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Prediction of Transformers Conditions and Lifetime Using Furan Compounds Analysis

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ABSTRACT Power transformers are considered as one of the main parts of any power system. Because of their importance and high cost, it is important to check the state of the insulation system inside them from time to time. Dissolved gas analysis test as well as Furan compounds analysis has been widely used as recommended methods to assess the transformer insulation system state. This paper introduces an empirical form that can predict the degree of polymerization of the paper insulation system inside the transformer by measuring Furan compounds. This proposed empirical form is validated by comparing its results with other methods reported in the literature in two different case studies. Subsequently, the proposed formula is used to predict the lifetime and the insulation system state of a transformer that operates in Abo Sultan steam power plant in Egypt. The 2-FAL had been measured five times for this transformer in the period between 2013 and 2015. Depending on these five measurements, an equation that can predict 2-FAL level inside this transformer in relation to its age has been proposed. This proposed equation is validated by comparing the measured and estimated 2-FAL in the period between 2016 and 2019. According to the attained results, it was found that the insulation system inside the investigated transformer seems to face a serious problem and this transformer cannot remain in service after 2027. Finally, the paper introduced a general technique that can be used for any transformer in order to predict its remaining lifetime.

INDEX TERMS Furan compounds, oil-paper insulation system.

I. INTRODUCTION

The reliability of the power transformer insulation system is a major concern point for electric power utilities. The aging process of the insulation system may take place accompanied with degradation in the insulating characteristics. This degradation may lead to a complete failure in the transformer insulation system and consequently, a serious problem can take place [1]. Due to its low cost and the ability to withstand high electrical and mechanical stresses, oil-paper insulation system is widely used as the main power transformers insulation system [2], [3]. In different sites all over the world, many transformers have reached their designed lifetime. Due to the lack of replacement costs, these transformers are kept in service while implementing periodic monitoring and tests to the state of the internal insulation system. Thus, diagnostic methods such as dissolved gas analysis tests and Furan compounds analysis are gaining more concern as an efficient yet effective approach to assess the reliability of transformers insulation systems [4].

Chemical construction of the insulating paper consists of a chain of anhydroglucose connected together with glycosidic bonds [5], [6]. As a result of multi anhydroglucose rings presence in this chemical compound, two weak points are formed. Firstly is C-O molecular bonds, and secondly is the glycosidic bonds [7]. These bounds have low thermal stability in comparison with hydrocarbon bonds that exist in the transformer oil [5]. Thus, carbon monoxide, carbon dioxide, hydrocarbon byproducts, water and Furan compounds are generated during insulating papers decomposition that may occur as a result of the thermal aging process [8]–[10]. Fortunately, Furan compounds are generated only from cellulose. However, other degradation byproducts can be emitted during oil aging phenomenon [10]. Furthermore, most of these Furan compounds are stable in transformer oil for high temperatures up to 140°C. [11]. Thus, the presence of Furan compounds

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remains in oil transformers even at high temperatures in order to provide an indication to a serious problem facing paper insulation system.

2-Furfural (2-FAL), 2-Furfurol (2-FOL), 5-Hydroxy methyl 2-furfural (5-HMF), 5-Methy-2-furfural (5-MEF), and 2-Acetylfuran (2-ACF) are the five chemical products that defined as Furan Compounds [12]. 2-FAL can be considered the main component of Furan compounds and many researchers studied the relation between its presence and the decrease in the Degree of polymerization (DP) of the insulating paper [13]–[15]. DP can be defined as the average number of glycosidic rings in cellulose macromolecule chain [1]. New Kraft insulating paper has a DP value approximately equal to 1200 while a DP value less than 200 indicates that the insulating paper must not be used any more [16].

Previous literature indicated that the age of the transformer is mainly correlated to the state of the solid insulating system [16]–[19]. DP is a widely accepted measurement that examines the health state of the insulating paper inside the transformers [16], [17], [20], [21]. However, it is not practically recommended to take a sample of insulating paper from an operating transformer in order to measure DP. This may lead to local damage in the winding system. Moreover, viscometry method that used to measure DP, is not a definite accurate method because it is affected by the surrounding temperature [22]. Consequently, different mathematical models have been presented in order to estimate the DP factor depending on Furan tests instead of measuring it. Chendong and Xue [23] and Pablo [24] have introduced two widely applied models presented by equations 1 and 2 respectively. Many researches have depended on these two models as accurate and applicable models for DP estimation [5], [25]–[31].

