frac{1}{DP_t} - \frac{1}{DP_0}\right)\right]\right\} \quad 17$$

Where: k_i=initial rate at which bond breaks; k_j =rate at which k_i changes; DPt = insulation DP value at any instant, t; DP_0 = initial insulation DP value; t = time in hours

Thus, the remaining life can be determined by equation 17 and the lifespan of the transformer will be:

$$LIFESPAN\ (hours) = SA + RL \quad 18$$

Where the SA = Service Age which 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; RL = remaining lifetime

However, using the Arrhenius Parameters for kraft paper in oil, K_i and K_j can be expressed as:

$$k_i = Ai \times e^{\frac{Eai}{R \times T}} \qquad 19$$

$$k_j = A_j \times e^{\frac{Ea_j}{R \times T}} \qquad 20$$

Table 1: Arrhenius Parameters to Determine the Value of K

	Ea (J/mol)	A(h^{-1})
K_i	123800	9.0×10^8
K_j	165900	3.06×10^{12}

The Constants K_i, K_j, Ea and A: The Constants K_i, K_j, Ea and A used in the developed model above represent initial rate at which bond breaks, rate at which Ki changes, activation energy and pre-exponential factor respectively. From the definitions, the value of Kj is dependent on the value of Ki since Kj is the rate at which k_1 changes. Hence, Ki is the major determining parameter. Meanwhile Ki and Kj are both functions of Ea and A according to equation 18 and 19. From the equation, temperature T remains constant for the evaluation of both Ki and Kj. Hence, the actual variables or determinants of k are the activation energy Ea and pre-exponential factor A at any given temperature. Ki and Kj were found to be 1.173×10^{-8} and 7.227×10^{-11} respectively.

The Graphical User Interphase (GUI) of the Model: A graphical user interphase (GUI) where data values can be inputted for easy output was assembled in a MATLAB 8.2 environment. Every interphase on the SIMULINK has a block where the mathematical relationships are coded and mathematical values or constants are inserted. This is usually shown on the subsystem interphase as shown in Figures 3.3 and 3.4.

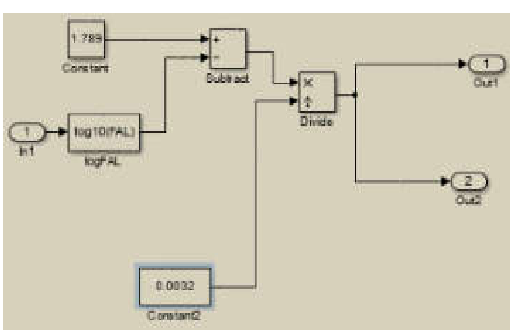

Fig 2: Simulink Subsystem for Calculating the Degree of Polymerisation, DP

The developed model is in three major sections. The first is used to evaluate the DP value for different 2FAL values using the result of the DP model developed using the iterative techniques. The DP model developed will be discussed later. The second is used to evaluate the ageing rate constant, k using equation 19. The last combines the first two and is used to calculate the remaining life and the lifespan according to equations 17 and 18. Figure 3 shows the Simulink Model for calculating the degree of polymerisation, DP using the 2FAL input interphase (2FAL = 10, DP = 246.6).

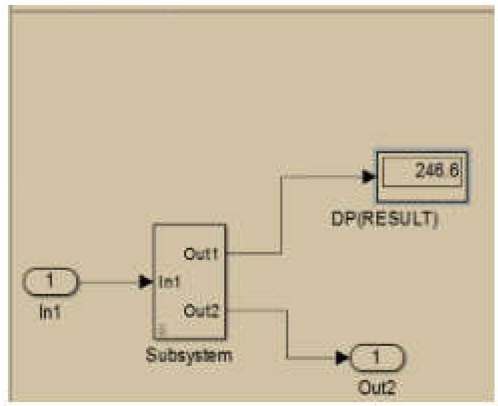

Fig 3: 2FAL Input Interphase (2FAL = 10, DP = 246.6)

Figure 4 shows the input interphase for the constants for calculating the ageing rate constant k. The function box parameters in the figure shows where the constants are inputted.

