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Transformer Remaining Life Calculation Based on Degree of Polymerization (DP)

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***Abstract*—Oil and insulating paper are the two main components that constitute the insulation system of a transformer. Aging of the insulation system is a process that is affected by several factors such as operating stresses in the transformer, overloads, operation of the transformer at temperatures above the limits, and short circuits, these are some of the factors. Therefore, these materials are degraded during the operation of the transformer, as a result of these processes, and its condition determines the status of the transformer. The degree of polymerization is the main indicator that determines the aging of the insulation system and consequently leads to a decrease in the tensile mechanical strength of the solid insulation. A direct approach to material sampling in this case of insulating paper and testing, is a complicated process, sometimes impossible, so as an alternative oil sample with an indirect non-invasive method is used to estimate the DP value. The concentration of furan compounds provides a paper degradation residue in the insulating oil, which is created as a result of the degradation of the insulating system.**

This paper analyzes the influence of the degree of polymerization and the correlation it has with 2-furaldehyde (2-FAL), to create new formulas by generating an analogy between DP and 2-FAL, to evaluate the aging process and to calculate the remaining lifetime of the transformer. As a mathematical model, a regression analysis based on 50 transformer oil samples was used. In this study to verify the proposed formulas, ten transformers were used to calculate DP based on 2-FAL concentrations. The results have been compared with models according to different authors with the results of measurements and DP. The results show an estimation error of less than 4.06 % for logarithmic and 5.87 % polynomial equations, against the measured DP.

Keywords—Transformer aging; insulation system; degree of polymerization (DP); 2-furaldehyde (2-FAL); remaining life.

I. Introduction

Overall, power transformers are very reliable devices, with an expected life cycle of 25 to 30 years, according to the IEEE standard [2]. However, operational experiences have shown that power transformers can operate for more than 40 years, or sometimes their lifetime can be shorter than 20 years [3]. For this purpose, it is very important to predict and estimate the lifetime of the transformer, to be able to balance the number of expected and unexpected failures in the number of actions to improve the condition. Power transformer faults not only cause power outages and energy supply, but also reduce system reliability and have a significant impact on power quality, but the financial impact is also very high [4]. It has been determined that the life of the transformer is equal to the life of the insulation system because eventual breakdowns of the dielectrics in the insulation system cause the collapse of the transformer. Therefore, monitoring the condition of the transformer during operation is necessary, and the topic is of great interest to engineers and researchers [4, 5]. During normal operation, the insulation system consisting of oil and insulation paper is exposed to electrical, thermal, and mechanical stresses, causing degradation and aging [6]. Degradation [7] of the insulation system in transformers is a chemical phenomenon, where three degradation mechanisms act together: hydrolysis, pyrolysis, and oxidation [8]. Thus, temperature, water, and oxygen are the main agents for cellulose degradation as well as oil oxidation. In addition to the electrical properties, the mechanical properties of the insulating paper are also a key parameter, as they must be able to withstand any electrical or mechanical stress [9]. To evaluate the level of decomposition of the insulation paper, including the mechanical strength and durability of the paper insulation, the degree of polymerization DP is used. According to some studies, the new insulation paper has an average DP of 1200-1500 [10]. As the paper ages, the DP decreases and the paper turns dark brown and loses its tensile strength, while when the DP value is between 200-250 it marks the end of its life [11]. However, sampling the insulation paper when the transformer is in service or not is complex. Due to this, alternative indirect evaluation methods have been developed, which essentially involve the analysis of cellulose by-products released during thermal or electrical processes. The by-products resulting from the decomposition of the insulation-cellulose (furan compounds, gases, acids, water, and alcohols), their presence and concentration represent a good basis for assessing the condition of the insulation paper. This work presents an overview of the development of furan compounds and the relationship between 2-FAL and DP. Furthermore, a thorough examination of the different PDs, the model-defining patterns they describe, and the relationship between 2-FAL and PD is presented. New formulas proposed based on regression analysis of a fleet of transformer oil samples are also presented. Furthermore, a comparative study was conducted for the considered models considering the 2-FAL data to determine the DP and thus the remaining life.