$$\log_{10}(2-\mathrm{FAL}_{\mathrm{ppm}}) = 1.51(.0035)\times(\mathrm{DP}) \quad (1)$$

$$\mathrm{DP} = (800)/\{(0.186\times 2-\mathrm{FAL}_{\mathrm{ppm}})+1\} \quad (2)$$

where ppm: part per million

In this paper, a new proposed formula used to predict DP factor in relation with 2-FAL is presented. This empirical form has been deduced by experimental tests. The validity of this formula is examined by estimating the DP of the insulating paper and comparing the obtained results with other results obtained by De Pablo and Chendong models. Finally, the new form is used to predict the lifetime and the insulation system state of a transformer that operates in Abo Sultan steam power plant in Egypt. Furthermore, a general technique that can be used in order to estimate the remaining lifetime of any transformer will be introduced.

II. EXPERIMENTAL RESULTS OF (DP) AND (2-FAL) TEST

In the present work, the impregnation process has been properly accomplished in order to provide accurate results and consistent testing conditions. Following the DIN EN 60763-2 standard, 0.5 mm thickness Kraft papers have been dried at a pressure that does not exceed 1 mbar at a temperature of 105°C for 24 hours. Then, the dried Kraft papers are impregnated with the insulating oil at a pressure lower than 1 mbar. Finally, the oil-paper insulation is kept in a ten liter capacity aluminum vessel. After finishing the impregnation process, the papers are able to withstand the aging tests [32].

In the current research Kraft insulating papers have been impregnated with two different types of oil and kept in two separated aluminum vessels. The first oil is paraffinic-based oil, while the other is naphthenic-based oil. These two vessels have been kept in an electrical oven at a temperature of 130°C in order to simulate the thermal aging process. Every 28 days, a sample of the impregnated paper has been taken from each vessel as a cycle of the thermal aging process as reported in [33]. The 2-FAL compound and the DP factor have been measured for every sample in order to obtain the proposed empirical form.

In this experiment, DP has been measured according to ASTM D4243 standard and 2-Fal has been measured according to ASTM D5837 standard. Every test has been repeated six times with five paper samples for each oil in order to get accurate results. DP has been measured for all paper samples before the thermal aging cycles. It has been found that DP of all samples was 1100 ± 15 in the pre-aging period.

TABLE 1. Measured values of DP and 2- FAL {part per billion (ppb)}.

Ageing cycle (days)	Naphthenic oil DP	Naphthenic oil 2-FAL	Paraffinic oil DP	Paraffinic oil 2-FAL
28	580	700	520	1000
56	390	4000	380	4000
84	230	7000	230	7000
112	210	9000	200	14000
140	160	12000	150	20000

It is clear from Table 1, that the DP of Kraft papers has been decreased to be approximately 50% from its value in the pre-aging tests. These results agree with previous results showed that the insulating papers suffer from excessive deterioration in the primary stage of the thermal aging [17], [34]. It can be also concluded from table 1 that, the DP of the impregnated papers in Paraffinic-based oil is slightly lower than its value in the case of Naphthenic one. This result can be explained according to the fact that Kraft papers degrade in the case of Paraffinic-based oil with a faster rate than in the case of Naphthenic-based oil [35]. Not only the DP but also the color of the insulating paper differs with the change of the oil. Fig.1 shows the changing in the insulating paper color after 112 days of thermal aging. The color of Kraft papers immersed in paraffinic oil turned to be dark brown while in the Naphthenic oil they turned to be dark yellow. This change in color may be correlated to the different deterioration rate of the Kraft papers in Naphthenic and paraffinic oils.

III. PROPOSED EMPIRICAL FORMULA BETWEEN (2-FAL) AND DP

Based on the experimental results presented in Table 1, a new empirical form has been proposed with the use of MATLAB

TABLE 2. Empirical form parameters.

