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Estimation of Life Cycle of Distribution Transformer in Context to Furan Content Formation, Pollution Index, and Dielectric Strength

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ABSTRACT Distribution transformer is the most vital component in the power system. Failure of a transformer leads to loss of revenue besides affecting the reliability of power supply to consumers. It can lead to the non-availability of the transformer for a long duration. Due to this, it is important to maintain the good quality of mineral oil. Thus, if the quality of the mineral oil is reduced then its dielectric strength/quality is degraded. Finally, it can affect the services of the transformer, in terms of continuity of power supply. This paper entails the development of a mathematical MATLAB/Simulink model which able to calculate the life cycle of distribution transformer and exact oil changing frequency. With the help of proposed Matlab/Simulink models, the plot curves between furan content formation versus time, pollution index versus time, and dielectric strength of oil versus time are also prepared. The article methodology uses the newly proposed equations, that are in accordance with IEEE standards: IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators (IEEE Std. C57.91-2011) and IEEE Guide for the Reclamation of Insulating Oil and Criteria for Its Use (IEEE Std C57.637-2015). Then the case study for a 100 kVA distribution transformer is realized. So, with the input values in the Simulink model of load current of the transformer, dielectric constant of oil and flash point of oil we can estimate the life of the distribution transformer. Harmonic load factor in our research work is not included, in order to reduce influence of harmonic load we need to installed the active filter, which is not covered in this paper.

INDEX TERMS Distribution transformer, furan content formation, reliability, pollution index, dielectric strength.

I. INTRODUCTION

The distribution transformers or line transformers provide 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 customers [1], [2]. Distribution transformers normally have ratings of less than 200 kVA [3], [4]. Since distribution transformers are energized for 24 hours a day (even when they don't carry any load), failures of distribution transformer have a serious impact on the reliability and operational stability of the electric power system [5], [6]. Many factors may have an impact on the life of distribution transformer, e.g. surrounding weather conditions [7], high penetration of distributed generation [8], especially PV [9], high penetration of electric vehicles [10]. Also, gradual insulation aging (of paper and winding insulation) caused by thermal effects in transformers is one of the significant factors which harm operation stability [11]–[13]. To ensure that distribution transformers provide long and worry-free service, several diagnostic tests

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are carried out. For the oil-filled transformers, more predominantly which are in service for more than or around 20 to 25 years, it is suitable to estimate the remaining life of the transformers [14], [15]. It can be done by assessing the details of degradation of the paper and winding insulation and development of furan and moisture content in transformer oil [16]–[18]. Due to this, the dielectric strength of insulation oil is affected [19].

Main parameters like furan content, pollution index and dielectric strength of transformer oil are the parameters associated with the oils quality as the overall performance of the transformer is dependent on its cooling and dielectric strength of oils.

But in this article, there are considered 3 electrical factors that may have an impact on the life of the distribution transformer. Thus, by generating the graph between intervals (in terms of time, yearly up to 30 years) [20] versus parameters like:

- furan content (FC),
- pollution index (PI),
- dielectric strength (DS) of transformer oil, it is possible to describe the life duration and the exact oil changing frequency.

The measurements of the indicated parameters content are generally conducted offline and include electrical tests on the device terminals and physicochemical tests of insulating oil samples taken from the transformer tank. However, recent trends are towered to analyze the spectral response of transformer oil [21]–[23]. The example may be indicated for furan content: the quantitative spectral analysis of dissolved gas in transformer oil based on the method of optimal directions is proposed in the paper [24]. The described model can be used for quantitative spectral analysis of dissolved gas in transformer oil and can predict the component concentrations of the dissolved gas in transformer oil correctly and has high effectiveness [24]. In w paper [25], the authors proposed the use of a laboratory measurement technique using gas chromatography with mass spectrometry (GC / MS) to determine the number of gases dissolved in oil. In the case of infrared spectroscopy (IR), the tested oil sample is placed on the path of an infrared beam of a different wavelength, which absorbs light when the energy of a typical molecular vibration corresponds to the incident radiation [25]. After this beam has passed through the sample, the beam from the same source is interfered with but has not passed through the sample, and the spectrum is "extracted" using the Fourier transform of the recorded interference spectrum. This method is named as Fourier transform infrared (FTIR) spectroscopy.

In this paper, there is a position on how to calculate the life cycle of the distribution transformer and the exact oil changing frequency. To realize this task the new equations are proposed. Equations were defined in accordance with IEEE standards: IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators (IEEE Std. C57.91-2011) and IEEE Guide for the Reclamation of Insulating Oil and Criteria for Its Use (IEEE Std C57.637-2015). Then, using proposed equation 3 models in Matlab/Simulink are defined for furan content formation, pollution index, and dielectric strength of the oil. Additionally, the case study for a 100 kVA distribution transformer is presented. Thus, the organization of the article is as follows: section 2 concerns life accession of distribution transformer; section 3 describes methods of parameters calculation; section 4 is results and discussion; section 5 concludes.