II. Furanic Compound

The furanic compounds of oils have been studied for years, and some theoretical models have been proposed to estimate the polymerization degree of paper from the furan content [12, 13]. Cellulose paper in the transformer when subjected to temperatures of 100 °C and above for various reasons and as a result of various degradation processes will generate degradation by-products and some of them are soluble in oil. These by-products are formed as a result of the aging process and dissolve in the oil, so this oil can be analyzed for the presence of furan concentration. Recent studies suggest that furan compounds that are created due to electrical discharges affect the cellulose but in much smaller amounts. Due to thermal stress or thermal aging, large amounts of furanic compounds can be generated after these solid cellulosic insulation materials are subjected to a very high temperature (ie 120 °C and above) [14]. The rate of formation of these furanic compounds can be a function of various other factors such as water content and oxygen concentration. Five main furanic compounds have been identified in transformer insulating oil, namely 2-Furaldehyde (2FAL), 2-Acetylfuran (2ACF), 5-Hydroxymethyl-2-Furaldehyde (5H2F), 2-Furfurol (2FOL), and 5-Methyl-2-Furaldehyde (5M2F) [15]. In the following table, the furan components and the main causes are presented:

TABLE I. Causes of Furanic Compound Generation

Abbreviation	Furan Compound Name	Observed Cause
2FAL	2-Furaldehyde	Over-temperature and regular aging
2-ACF	2-Acetylfuran	Scarce, no conclusive trigger
5H2F	5-Hydroxymethyl-2-Furaldehyde	Elevated temperatures
2FOL	2-Furfurol	Elevated moisture content
5M2F	5-Methyl-2-Furaldehyde	Oxidation

Therefore, the stability of these products is very essential, because otherwise, it will lead to incorrect conclusions drawn from the analysis. Some of the above furan compounds are formed during aging but are very unstable under many conditions. Therefore, they cannot be used or are not useful for diagnosis [16]. An exception is the byproduct 2-furaldehyde (2-FAL), also known as cellulose 2-furfural, which is considered the most stable byproduct and is commonly used to predict the PD value of insulation paper.

III. Interrelation Between Furans and Degree of Polymerization

However, measuring the concentration of furanic compounds from an oil sample is a relatively simple process, while the interpretation is complex since more than one mechanism is involved in the aging process. Recent studies suggest that furan compounds that are created due to electrical discharges affect cellulose but in much smaller amounts. Due to thermal stress or thermal aging, large amounts of furanic compounds can be formed after these solid cellulosic insulating materials are subjected to a very high temperature (ie 120 °C and above) [16]. The rate of formation of these furanic compounds can be a function of various other factors such as water content and oxygen concentration. The number of furans that are created by this process in transformer oil is large, but one of which is related to the degree of polymerization of paper insulation (DP), is 2-furaldehyde (2FAL) [17]. The correlation between the degree of polymerization and the furan component 2-FAL is presented in the following table:

TABLE II. Correlation between DP and 2-FAL [24]

Furan (2-FAL) Content (ppm)	DP value	Significance
<0.01	>1200	New Oil
0 – 0.1	1200 – 700	Healthy Transformer
0.1 – 1.0	700 – 450	Moderate Deterioration
1 – 10	450 – 250	Extensive Deterioration
> 10	<250	End-of-Life Criteria

Correlation is a process that shows the nature and strength of the presence or absence of a relationship between variables, while the indicator of this relationship of the form of spread between variables is the correlation coefficient (R^2) and as a first step in determining this relationship is drawing the shape than distribution [18], [19], [20]. In this process, one of the variables is considered the dependent variable, and the other variable or variables are the independent variables. The correlation coefficient can be positive, or negative and have zero value.