Parameters	Naphthenic oil	Paraffinic oil
a	634.95605	608.57587
b	-0.076591657	-0.08562357
c	3.097411×10^{-6}	5.9920883×10^{-6}
d	0	$-1.426611 \times 10^{-10}$

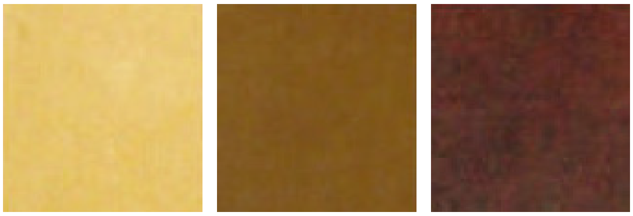

FIGURE 1. Variation of the color of the Kraft papers before thermal aging cycles (a), and after 112 days in Naphthenic (b) and Paraffinic (c) oils.

program. MATLAB program can provide a mathematical formula between two constraints depending on the existing results as explained in [36]. Equation 3 is proposed in order to estimate the DP for the aged Kraft insulating papers accurately after 2-FAL measuring. This empirical form is valid for 2-FAL that does not exceed 12000 ppb in the case of Naphthenic oil and 20000 ppb in the case of Paraffinic oil. Values of a, b, c, and d constants differ with the change of the oil type either it is Naphthenic or Paraffinic based oil. Table 2 represents the different constants values for the two types of used oil.

By applying this new formula, Fig. 2 has been obtained. This figure illustrates the graphical representation of the relation between DP and 2-FAL in cases of Naphthenic and Paraffinic-based oils in the previously mentioned limits of 2-FAL. Either with the use of Fig. 2 or equation 3, one can detect the value of DP that corresponds to the measured 2-FAL and estimate the state of the insulating papers inside an operating transformer.

$$DP = a + b(2 - FAL_{ppb}) + c(2 - FAL_{ppb})^2 + d(2 - FAL_{ppb})^3 \tag{3}$$

IV. VALIDATION OF THE PROPOSED EMPIRICAL FORM

In order to validate Equation 3, two case studies have been examined. The DP values are estimated using the proposed formula, De Pablo formula, and Chendong formula. Subsequently, the estimated DP values are compared with the experimentally measured DP in the two case studies. Thus the accuracy of the proposed formula can be assessed in comparison with these two widely accepted techniques.

A. CASE STUDY I

In the first case study, DP and 2-FAL had been experimentally measured for five different transformers that suffer from severe failure and could not remain in the power network anymore. The insulating oil inside these transformers was paraffinic-based oil [33].

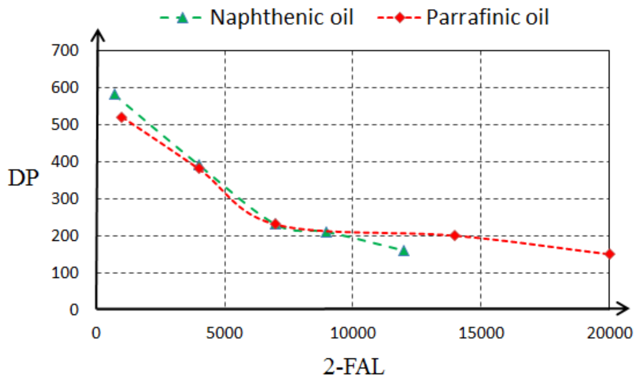

FIGURE 2. The relation between DP (y-axis) and 2-FAL (x-axis) for Naphthenic and paraffinic-based oil.

Table 3, illustrates a comparison between the values of DP measured in [33], the DP values estimated by Chendong form, De Pablo form, and the proposed one. In order to assess the accuracy of each method, the differences between the estimated ($DP_{Est.}$) and the measured ($DP_{Measu.}$) values have been calculated with the use of equation 4. It is obvious that the estimation error of each method is calculated as the percentage of the experimentally measured DP. The numerator of equation 4 is an absolute value in order to calculate the magnitude of the difference between the estimated and the measured DP values regardless that the value is positive or negative. Thus, one can compare between the different methods on the same bases.

$$\text{Estimation error} = \{|DP_{Est.} - DP_{Measu.}|/DP_{Measu.}\} \times 100 \tag{4}$$

The calculated estimation error in the cases of Chengdong, De Pablo, and the proposed form for the five transformers is illustrated graphically in Fig. 3. It is clear that the proposed formula has error values less than Chendong form in all cases. The proposed formula is more accurate than De Pablo formula in three of the five evaluated transformers, i.e., with a percentage of 60% from the whole cases. Thus, it can be concluded that the proposed formula gives an accurate estimation of the DP values in compared to Chendong and De Pablo forms in this case study.

B. CASE STUDY II

Leibfried *et al.* [37] introduced a database for more than thirty five transformers that operate in a German power network. These transformers have been classified into three main categories. The first category includes generation step-up transformers. The second category includes grid-power transformers. The final category includes 16.7 Hz railway transformers. In this database not only the age of each transformer but also voltage rate, complex power, 2-FAL amount, and average DP of the insulating papers have been mentioned. In the present research the measured data of the first category

TABLE 3. Comparison between Chendong form, De Pablo form, and the proposed formula (Case study I).