II. SECTION LIFE ACCESSION OF DISTRIBUTION TRANSFORMER

Distribution transformers are designed for paramount efficiency at a 60-70% load and do not normally operate at full load every time [26]. The load of the distribution transformer rests on distribution demand. However, in most cases distribution transformer runs on 90% loading [27], [28]. Due to this loading in the transformer minor faults are always available. Those minor faults after a long time change into the major fault and this results in the failure of the distribution transformer [29], [30]. Mainly such minor faults produce because of the overloading of transformers [31]. Overloading can be categorized into two types: over voltage and over current loading, consequences as increasing in the temperature of the transformer winding and paper insulation mentioned in [20], they degrade then mix with oil and weaken oil's dielectric property. This over thermal effect in winding and oil degrades their insulating quantity [32]. As the life of the distribution transformer increases their oil quality also decreases [33]. Mainly by changing of oil of the transformer after a particular time this will increases the average life and reduce the maintenance cost of the transformer.

By maintaining quality or by changing the oil after a specified time the life of the distribution transformer can be increased. So, to provide oil changing frequency of distribution transformer, it needs to consider the pollution index in oil. The pollution index in transformer oil can be defined as and the oil changing frequency depends on:

- furan content formation.
- pollution index.
- dielectric strength of the oil.

All three factor depends on time. As the life of the transformer increases, the furan content formation and pollution index is increases, because of this the dielectric strength of oil is reduced. By developing the mathematical Simulink model it is possible to plot curves with respect to time versus furan content formation, pollution index, and dielectric strength of the oil. Also elaborate the rate of degradation in oil, oil changing frequency, and also the total life span of the transformer (for a specific rating of the transformer) and give desirable solution to the utility for repair or replace the distribution transformer and also provide data of periodically oil change requirement.

A. FURAN CONTENT FORMATION

Furan is a heterocyclic organic compound, consisting of a five-membered aromatic ring with four carbon atoms and one oxygen. Chemical compounds containing such rings are also referred to as furans. Furan analysis of transformer oil indicates the degree of degradation of the transformer paper insulation. This is usually done in transformers aging above 15 years [34]. Furan indicates the compounds of carbon and hydrogen. When the furan count is above 2500 ppb [41], it means the transformer is about to fail or oil must have to change or replace. Furan analysis is important in deciding when to discard a transformer unit or retain it.

This proposed formula of Furan content formation does not require any physical check or spectral oil analysis.

The calculation for furan content formation, F(t) Furan content formation is taken as a function of time because it's increasing with time due to temperature.

Let consider F(t) is furan formation and it possible to obtain as

$$F(t) = \left(e^{\sqrt{t*\xi}}\right) - 1, \tag{1}$$

where ξ is the heating factor depends on hotspot temperature (Θ_{bubble}) and full load current. Θ_{bubble} is possible to fit the hot spot temperature as a function of moisture and gas content and the total external pressure (atmospheric plus oil head). The equation is as,

$$\Theta_{bubble} = \left[\frac{6996.7}{22.454 + 1.4495\ ln\ Wwp - lnln\ P\ pres}\right] - \left[\left(e^{(0.473Wwp)}\right)\left(\frac{Vg^{(1.585)}}{30}\right)\right] - 273\text{a}, \tag{2}$$

where Θ_{bubble} is the temperature of bubble evolution °C, P_{pres} is total pressure, mm mercury (torr.) V_g is the gas content of oil % (v/v), W_{wp} is the percentage by weight of moisture in the paper (dry basis) formula from IEEE guide for loading mineral-oil-immersed transformers and step-voltage regulators (IEEE Std. C57.91-2011) [35].

B. POLLUTION INDEX

The pollution index can be defined as the life of the transformer's oil increases the pollution in oil in terms of furan content formation and another factor like insulation aging acceleration factor, due to this they degrade the dielectric quality of the oil. The quality of your transformer oil will affect its insulation and cooling properties. Under normal operating conditions, a minimal breakdown of oil quality will occur from oxidization and contamination [36]. These are summarized as follows:

- Contamination commonly found in transformer oil includes water and particulate. The presence of either of these contaminants will reduce the insulating qualities of your transformer oil. Oxidization is acid that forms in the oil when it comes in contact with oxygen. The acid will form sludge which settles on the windings of the transformer resulting in reduced heat dissipation. The windings will run hotter thereby creating more sludge which in turn will create even more heat. The high acid content and increased temperatures will accelerate the deterioration of the insulating qualities of the oil and if left untreated will reason the transformer to fail.