IV. THE PROPOSED LOGARITHMIC AND POLYNOMIAL EMPIRICAL FORMULA

In this research, mathematical models have been developed based on the mathematical regression model. It is a method used to estimate the value of one of the two parameters [x, y], using the values of the other variables. Regression can be simple linear regression, multiple linear, and non-linear regression. The proposed logarithmic and polynomial experimental formulae in this study are then expressed as follows in Eq. (1) and Eq. (2).

$$DP = -120{,}3 \cdot \ln(2FAL) + 449{,}83 \quad (1)$$

The coefficient of determination (R^2) is a mathematical measurement that explores how a change in one variable affects another [1]. It's a measure of how powerful the interactions between two or more variables are. For Eq. (1), the computed coefficient of determination value is:

$$R^2 = 0.9995$$

The proposed polynomial is expressed as:

$$DP = 9{,}0087 \cdot 2FAL^6 - 122{,}87 \cdot 2FAL^5 + 650{,}81 \cdot 2FAL^4 - 1691{,}1 \cdot 2FAL^3 + 2255{,}4 \cdot 2FAL^2 - 1546{,}9 \cdot 2FAL + 902{,}24 \quad (2)$$

The corresponding coefficient of determination:

$$R^2 = 0.983$$

Where:

R-squared (R^2) is the coefficient of determination, and it is a statistical measurement examining how the change in one variable can influence another [21].

It is an indicator of the strength of the relationship between two or more variables. It can be computed as follows [22]:

$$R^2 = 1 - \frac{\sum(estimated\ X - actual\ X)^2}{\sum(actual\ X - \bar{X})^2} \quad (3)$$

Where $\bar{X}$ refers to the mean value of X.