Case study transformer (measured values) [33]		Chendong form Eq. (1)	Chendong error percentage %	De Pablo form Eq. (2)	De Pablo error percentage %	Proposed formula Eq. (3)	Proposed formula error percentage %
2-FAL (ppm)	DP- measured	DP- estimated		DP-estimated		DP-estimated	
6.6	245	197	19.5%	359	46.5%	263	7.2%
7.5	298	181	39.1%	334	12%	243	18.5%
12	208	123	40.8%	248	16%	197	5.2%
9	237	158	33%	299	26%	219	7.6%
9.2	322	156	51%	295	8%	216	32%

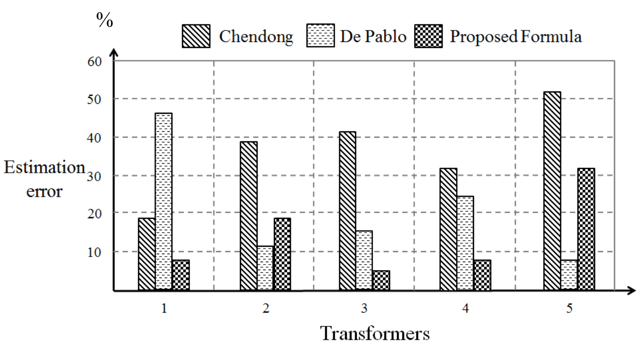

FIGURE 3. Comparison between the estimation error values in Chengdong, De Pablo and the proposed formula (case study I).

of transformers is used to assess the accuracy of the three previously mentioned formulas used to estimate the DP values in terms of the measured 2-FAL.

The first category has been chosen because in this category $250 \leq DP \leq 935$. However, in the second category $442 \leq DP \leq 942$ and in the third category $189 \leq DP \leq 542$. Thus, it is clear that the first category includes different transformers with a wider range of DP values compared to the other two categories. Consequently, one can assess the accuracy of the different DP estimation formulas not only for the aged transformers but also for relative new ones. As the type of the insulating oil used in each transformer has not been mentioned in [37], DP has been estimated by the proposed formula for both Paraffinic and Naphthenic-based oil.

Depending on the results obtained in table 4, four two-side comparisons have been conducted as shown in Fig.4. The first comparison is between Chendong and the proposed. formula in the case of Paraffinic oil. The second comparison is between De Pablo and the proposed formula in the case of Paraffinic oil. The third comparison is between Chendong and the proposed formula in the case of Naphthenic oil. The final comparison is between De Pablo and the proposed formula in the case of Naphthenic oil.

It can be concluded from Fig. 4 that, the proposed formula yield more accurate DP estimations with error values less than the other two formulas in all comparisons except the first one.

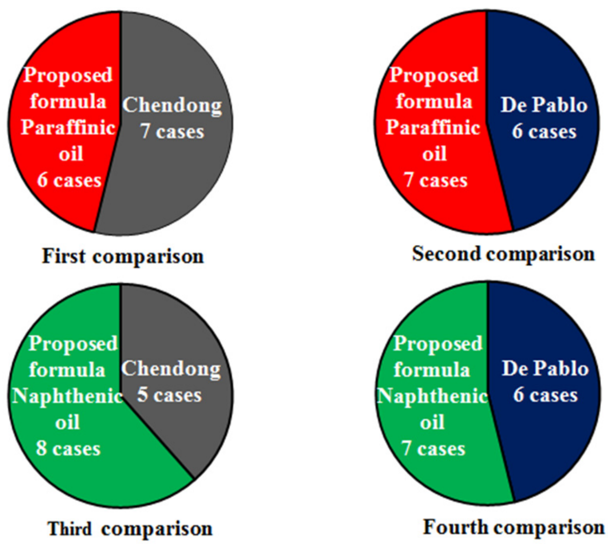

FIGURE 4. Four Comparisons between the proposed formula, Chendong, and De Pablo methods (case study II).

In the second comparison, the proposed formula in the case of Paraffinic oil gives accurate DP estimation more than De Pablo's formula in seven cases out of the thirteen test cases. Similar results were obtained in the fourth comparison. The proposed formula in the case of Naphthenic oil gives more accurate DP estimation than De Pablo method in seven cases out of the thirteen examined cases. Thus it can be said that the proposed formula archives more accurate DP estimation for both Paraffinic and Naphthenic oil compared to De Pablo's formula in 54% of the whole test cases.