Pollution Index Formulation can be obtained as,

$$P.I. = F(t) + \$FAA(t), \tag{3}$$

where $F(t)$ is furan content formation, \$ is relative factor which define the percentage for FAA (\$ = 0.42), FAA is Insulation Aging Acceleration Factor (function of time) [37]. Here, FAA is based on transformer standards and calculates an insulation aging acceleration factor (FAA) which indicates how fast the transformer insulation is aging [35]. The FAA for each time interval (Δt) can be obtained as:

$$FAA = e^{\left[\frac{B}{(\theta_{HR}+273)} - \frac{B}{(\theta_{H}+273)}\right]}, \tag{4}$$

where FAA is the insulation aging acceleration factor, B is designed constant (typically 15000 oC), ΘHR is winding hottest-spot temperature at rated load 90°C if $\Delta\theta\frac{W}{A}, R$ is 55°C and 110°C if $\Delta\theta\frac{W}{A}, R$ is 65 °C, $\Delta\theta\frac{W}{A}, R$is average winding rise over ambient at rated load (setting). The formula from the IEEE guide for loading mineral-oil-immersed transformers and step-voltage regulators. (IEEE Std. C57.91-2011) [35].

C. DIELECTRIC STRENGTH OF OIL

Dielectric strength is an indicator used to assess the insulation properties of transformer oil. It is very often equated with breakdown voltage, but their numerical values are not equal. The breakdown voltage is a minimum voltage applied to insulation, resulting in its breaking down and becoming electrically conductive [38]. At the same time, dielectric strength is a maximum electric field that the insulation can withstand in ideal conditions without breaking down. The dielectric strength of transformer oil is also known as the breakdown voltage of the transformer oil. The "Breakdown Voltage" (BDV) is measured by observing the voltage that is required to jump a spark between two electrodes immersed in the oil separated by a specific gap or distance [36]. Also known as the sparking strength, the higher the voltage required to jump the spark, the higher the BDV will be in the oil. The lower the voltage required to jump the spark, the BDV will be lower indicating the presence of moisture content and other conducting substances in the oil. The value of dielectric strength of fresh oil is 38.63 kV/mm, so as the life of the oil is increasing it needs to replace oil around its value reduces to 60% of 38.63kV/mm which is around 23.17 8kV/mm (after 23 to 24 years). As per the IEEE Guide for the Reclamation of Insulating Oil and Criteria for Its Use [39] criteria for reclamation of insulating oil is when dielectric strength less than 17kV, so here we assume at least 60% (average range percentage of total value) because after this it's not safe to run transformer. It is known that the dielectric strength of Transformer oil degrades with time when the increasing life

TABLE 1. Specification of 100 kVA distribution transformer.

Continuous rated capacity	100 kVA
System Voltage (max.)	12 kV
Rated Voltage (HV)	11 kV
Rated Voltage (LV)	433V
Line Current (HV)	5.25 A
Line Current (LV)	133 A
Frequency	50 Hz
HV Connection	Delta
LV Connection	Star

of the oil.

$$D.S. = 38.63 * \left(e^{(-P.I./X)}\right) a \tag{5}$$

where 38.63 kV is the value of dielectric strength of fresh natural oil, PI is the pollution index, and X is the dielectric degradation factor depends upon load current (133 A in case of 100 kVA distribution transformer), dielectric constant (3.2), and flashpoint of oil (188 °C).

III. CALCULATIONS OF FC, PI, AND DS FOR 100 kVA DISTRIBUTION TRANSFORMER

Consider a 100 kVA distribution transformer and detail technical specifications are given in Table 1. It needs to calculate oil changing frequency and life scale (in terms of furan content formation, PI, and dielectric strength) of 100 kVA distribution transformer.

A. CALCULATION FOR FURAN CONTENT FORMATION F (T)

F (t) furan content is taken as a function of time because it's increasing with time due to temperature [40]. In case the total furan content formation is more than 2500 ppb, the transformer oil needs to be replaced. The calculated value of Θ bubble is 167 °C. With a gas content of 8%, the bubble evolution temperature would drop by only a degree.

Assume 1.2% water in the paper insulation. To compute the bubble evolution temperature from a winding at a depth of 2.4384 m from the top oil level of a large power transformer, the oil head must be added to the pressure in the gas space above the oil. Assume 1% gas content in the oil. Then,

Water in paper, WWP = 1.2 %

External pressure = 750 torr

Oil head (2.4384 m) = 176 torr

Total pressure, Ppres = 926 torr

Gas content, Vg = 1.0 %

(Solution from IEEE guide for loading mineral-oil-immersed transformers and step-voltage regulators (IEEE Std. C57.91-2011))[35], and from Table 1, load current value is,

$$\xi = 2 * \sqrt{(167/133)} = 2.24, \tag{6}$$

By putting all values in equation (1),

$$F\,(t) = e^{\sqrt{t*2.24}} - 1, \tag{7}$$

In this equation taking values of t from 0 to 30 years by an increment of 6 months.