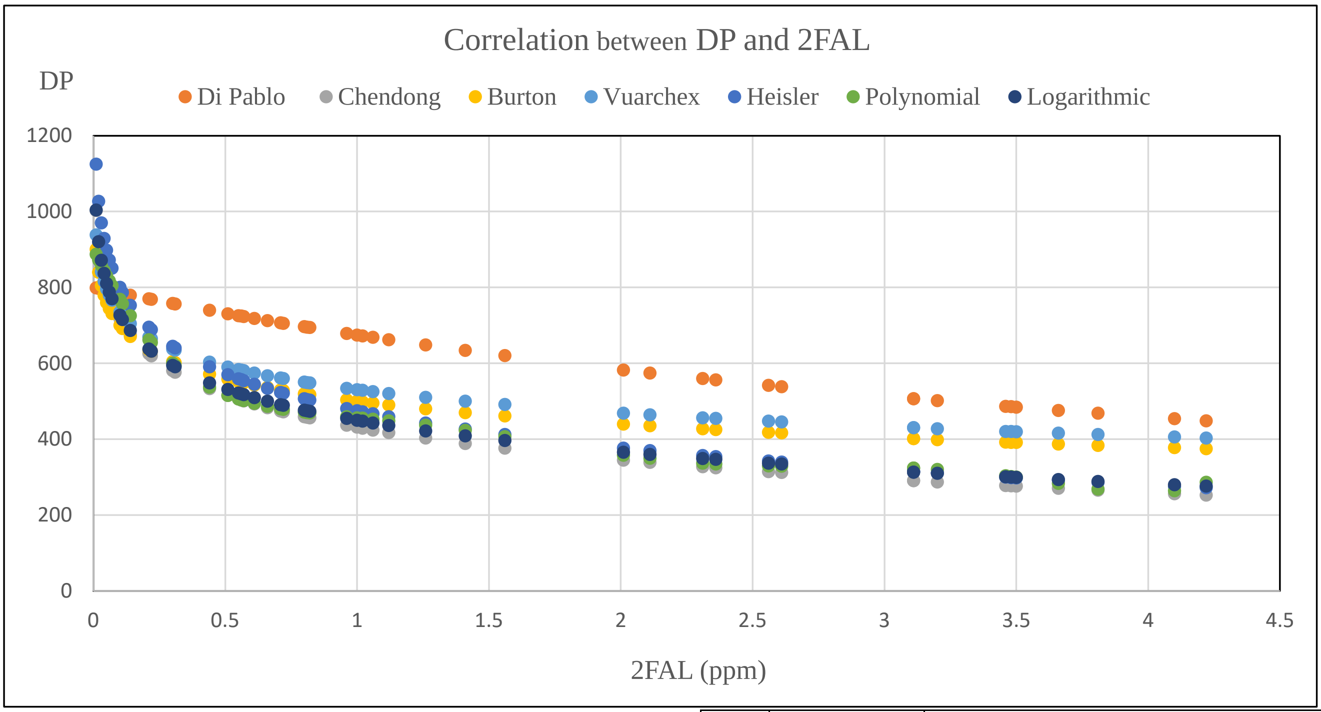
V. ESTIMATION OF TRANSFORMER'S LIFE EXPECTANCY THROUGH MATHEMATICAL MODELS

The evaluation of the current state and the remaining life of the transformers can be determined through mathematical equations that establish a relationship between the concentration of furans (2-FAL) and the degree of polymerization (DP). Besides the proposed logarithmic and polynomial models, to compare the results, are used the models proposed by different authors. Below are the models that have been proposed by the authors: Di Pablo, Chendong, Burton, Vaurchex, and Heisler.

TABLE III. MODELS RELATING DP AND 2-FAL

Eq.	Author	DP Experimental Formula
(3)	Pablo	$DP_{Pablo} = \frac{800}{1 + 0.186x(2FAL)}$
(4)	Chendong	$DP_{Chendong} = \frac{1.51 - log_{10}(2FAL)}{0.0035}$
(5)	Burton	$DP_{Burton} = \frac{5.5 - log_{10}(2FAL)}{0.005}$
(6)	Vaurxhex	$DP_{Vuarchex} = \frac{2.6 - log_{10}(2FAL)}{0.0049}$
(7)	Heisler	$DP_{Heisler} = 325x\left(\left(\frac{19}{13}\right) - log_{10}2FAL\right)$
(1)	Proposed Logarithmic Eq.(1)	$DP = -120{,}3 \cdot ln(2FAL) + 449{,}83$ $R^2 = 0.9995$
(2)	Proposed Polynomial Eq.(2)	$DP = 9{,}0087 \cdot 2FAL^6 - 122{,}87 \cdot 2FAL^5 + 650{,}81 \cdot 2FAL^4 - 1691{,}1 \cdot 2FAL^3 + 2255{,}4 \cdot 2FAL^2 - 1546{,}9 \cdot 2FAL + 902{,}24$ $R^2 = 0.983$

The performance of the models considered according to the authors and the proposed logarithmic (Eq1.) and polynomial (Eq.2) models in the different concentrations of 2FAL are presented as shown in Figure 1.



VI. Remaining Life of Transformer

The remaining life of a transformer is calculated as the difference between the transformer's lifetime operation and elapsed life in years and is given by the following expression:

$$RemainigLifetime\ (RL)_{(years)} = Transformer\ lifetime\ operation(TRL) - Elapsed\ life(EL) \quad (4)$$

The percentage of remaining transformer life is determined using the following equation, where the assumed DP values range from 1200 to 200 which means the end of life of the insulating paper. The remaining service life (RSL) of a unit in service and their percentage respectively can be ascertained from Eq. (8) and Eq. (9) below. The life of the transformer is around 40 years.

TABLE IV. The Empirical Formula for Elapsed Life Calculated

Eq.	Author	Empirical Formula
(8)	Pradhan	$EL = 20{,}5 \cdot ln\left(\frac{1200}{DP}\right)\ (years)$
(9)	Kanumuri	$\%RSL = \frac{Log_{10}(DP) - 2.903}{-0.006021}$

VII. Analyses and Results

This section presents the results of the furan analysis sample of ten transformers. In Table V, the models proposed in the equation are presented (Eq.1) and (Eq.2) to estimate the amount of DP in the insulating cellulose paper of the transformer compared with the measured data and other models in the literature. To validate the proposed models and evaluate their performance against existing models, the DP of the presented case studies was calculated using 2-FAL concentrations (in ppm) and are shown in Table V, as below.