In the third comparison, the proposed formula in the case of Naphthenic oil gives accurate DP estimation compared to Chendong method in eight cases of the thirteen testes cases. However, in the first comparison Chendong formula gives a more accurate DP estimation compared to the proposed formula in case of Paraffinic oil in seven cases out of the thirteen examined cases. Thus it can be said that the proposed formula archives more accurate DP estimation for both Paraffinic and Naphthenic oil compared to De Pablo's formula in 54% of the whole test cases.

TABLE 4. Comparison between Chendong form, De Pablo form, and Proposed formula (Case study II).

Case study transformer (measured values) [37]		Chengdong form Eq. (1)	Chengdong error percentage %	De Pablo form Eq. (2)	De Pablo error percentage %	Proposed formula Paraffinic oil Eq. (3)	Proposed formula error percentage % Paraffinic oil	Proposed formula Naphthenic oil Eq. (3)	Proposed formula error percentage % Naphthenic oil
2-FAL (ppm)	DP-measured	DP-estimated		DP-estimated		DP-estimated		DP-estimated	
2.2	250	333.6	33.4 %	567	126.8 %	447	78.8 %	481	92.4%
4.5	219	243	10.95 %	434	98.1%	329	50.2%	351	60.2%
0.63	585	488	16.6 %	716	22.4 %	556	4.9 %	587	0.34%
0.24	636	608	4.4 %	765	20.3 %	587	7.7%	616	3.14%
0.43	605	536	11.4 %	740	22.4 %	571	5.6 %	602	0.5%
0.25	733	603	17.7%	764	4.1%	586	20.2%	615	16.13%
0.3	746	580	22.3%	757	1.5%	584	21.7%	612	18%
1.68	519	367	29.3%	609	17.3%	481	7.32%	516	0.57%
2.9	483	299	38%	519	7.5%	406	16%	438	9.4%
0.29	465	585	25.8%	759	63.2%	583	25.1%	613	31.8%
0.08	714	744	4.2%	788	10.4%	601	15.8%	627	12.18%
0.05	801	803	0.25%	792	1.12%	604	24.9%	631	21.2%
0.22	935	619	33.8%	768	17.8%	589	37%	620	33.6%

In the third comparison, the proposed formula in the case of Naphthenic oil gives accurate DP estimation compared to Chendong method in eight cases of the thirteen testes cases. However, in the first comparison Chendong formula gives a more accurate DP estimation compared to the proposed formula in case of Paraffinic oil in seven cases out of the thirteen examined cases.

It can be generally concluded from the two previously mentioned case studies that, the proposed empirical formula presented in the current research gives accurate DP estimation results in comparison with Chendong and De Pablo formulas.

V. PREDICTION OF THE REMAINING LIFETIME OF AN OPERATING TRANSFORMER USING THE PROPOSED EMPIRICAL FORMULA

DP and 2-FAL values have been measured for different transformers that operate in Abo Sultan power plant in Egypt. This power plant contains six transformers that are classified into three main groups. The first group includes the two main transformers in the plant. The second group includes two startup transformers. Finally, the third group includes two auxiliary transformers. The insulating oil inside these six transformers is Naphthenic-based oil. As a result, DP has been estimated in relation with the measured 2-FAL by using the proposed formula. Next, the estimated values are compared to the measured values in order to assess the accuracy of the proposed formula another time. DP has been measured for these transformers while they were in maintenance.

The error between the estimated and the measured DP values for the six transformers is presented in Table 5. The error has been calculated by equation 4. It is obvious from Table 5, that the proposed formula yield accurate predictions with an estimation error that does not exceed 7% from the DP measured values. It can be also concluded that the first five transformers have insulating papers with relatively good DP values. These DP values indicate that these transformers have a moderate aging rate. However, the last auxiliary transformer has an extensive deterioration rate in its insulating paper system as the measured DP is lower than 450 [38]–[40]. Thus, the remaining lifetime of this transformer has to be

TABLE 5. Data of under evaluation transformers in Abo Sultan steam power plant (validation of Eq.3).