TABLE 2. Dielectric strength vs. time.

Time (t)	Dielectric Strength (D.S.) kV/mm	Time (t)	Dielectric Strength (D.S.) kV/mm	Time (t)	Dielectric Strength (D.S.) kV/mm
0.0	38.63	10.0	36.90	20.0	28.89
0.5	38.59	10.5	36.71	20.5	28.20
1.0	38.56	11.0	36.51	21.0	27.47
1.5	38.52	11.5	36.28	21.5	26.72
2.0	38.48	12.0	36.04	22.0	25.93
2.5	38.43	12.5	35.78	22.5	25.11
3.0	38.38	13.0	35.50	23.0	24.27
3.5	38.33	13.5	35.20	23.5	23.39
4.0	38.27	14.0	34.87	24.0	22.50
4.5	38.21	14.5	34.53	24.5	21.58
5.0	38.13	15.0	34.16	25.0	20.64
5.5	38.05	15.5	33.76	25.5	19.68
6.0	37.97	16.0	33.33	26.0	18.71
6.5	37.87	16.5	32.88	26.5	17.73
7.0	37.77	17.0	32.40	27.0	16.74
7.5	37.65	17.5	31.89	27.5	15.75
8.0	37.53	18.0	31.36	28.0	14.76
8.5	37.39	18.5	30.79	28.5	13.77
9.0	37.24	19.0	30.19	29.0	12.80
9.5	37.08	19.5	29.56	29.5	11.84

TABLE 3. Furan content formation vs. time.

Time (t)	F (t) Furan content Formation (ppb)	Time (t)	F (t) Furan content Formation (ppb)	Time (t)	F (t) Furan content Formation (ppb)
0.0	0.00	10.0	112.62	20.0	805.96
0.5	1.88	10.5	126.71	20.5	875.93
1.0	3.47	11.0	142.15	21.0	951.01
1.5	5.25	11.5	159.04	21.5	1031.50
2.0	7.30	12.0	177.50	22.0	1117.75
2.5	9.66	12.5	197.64	22.5	1210.11
3.0	12.36	13.0	219.59	23.0	1308.95
3.5	15.44	13.5	243.47	23.5	1414.65
4.0	18.95	14.0	269.43	24.0	1527.62
4.5	22.92	14.5	297.61	24.5	1648.30
5.0	27.41	15.0	328.16	25.0	1777.13
5.5	32.45	15.5	361.26	25.5	1914.58
6.0	38.10	16.0	397.08	26.0	2061.17
6.5	44.41	16.5	435.80	26.5	2217.41
7.0	51.45	17.0	477.62	27.0	2383.84
7.5	59.27	17.5	522.74	27.5	2561.06
8.0	67.94	18.0	571.38	28.0	2749.66
8.5	77.53	18.5	623.77	28.5	2950.28
9.0	88.12	19.0	680.16	29.0	3163.58
9.5	99.79	19.5	740.80	29.5	3390.27

B. CALCULATION FOR POLLUTION INDEX PI(T)

The pollution index can be defined as that not only Furan content formation degrades the oil dielectric property there are some other factors like Insulation Aging Acceleration factor which depends upon winding hottest-spot temperature at rated load 90°C and average winding rise over ambient at rated load. So with the life of the transformer's oil is increases the pollution in oil in terms of Furan content Formation and another factor like Insulation Aging Acceleration factor [37], due to this they degrade the Dielectric quality of the oil. FAA (Insulation Aging Acceleration Factor) = 4.930 (Solution from IEEE Guide for loading mineral-oil-immersed