TABLE V. DEGREE OF POLYMERIZATION (DP)

Case	2FAL (ppm)	Measured DP	Logarithmic Eq.(1)	Polynomial Eq.(2)	Di Pablo	Chendong	Burton	Vuarchex	Heisler
S1	1.02	430	447.45	455.26	672.43	428.97	498.28	528.86	472.20
S2	0.82	470	473.70	469.33	694.13	456.05	517.24	548.20	503.01
S3	3.66	293	293.75	283.32	475.98	270.43	387.30	415.62	291.87
S4	1.41	408	408.50	422.92	633.78	388.79	470.16	500.16	426.50
S5	0.56	520	519.58	503.80	724.53	503.37	550.36	582.00	556.84
S6	3.5	300	299.12	299.7	484.55	275.98	391.19	419.58	298.18
S7	0.1	727	726.83	768.48	785.39	717.14	700.00	734.69	800.00
S8	0.72	490	489.35	478.85	705.52	472.19	528.53	559.73	521.37
S9	4.22	277	276.62	286.63	448.20	252.77	374.94	403.00	271.77
S10	1.12	436	436.20	448.32	662.08	417.37	490.16	520.00	459.00

Table VI shows the error of estimation of some of the 50 case studies using the equation (1) and Eq. (2) and other DP models from the literature. The 10 cases in Table V are used to examine the accuracy of Eq. (1) and Eq. (2). Only one case (Case 1) shows a slightly higher estimation error of 4.06 % against the measured data, but all cases for Eq. (1). As for the (Eq.2) the error values are 5.87 % and 5.71 % respectively. The estimation errors for Di Pablo are 62.45 %, Chendong is less than 8.01%, Burton is less than 32.19 %, Vaurchex is less than 45.49 %, and Heisler is less than 10.04 %.

TABLE VI. ERROR OF ESTIMATE DEGREE OF POLYMERIZATION (DP)

Case	2FAL (ppm)	Measured DP	Error % Logarithmic Eq.(1)	Error % Polynomial Eq.(2)	Error % Di Pablo	Error % Chendong	Error % Burton	Error % Vuarchex	Error % Heisler
S1	1.02	430	4.06	5.87	56.38	-0.24	15.88	22.99	9.82
S2	0.82	470	0.79	-0.14	47.69	-2.97	10.05	16.64	7.02
S3	3.66	293	0.25	-3.30	62.45	-7.70	32.19	41.85	-0.39
S4	1.41	408	0.12	3.66	55.34	-4.71	15.23	22.59	4.54
S5	0.56	520	-0.08	-3.12	39.33	-3.20	5.84	11.92	7.08
S6	3.5	300	-0.29	-0.08	61.52	-8.01	30.40	39.86	-0.61
S7	0.1	727	-0.02	5.71	8.03	-1.36	-3.71	1.06	10.04
S8	0.72	490	-0.13	-2.28	43.98	-3.63	7.86	14.23	6.40
S9	4.22	277	-0.14	3.48	61.80	-8.75	35.36	45.49	-1.89
S10	1.12	436	0.05	2.82	51.85	-4.27	12.42	19.40	5.28

The elapsed life is calculated according to Pradhan's equation, in the conditions assuming DP=1200 and the life of the transformer is 40 years, the equation is presented as follows:

$$EL = 20{,}5 \cdot \ln\left(\frac{1200}{DP}\right) \text{(years)} \qquad (5)$$

TABLE VII. ELAPSED TRANSFORMER LIFE (EL)

Case	2FAL (ppm)	Measured DP	Logarithmic Eq.(1)	Polynomial Eq.(2)	Di Pablo	Chendong	Burton	Vuarchex	Heisler
S1	1.02	21.04	20.22	19.87	11.87	21.09	18.02	16.80	19.12
S2	0.82	19.22	19.05	19.24	11.22	19.83	17.25	16.06	17.82
S3	3.66	28.90	28.85	29.59	18.96	30.55	23.18	21.74	28.98
S4	1.41	22.12	22.09	21.38	13.09	23.10	19.21	17.94	21.21
S5	0.56	17.14	17.16	17.79	10.34	17.81	15.98	14.83	15.74
S6	3.5	28.42	28.48	28.44	18.59	3.68	22.98	21.54	28.54
S7	0.1	10.27	10.28	9.14	8.69	10.55	11.05	10.06	8.31
S8	0.72	18.36	18.39	18.83	10.89	19.12	16.81	15.63	17.09
S9	4.22	30.05	30.08	29.35	20.19	31.93	23.85	22.37	30.44
S10	1.12	20.75	20.75	20.18	12.18	21.65	18.35	17.14	19.70