Transformer category	Operating date	Rated Power (MVA)	Rated voltage (kV)	Sampling date	Measured 2-FAL (ppb)	Measured DP	Estimated DP by Eq. (3)	Estimation Error %
Main transformer unit (A)	19/3/1983	192	15/220	21/1/2013	41	635	631.7	0.51%
Main transformer unit (B)	15/8/1983	192	15/220	21/1/2013	42	637	631.8	0.82%
Startup transformer unit (A)	19/3/1983	16	220/6.3	21/1/2013	56	632	630	0.317%
Startup transformer unit (B)	15/10/1984	16	220/6.3	21/1/2013	44	634	631	0.47%
Auxiliary transformer unit (A)	19/3/1983	16	15/6.3/63	20/7/2011	149	622	623.5	0.24%
Auxiliary transformer unit (B)	15/8/1983	16	15/6.3/6.3	21/1/2013	3407	409.9	384	6.4%

investigated in order to avoid any sudden failure in its insulation system due to the aging process.

In order to estimate the remaining lifetime of a transformer, the deterioration rate of its insulating system has to be taken into account. This deterioration rate is correlated to the change in the DP value of the insulating papers inside this transformer. As the changing in DP value can be estimated by Furan compounds analysis, the recorded results of Furan compound tests must be studied. Previous literatures had also depended on Furan test analysis in order to determine the remaining lifetime of operating transformers [29], [40]–[42].

Table 6 presents the measured Furan compounds and also the 2-FAL for the investigated transformer since January 2013 until January 2015. With the using of these five 2-FAL measurements an empirical formula is obtained. This empirical formula is used to estimate the aging rate of the insulating paper inside this transformer for the next years.

Equation 5 shows the empirical formula that is used to estimate the amount of 2-FAL produced as a result of paper degradation inside the power transformer. This formula enables the user to calculate the 2-FAL knowing of the age of the transformer. Values of x, y and z constants differ for each transformer as every transformer has its own aging rate. In the case of the second auxiliary transformer in Abo Sultan station x = 13169.05, y = - 826.337 and z = 16.662. These constants can be determined for any other transformer by studying the amount of 2-FAL produced inside it.

$$2 - \mathrm{FAL}_{(\mathrm{ppb})} = x + \mathrm{y(t)} + \mathrm{z(t)}^2 \quad (5)$$

where t: transformer age at sampling time (years).

Equation 5 has been experimentally validated by estimating the amount of 2-FAL at different sampling times since January 2016 until January 2019. Then, the estimated values ($2\text{-FAL}_{\mathrm{Est.}}$) have been compared to the measured values ($2\text{-FAL}_{\mathrm{Measu.}}$) at this period in order to calculate the estimation error. Equation 6 shows that the estimation error in this case is calculated as a percentage from the $2\text{-FAL}_{\mathrm{Measu}}$. exactly as in the DP case. It is obvious from Table 7 that the suggested formula gives 2-FAL accurate estimation with an estimation error that does not exceed 2% from the measured values.

TABLE 6. Measured Furan compounds and 2- FAL of auxiliary transformer unit (B) since 2013 until 2015.

Sampling date	Transformer age (years)	Total Furan compounds (ppb)	2- FAL (ppb)
1/2013	29.41	3757	3275
5/2013	29.75	3810	3332.38
11/2013	30.25	3909	3384
8/2014	30.9	4070	3647
1/2015	31.41	4184	3682

$$\mathrm{Error} = \{|2-\mathrm{FAL}_{\mathrm{Est.}} - 2-\mathrm{FAL}_{\mathrm{Measu.}}|/2-\mathrm{FAL}_{\mathrm{Measu.}}\} \times 100 \quad (6)$$

Depending on equations 3 and 5 which have been proved to give accurate estimations, the remaining lifetime of the assessed transformer in Abo Sultan power plant can be calculated. The insulating oil inside this transformer is Naphthenic-based oil. Therefore, DP can be calculated by equation 3 and with the use of the constants presented in

TABLE 7. Measured and estimated 2- FAL of the auxiliary transformer unit (B) since 2016 until 2019. (validation of Eq.5).

Sampling date	Transformer age (years)	2-FAL (ppb) Measured	2-FAL (ppb) Estimated Eq: (5)	Estimation error %
1/2016	32.41	3952	3887.49	1.63 %
12017	33.4	4189	4154.8	0.815%
1/2018	34.4	4497	4458.8	0.848%
1/2019	35.4	4882	4794.7	0.21%

table 2. By substituting the 2-FAL term in equation 3 with its value in equation 5, a new relation can be obtained between DP and the operating age of the assessed transformer as shown in equation 7. This equation can estimate the DP of the insulating paper inside the auxiliary transformer in relation with the age of this transformer. The value of the constants represented in equation 7 belongs to the assessed transformer and differ from one transformer to another.

$$DP = \alpha+\beta(t)+\gamma(t)^2 + \delta(t)^3+\lambda(t)^4 + \zeta(t)^5+\eta(t)^6 + \kappa(t)^7 \quad (7)$$

where t: transformer age at sampling time (years).