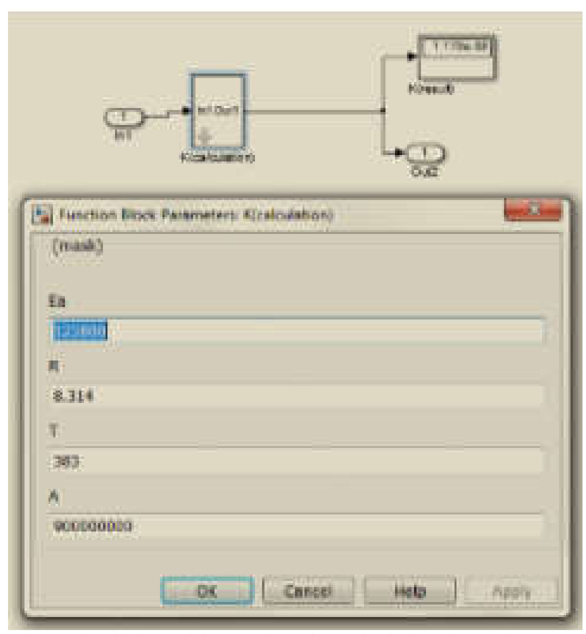

Fig 4: Simulink Model Interphase for Calculating the Ageing Rate Constant, k

Figure 5 shows the complete blocks. The constants involved are inputted to calculate Ki, Kj, DP_0 and DP_t respectively. These are further linked according using the remaining lifetime equation.

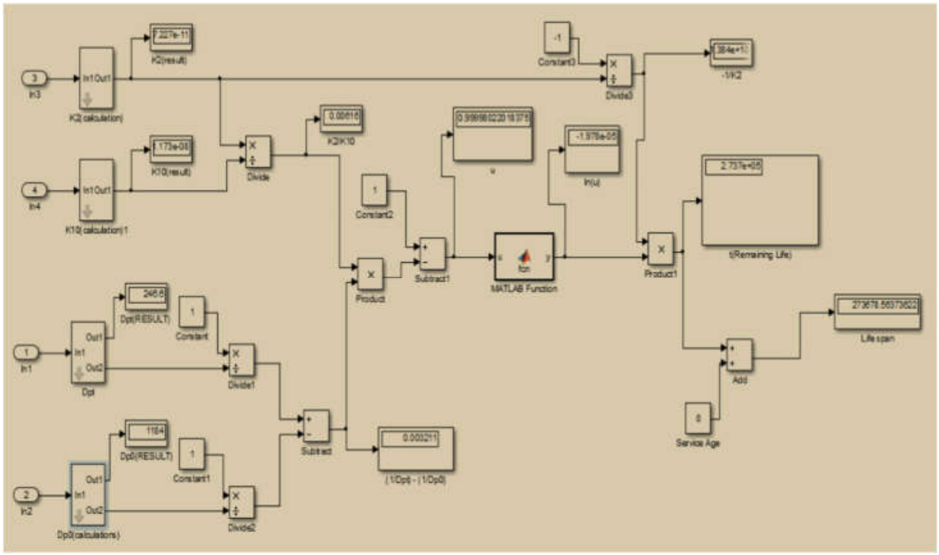

Fig 5: Complete Simulink Model for the Determination of Lifespan of a Power Transformer

The Ageing Rate Constant and the Remaining Life Model: Substituting the values of Ki and Kj into (17) and also adopting the standard values of DP_0 and DP_t as 1200 and 250 respectively as recommended by IEEE, the age of the new transformer with the parameters given above was determined as:

$$t = -\frac{1}{k_j}\ln\left\{1 - \left[\frac{k_j}{k_i} * \left(\frac{1}{DP_t} - \frac{1}{DP_0}\right)\right]\right\}$$

$$t\ (\text{years}) = \frac{11245.1}{365}\ \text{years}$$

$$t\ (\text{years}) = 30.81\ \text{years} \qquad 21$$

Substituting the values of DP_0 and DP_t as 1184 and 247 respectively as evaluated from the developed DP model, the following values are derived for "t"

$$t\ (\text{hours}) = 273678\ \text{hours}$$
$$t\ (\text{days}) = 11403.3\ \text{days}$$
$$t\ (\text{years}) = 31.2\ \text{years}$$

This is a deviation of about 155 days representing about 1.4% deviation from the 1200 – 250 DP boundary.

Validation of Model: A number of DP models had existed before now. To validate the developed model, an average of the DP values derived from the seven models considered was determined. This average values were compared with the DP values gotten from the developed model and both were plotted on the same graph against the 2FAL value chosen from the range 0.01ppm to 10ppm.

RESULTS AND DISCUSSION

The results obtained from the Jacobi and the Gauss Seidel Methods are discussed in the following sections.