The remaining life of a transformer is calculated as the difference between transformer lifetime operation (TRL) and elapsed life (EL) in years and is given by the following expression:

$$RL = TRL - EL \qquad (6)$$

The results are presented in the following table:

TABLE VIII. REMAINING LIFETIME (RL)

Case	2FAL (ppm)	Measured DP	Logarithmic Eq.(1)	Polynomial Eq.(2)	Di Pablo	Chendong	Burton	Vuarchex	Heisler
S1	1.02	18.96	19.78	20.13	28.13	18.91	21.98	23.20	20.88
S2	0.82	20.78	20.95	20.76	28.78	20.17	22.75	23.94	22.18
S3	3.66	11.10	11.15	10.41	21.04	9.45	16.82	18.26	11.02
S4	1.41	17.88	17.91	18.62	26.91	16.90	20.79	22.06	18.79
S5	0.56	22.86	22.84	22.21	29.66	22.19	24.02	25.17	24.26
S6	3.5	11.58	11.52	11.56	21.41	36.32	17.02	18.46	11.46
S7	0.1	29.73	29.72	30.86	31.31	29.45	28.95	29.94	31.69
S8	0.72	21.64	21.61	21.17	29.11	20.88	23.19	24.37	22.91
S9	4.22	9.95	9.92	10.65	19.81	8.07	16.15	17.63	9.56
S10	1.12	19.25	19.25	19.82	27.82	18.35	21.65	22.86	20.30

Table VIII shows the remaining life according to the proposed logarithmic (Eq.1) and polynomial (Eq.2) equations, while Table IX demonstrates the remaining service life percentage of 10 of the 50 cases analyzed in this research. The results show that there is an inversely proportional relationship between the percentage of remaining service life and 2-FAL concentration while a proportional relationship is observed vs degree of polymerization. The percentage residue results service life by applying Eq. (9) is presented in the below table. An increase in the concentration of 2-FAL results in a decrease in the degree of polymerization and consequently the remaining service life of the transformer.

TABLE IX: PERCENTAGE REMNANT SERVICE LIFETIME (%RSL) ACCORDING EQ. (9)

Case	2FAL (ppm)	Measured DP	Logarithmic Eq.(1)	Polynomial Eq.(2)	Di Pablo	Chendong	Burton	Vuarchex	Heisler
S1	1.02	44.77	41.90	40.65	12.52	44.94	34.13	29.84	38.01
S2	0.82	38.35	37.78	38.45	10.22	40.52	31.44	27.25	33.45
S3	3.66	72.44	72.25	74.86	37.44	78.22	52.31	47.22	72.71
S4	1.41	48.55	48.47	45.96	16.78	52.03	38.32	33.86	45.35
S5	0.56	31.06	31.12	33.34	7.13	33.40	26.96	22.93	26.12
S6	3.5	70.73	70.94	70.79	36.15	76.75	51.59	46.53	71.17
S7	0.1	6.89	6.90	2.88	1.31	7.87	9.62	6.13	-0.01
S8	0.72	35.34	35.44	37.00	9.05	38.01	29.88	25.75	30.87
S9	4.22	76.49	76.58	74.02	41.78	83.09	54.65	49.44	77.86
S10	1.12	43.77	43.73	41.76	13.63	46.92	35.32	30.98	40.06

Based on the results presented in Table VIII and Table IX, it can be observed and concluded that the proposed logarithmic and polynomial evolution are a good basis to reliably estimate the remaining service life of transformers. The results of Di Pablo, Burton, Vaurchex, and Hesiler are erratic in the estimation of transformer service life, except for the results of Chendong,

Below are graphically presented transformer lifetime operation (TRL), elapsed transformer life (EL), and Remaining life (RL), as a function of the degree of polymerization (DP), from samples of 50 transformers of different voltage levels, assumption DP=1200, and transformer life is 40 year.