α : 166.63843 β : −4.793216
γ : 2.2588904 δ : −0.088332514
λ : 0.000950421 ζ : $-1.6065814 \times 10^{-6}$
η : 1.57627×10^{-8} κ : $-6.5894446 \times 10^{-11}$

Table 8 introduces the DP prediction of the insulating papers inside Abo Sultan auxiliary transformer since 2012 until 2027. It is worthy to be mentioned that the DP estimated in the period between 2012 and 2015 is $393.5 \leq DP \leq 423$. This estimation matches with the DP value that has been already measured in 2013 and represented in table 5. The estimated DP values have been graphically represented in Fig.5 in order to assess the change in the slope which indicates the rate of change in the DP values during different time periods. The state of the insulating papers has been presented in table 8 depending on the classification that is previously introduced in [21], [38]–[40].

It is commonly known that the insulating paper system suffers from moderate deterioration if $450 \leq DP \leq 1000$. If $250 \leq DP \leq 450$ the insulating paper seems to face an extensive deterioration problem. Critical state is the description of the insulating paper situation if the DP value decreased to be less than 250. Finally, it is a completely dangerous decision to keep a transformer in service while the DP value is less than 200 as it indicates that the insulating papers inside this transformer suffer from unstoppable deterioration and have no mechanical strength [21], [38]–[40]. Thus the end of transformer life can be identified as the instance at which the DP of its insulating papers reduced to be lower than 200.

TABLE 8. Estimated DP and corresponding insulating papers state of the auxiliary transformer unit (B).

Sampling date	Transformer age (years)	DP Estimated Eq: (7)	Insulating papers state
4/2012	28.66	423.11	Extensive deterioration
4/2015	31.66	393.47	
4/2018	34.66	350.8	
4/2021	37.66	299.77	
4/2024	40.66	246.72	Critical state
4/2027	43.66	199.63	Transformer must not remain in service any more

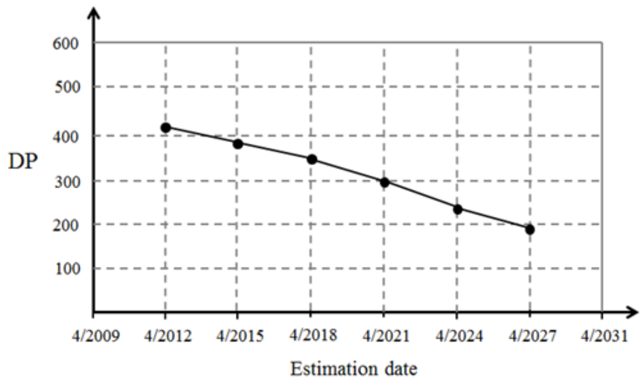

FIGURE 5. Estimated DP values of the insulating papers inside the Auxiliary transformer unit (B) in Abo Sultan power plant in Egypt.

This definition is only concerned about the insulating papers state. According to this definition, it can be noticed that the assessed transformer cannot remain in service after April 2027.

VI. RESULTS ANALYSIS

Depending on the results presented in this paper, a new technique can be suggested in order to estimate the remaining lifetime of any operating transformer. The proposed technique can be summarized by the flowchart shown in Fig. 6. The first step is to study the relation between previously measured 2-FAL values and the transformer age at the dates of these measurements. Thus, one can identify the deterioration rate of the insulating papers. This step is required to create a mathematical form as equation 5 by using MATLAB program. This form enables the users to predict the 2-FAL that will be emitted from the insulating papers in the upcoming years. In the present research, the mathematical formula has been suggested depending on five 2-FAL measurements implemented in the period between 2013 and 2015 for an operating transformer. Then, it has been validated by estimating the 2-FAL in the period between 2016 and 2019 and comparing the estimated values with the already measured values at the same period. The error between the estimated and the