Jacobi Iteration: The output of the Jacobi iteration method is shown in Table 2. The output shows that for the system of equations both x1 and x2 converged at the 13th iteration at an error value of 0.00. Hence, the values of x1 and x2 are 1.789 and 0.0032 respectively.

Table 2: Output of Simulation for the developed model using Jacobi iteration method

	x1	Error (%)	x2	Error (%)
0	0	100.0000	0	100.0000
1	1.0000	100.0000	0.0017	100.0000
2	1.4167	29.4118	0.0025	33.3333
3	1.6250	12.8205	0.0028	12.1951
4	1.7118	5.0710	0.0030	5.7471
5	1.7552	2.4728	0.0031	2.3386
6	1.7733	1.0198	0.0031	1.1558
7	1.7823	0.5073	0.0031	0.4793
8	1.7861	0.2109	0.0032	0.2391
9	1.7880	0.1054	0.0032	0.0995
10	1.7888	0.0439	0.0032	0.0497
11	1.7892	0.0219	0.0032	0.0207
12	1.7893	0.0091	0.0032	0.0104
13	1.7894	0.0046	0.0032	0.0043
14	1.7894	0.0019	0.0032	0.0022

Gauss-Seidel Iteration: The output of the Gauss-Seidel iteration method is shown in Table 3. The output shows that for the system of equations both x1 and x2 converged at the 7th iteration at an error value of 0.00. Hence, the values of x1 and x2 are 1.789 and 0.0032 respectively. While the Gauss Seidel iteration converged faster, both iteration methods still gave the same results.

Table 3: Output of Simulation for the Developed Model Using Gauss-Seidel Iteration Method

	x1	Error (%)	x2	Error (%)
0	0	100.0000	0	100.0000
1	1.0000	100.0000	0.0025	100.0000
2	1.6250	38.4615	0.0030	17.2414
3	1.7552	7.4184	0.0031	3.4674
4	1.7823	1.5220	0.0032	0.7172
5	1.7880	0.3161	0.0032	0.1492
6	1.7892	0.0658	0.0032	0.0311
7	1.7894	0.0137	0.0032	0.0065
8	1.7895	0.0029	0.0032	0.0013
9	1.7895	0.0006	0.0032	0.0003

The developed model in this study is:

$$DP = \frac{1.789 - \log[2FAL]}{0.0032} \quad 21$$

The approximate range of the hybridised model using the 2FAL value range from 0.01ppm to 10ppm is: Approximate Range: 1184 ≤ DP ≤ 247 (see appendix 1).

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

Comparison of the Average of Existing DP Models with Developed Model: Several models had existed before this model was developed. An average of the results gotten from these models was calculated and the graph of the average values was plotted with 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. The graph is shown in Figures 6 and 7.

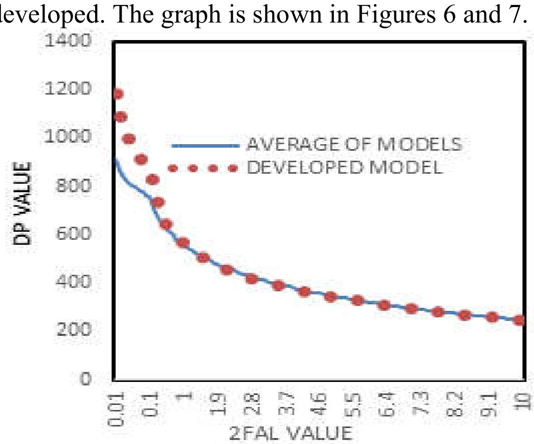

Fig 6: Average Value of Existing 'DP' Models against '2FAL' Values

Figure 6 shows a comparison of the average values of DP obtained for the existing models to that obtained from the developed model. Figure 7 shows the same graph plotted with greater precision of values but with graph truncated as it progresses. From both Figures 6 and 7, 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 6 is given a better view in Figure 7 which is plotted with better precision of values. Two major observations are distinctly noticeable. Firstly, the DP value has taken its range from 1184, 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.