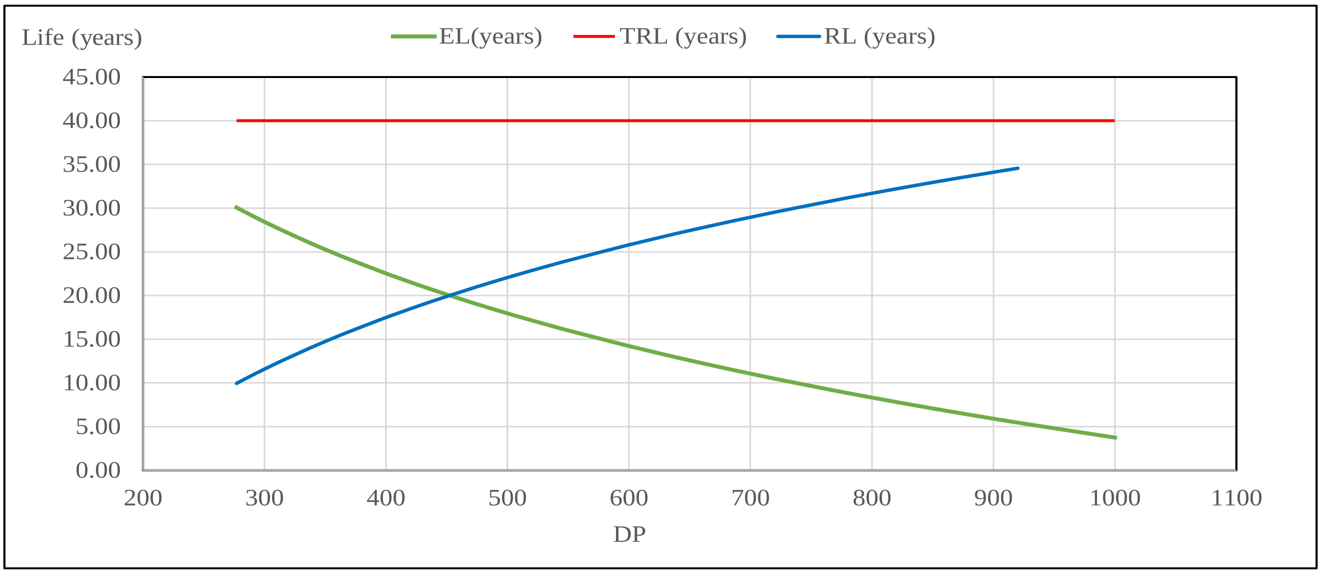


Fig. 2. Transformer Lifetime Operation (TRL), Elapsed Transformer Life (EL), and Remaining Life (RL), as a Function of the Degree of Polymerization (DP)

VIII. CONCLUSION

In this research, the mathematical models that show a correlation between the concentration of furan (2-FAL) and the DP of ten different transformers have been analyzed, making comparisons between the results obtained from the existing models and the proposed ones. The performance of the models considered according to the authors and the logarithmic and polynomial models proposed in different concentrations of 2-FAL has also been graphically demonstrated. During the research, the statistical method of regression through logarithmic and polynomial models was used, analyzing the correlation between the degree of polymerization and the concentration of 2-FAL. The results of the statistical [23] survey showed that there is a high correlation between cellulose DP and 2-FAL concentration, giving correlation coefficients of 0.9995 and 0.983 for the proposed models. The results of the studied cases prove that 2-FAL concentration is a convenient index for predicting the degree of polymerization. By comparing the models proposed in Eq. (1) and Eq. (2) with the DP models in the literature according to different authors, the results revealed that the proposed DP models based on the investigated transformers are an excellent measure of the degree of polymerization in which they show the residual and the percentage of service life of units that can be evaluated. The estimation error of the proposed logarithmic equation and the measured data is less than 4 % while the proposed polynomial equation is less than 5.87 %. Di Pablo, Chendong, Burton, Vaurchex, and Heisler gave an estimation error of no more than 62.45 %, 8 %, 32.19 %, 45.49 %, and 10.04 % compared to the measured data.

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