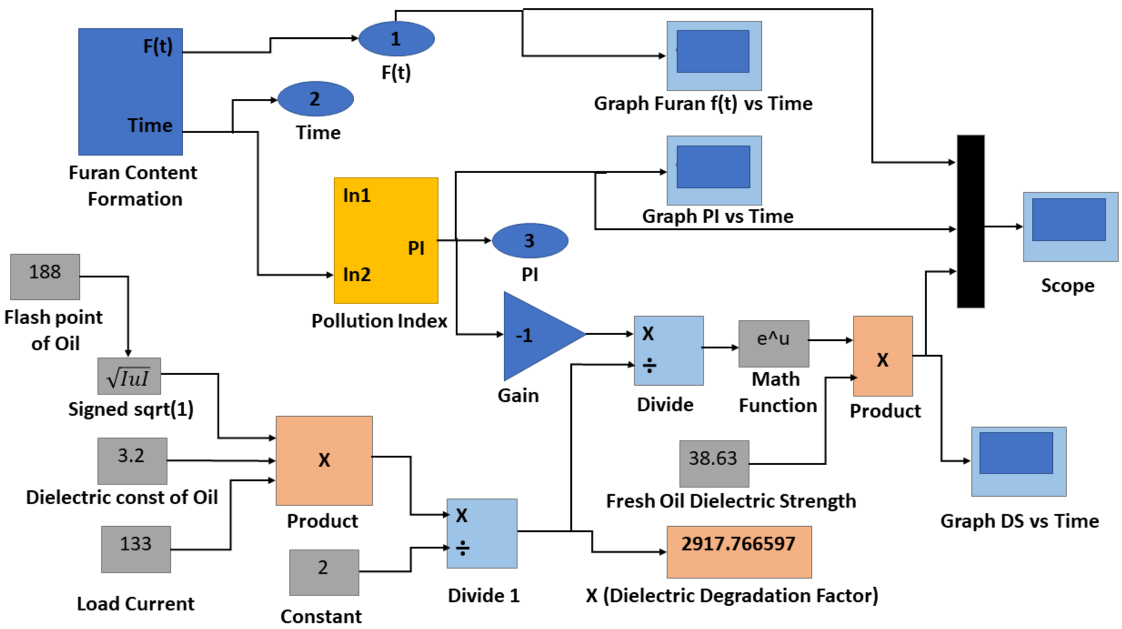

FIGURE 1. MATLAB simulink model for dielectric strength.

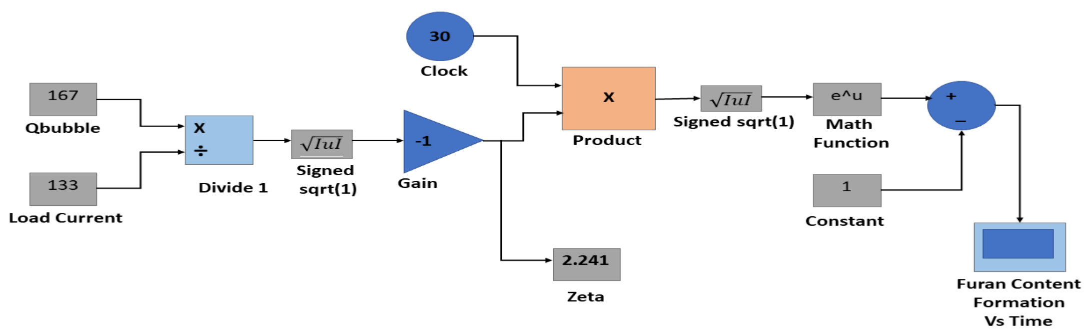

FIGURE 2. MATLAB simulink model for furan content formation.

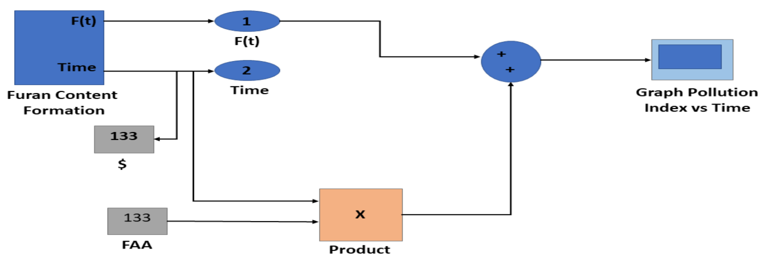

FIGURE 3. MATLAB simulink model for pollution index.

transformers and step-voltage regulators (IEEE Std. C57.91-2011)) [35].

The final Formula for PI(t) is obtained as,

$$PI = F(t) + 2.0706(t)\,1, \tag{8}$$

In this equation values of t from 0 to 30 years by an increment of 6 months.

C. CALCULATION FOR DIELECTRIC STRENGTH DS(T)

It is known that with the increasing life of oil its dielectric strength also degrades with time. The value of the dielectric strength of fresh natural oil is 38.63 kV and the dielectric strength of oil can be obtained as,

$$DS = 38.63 * \left(e^{(-PI/X)}\right) 1, \tag{9}$$

where 38.63 kV is the value of dielectric strength of Fresh Natural oil, and PI is the pollution index, and X is the dielectric degradation factor depends upon load current (133 A in case of 100 kVA distribution transformer), dielectric constant (3.2), and flashpoint of oil (188 Deg. Centigrade), X is 2917.76. The final value for DS(t) can be obtained by,

$$DS = 38.63 * \left(e^{(-P.I./2917.76)}\right), \tag{10}$$

TABLE 4. Pollution index vs. time.