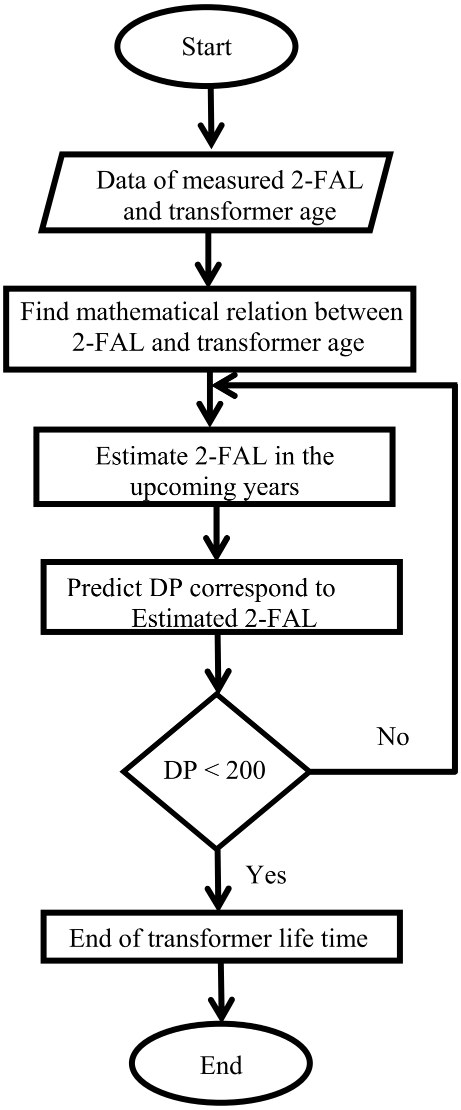

FIGURE 6. Flowchart illustrates the suggested scenario that can be used to estimate maximum transformer lifetime.

measured values did not exceed 1.63% from the measured value as shown in Table 7. Finally, the estimated 2-FAL values are substituted in equation 3 to calculate the DP of the transformer insulating paper. If the estimated DP is higher than 200, the transformer can remain in service. These two steps are repeated until reaching the instance when the DP value becomes lower than 200. This instance can be considered as the end of the transformer lifetime.

In the current research, the second step has been merged with the first one and presented in equation 7. This equation has connected the transformer age directly with the DP of its insulating papers. In order to check the state of the insulating paper inside the auxiliary transformer in Abo Sultan station, the 2-FAL amount will be measured annually and this measured value will be compared with values estimated by equation 5. This comparison is implemented to check whether the transformer can stay in service until 2027 as predicted or not.

FIGURE 7. Atmospheric air leakage in the transformer under-study [43].

In a previous research, the reasons of the extensive deterioration that takes place inside the paper insulating system of the auxiliary transformer unit (B) in Abo Sultan power plant have been studied [43]. It has been stated that atmospheric air leakage was the main cause of the deterioration that occurred to the insulating system. A small gas void had been explored in the cover of the transformer as shown in Fig.7 during the maintenance of the whole transformers in Abo Sultan power plant in 2013. The other transformers had been vacuumed then filled with Nitrogen under pressure 3 psi (pounds per square inch). The investigated transformer had been brought to service without maintenance as a case study. Due to this air leakage, the results of the dissolved gas analysis test that implemented periodically to the investigated transformer indicated a sudden increase in the dissolved gases quantities and also in CO_2/CO ratio. Thus, special care had been taken to this transformer and also the demand to predict its remaining lifetime had been increased. In order to be on the safe side, the transformer will be brought out of service when its insulating system will be in the critical state. According to Table 8, it is estimated that the insulating system will reach the critical state at 2024.

VII. CONCLUSION

The present research introduced two important new points. The first one is an empirical formula that can predict DP of insulating papers as a function of the measured 2-FAL. This suggested formula has been validated by comparing the estimated DP values with experimental results obtained in two different case studies. It has been proved that the proposed empirical formula presented accurate estimations of DP values compared to Chendong and De Pablo models in the two case studies examined in this paper.

The second point represented in this research is a proposed framework that has been implemented in order to predict the maximum lifetime of an operating transformer that serves in Abo Sultan power plant in Egypt. The insulating paper system inside this transformer seemed to face a serious problem. The relation between 2-FAL and the transformer age has been studied and used to predict the 2-FAL at any age of the assessed transformer. Then, the estimated values of 2-FAL are used to predict the corresponding DP. It 1has been stated that this transformer cannot remain in service after 2027.

For more safety, Furan compounds analysis will be conducted annually for this transformer. Measured 2-FAL will be compared with value estimated by equation 5 to check whether the transformer will run in the estimated track or not. Furthermore, the transformer will be brought out of service when DP of its insulating papers reaches 250 instead of 200.

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