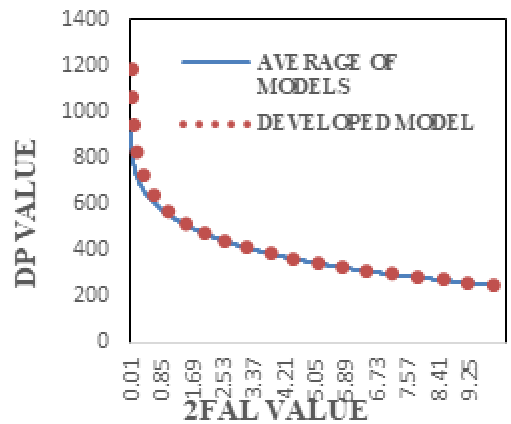

Fig 7: Average Value of Existing 'DP' Models against '2FAL'

A graph of the developed model was also plotted against the seven existing models considered. From the graphs, it was observed that all models generally follow a curve pattern, representative of the logarithmic nature of the models. Hence, we have clearly shown a trend in the evaluation of the DP values using the values of the 2FAL content. The Chendong and the Heisler & Banzer models in particular almost follow the same pattern like the developed model. The major difference 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 produces approximately the same DP value (see Appendix 1). Vuarchex and Burton Models gave clear deviations from the developed models on both sides of the curve. Figure 8 shows a graphical comparison of the results of the seven existing models discussed with the results of the developed model. From the graph, it is observed that at the early life of the transformer, only the DP of the developed model of the developed model is closer to the standard DP of 1200. All other models take lesser DP values. As the life of the transformer progresses however, there is an even distribution of the DP values. The wide departure of the existing models may not be unconnected with experimental conditions.

The Remaining Life: Comparing the values 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 form the standard of DP_0 and DP_t as 1200 and 250 respectively, the results are presented in Table 4.

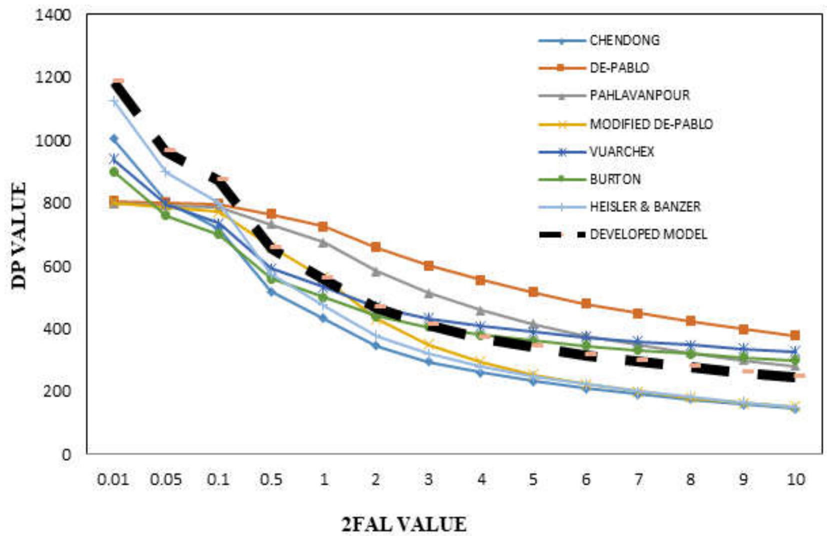

Fig 8: Comparison of the Developed Model with seven Existing Models

Table 4: Difference in remaining life between the developed model range and standard DP range

	t (hours)	t (days)	t (years)
Developed DP Model	273678.6	11403.3	31.20
Standard DP	269881.7	11245.1	30.81
Difference	3996.9	166.5	0.49

This is a deviation of about 166.5 days representing about 1.48% deviation from the 1200 – 250 DP boundary. This number of days may appear very significant. However, observing the trend of the curve in Figure 4.11 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. Notice that from a DP of about 500, the curve gradually approaches less steepness while at 400, the steepness becomes more significant.

Power Transformer Lifespan: As stated earlier in equation 18, the service age of the power transformer may be easily established from records of when the transformer was put to its first use. Hence, the model focuses more on the remaining life of the transformer. The lifespan is then be determined by the arithmetic summation of the service age (in hours) and the remaining life (in hours). The lifespan in hours is converted to days by dividing the output result by 24. It can also be converted to years by dividing the output result by 8760 (365 x 24).

Conclusion: The work has developed a hybrid model for the prediction of lifespan of power transformers based on two determinant parameters. These are the degree of polymerisation derived from the furan (2FAL) content level and the loading of the transformer which is a function of the hotspot temperature. The insulation level and the operating temperature were found to be key to the lifespan of the power transformer. A hybrid of these gives the useful model used to determine the remaining lifetime of the power transformer. The remaining lifetime, determined based on the prevailing operating conditions is added to the service age to determine the overall lifespan.

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