Time (t)	P. I. (Pollution Index)	Time (t)	P. I. (Pollution Index)	Time (t)	P. I. (Pollution Index)
0.0	0.00	10.0	133.33	20.0	847.38
0.5	2.92	10.5	148.45	20.5	918.38
1.0	5.54	11.0	164.92	21.0	994.49
1.5	8.36	11.5	182.85	21.5	1076.02
2.0	11.44	12.0	202.35	22.0	1163.31
2.5	14.84	12.5	223.52	22.5	1256.70
3.0	18.57	13.0	246.51	23.0	1356.57
3.5	22.69	13.5	271.42	23.5	1463.31
4.0	27.23	14.0	298.41	24.0	1577.32
4.5	32.24	14.5	327.63	24.5	1699.03
5.0	37.76	15.0	359.22	25.0	1828.89
5.5	43.84	15.5	393.36	25.5	1967.38
6.0	50.52	16.0	430.21	26.0	2115.00
6.5	57.87	16.5	469.96	26.5	2272.28
7.0	65.94	17.0	512.82	27.0	2439.75
7.5	74.80	17.5	558.97	27.5	2618.00
8.0	84.50	18.0	608.65	28.0	2807.64
8.5	95.13	18.5	662.08	28.5	3009.29
9.0	106.76	19.0	719.51	29.0	3223.63
9.5	119.46	19.5	781.18	29.5	3451.36

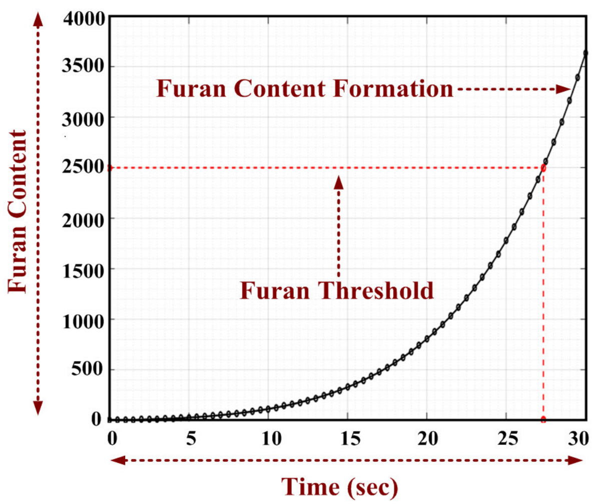

FIGURE 4. MATLAB script graph for furan content formation versus time.

In this equation taking values of t from 0 to 30 years by the increment of 6 months.

IV. RESULTS AND DISCUSSION

As per the problem statement (Table 1) for finding the oil change frequency for 100 kVA distribution transformer is given by solving the above-mentioned parameters. Furan content formation, pollution index, and dielectric constant. The threshold value of dielectric strength for oil is around 60% of fresh oil dielectric strength value. Table 2 shows (DS vs. time) as increasing the life of the distribution transformer the value of the dielectric strength of the transformer is decreased and it reaches its threshold value (60% of 38.63 kV equal to 23.17 kV). It is must change oil around 23 to 24 years, after the replacing the oil, the Furan content level will be reduced to all most zero, and also the solid insulation may

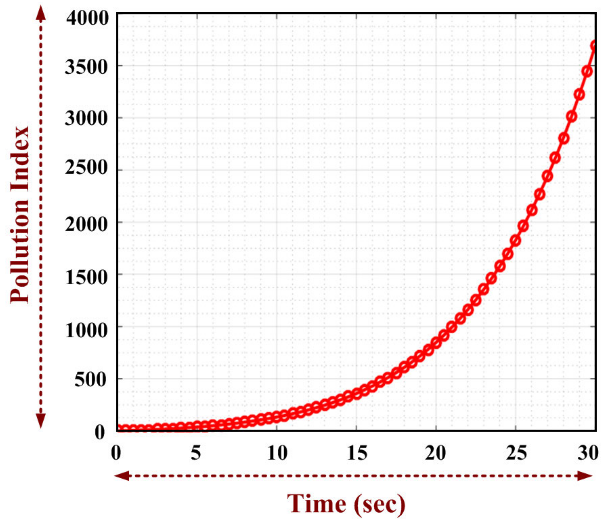

FIGURE 5. MATLAB script graph for pollution index versus time.

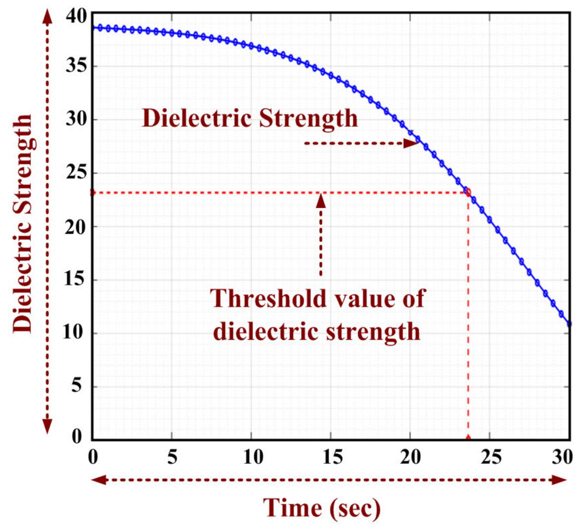

FIGURE 6. MATLAB script graph for dielectric strength versus time.

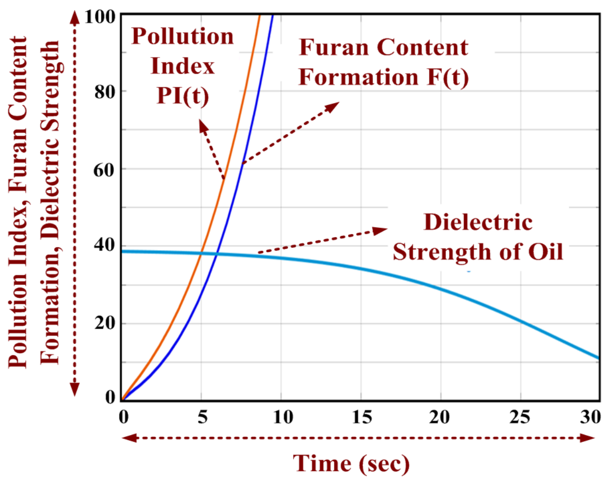

FIGURE 7. Graph furan content, pollution index and dielectric strength versus time.

have been its middle of operational life. So as per the IEEE Guide for the Reclamation of Insulating Oil and Criteria for

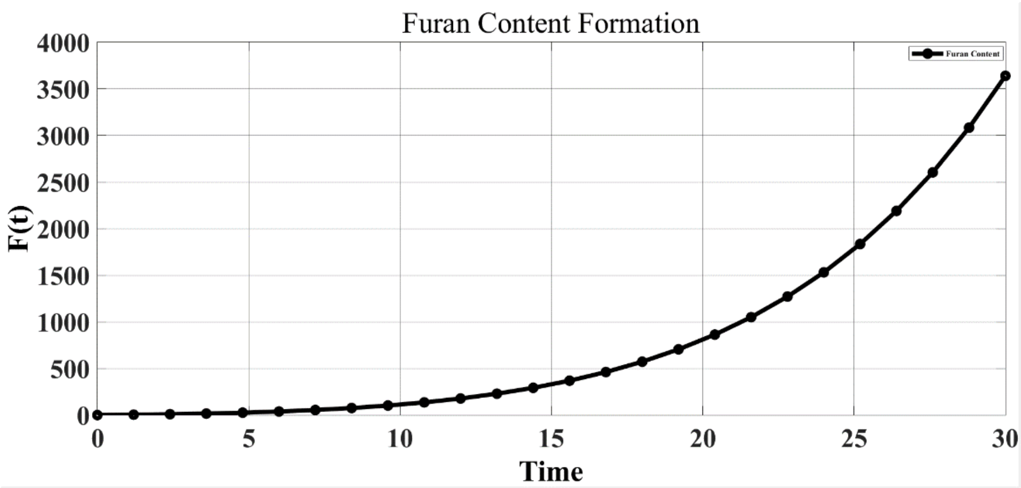

FIGURE 8. MATLAB simulink graph furan content formation versus time.

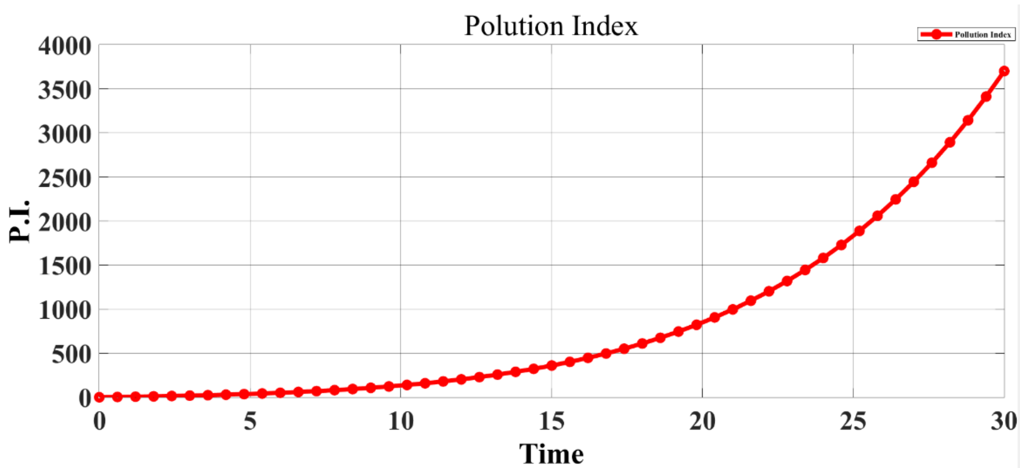

FIGURE 9. MATLAB simulink graph pollution index versus time.

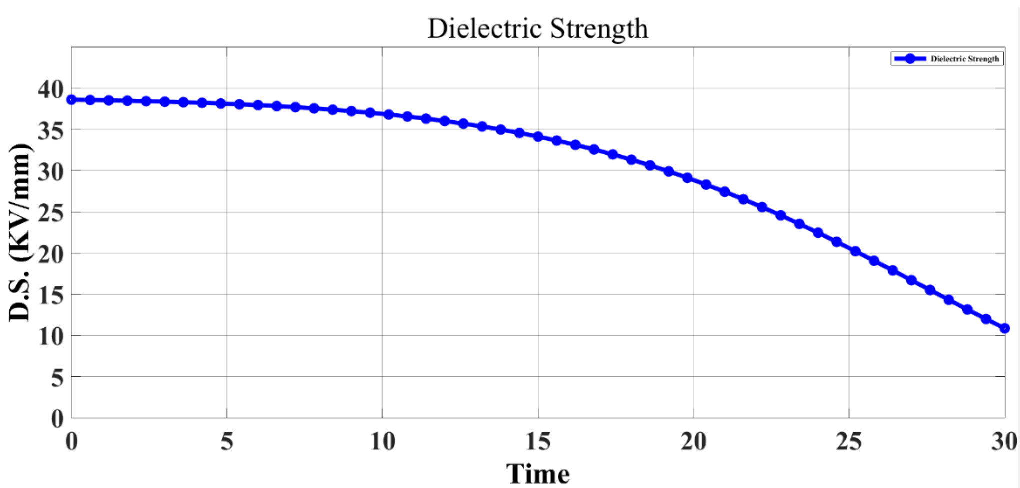

FIGURE 10. MATLAB simulink graph dielectric strength versus time.

Its Use (IEEE Std C57.637-2015), criteria for reclamation of insulating oil is when dielectric strength less than 17kV, our proposed range for an oil change is around 23 kV or at around 23 to 24 years, So at this age oil is not completely polluted and by changing the oil of transformer at this age this can be increased remanent life and also this process is more economical than changing the solid insulation. Table 3 shows Furan content formation versus time and Table 4 shows Pollution index versus time. In this paper, the MATLAB script is used for the validation of results. After validation of results MATLAB Simulink tool used for creating Simulink models (Fig. 1, Fig. 2, Fig. 3).

Fig. 4 shows the furan content formation increases with time and in case the total furan content formation is more than 2500 ppb, the transformer oil needs to be replaced, which is occurs in years around 27 to 28 years. So, around this period oil must need to change. Fig. 5 the graph (PI vs. time) shows that as the increasing life of the transformer the value of PI also increases. Fig. 6 shows that the dielectric strength of transformer oil is decreasing with time as furan content formation and pollution index increases. Therefore, for 100 kVA distribution transformer oil must need to change at the age of 22 to 23 years. The comparison plot of furan content, pollution index, and dielectric strength versus time are shown in Figs. 7 - 10 show MATLAB Simulink scope result of furan content formation versus time, pollution index versus time, and dielectric strength versus time respectively.

V. CONCLUSION

To ensure that distribution transformers provide long and trouble-free service, it can be done by assessing the extent of degradation of the paper insulation through furan content formation in transformer oil and dielectric strength of insulation oil. This can help the utilities in making optimum use of the Transformers and also taking timely decisions regarding the refurbishment/replacement of transformers. With the help of the Simulink model, the solution to the utility for distribution transformer (of any rating) is that calculate the accurate oil changing frequency and life cycle of the transformer. The mainly required data for inserting in this model for generating the life cycle of a distribution transformer is the full load current of the transformer (secondary current), flash point, and dielectric constant of oil. From the above solution, the life of transformers can also be increased.

It's important to notice that the measurement of furan content, pollution index, and dielectric strength we have performed with the help of IEEE standards IEEE Std. C57.91-2011 and IEEE Std C57.637-2015.

The dielectric strength of transformer oil is decreasing with time as furan content formation and pollution index increases. So, for 100 kVA distribution transformer oil must need to change at the age of 22 to 23 years, at this age its cross the limit of 2500ppb, so it is suggested to change the oil at this age and by this we can increase the remnant life of transformer.

The indicated standards are defined for natural mineral oil and kraft paper, so we have proposed the mathematical model by assuming the mineral insulation oil and kraft paper instead of thermally upgraded paper and bio-dielectric paper. So, the mathematical model is not compatible with thermally upgraded papers and for biodegradable dielectric oil.

REFERENCES

[1] S. Xiao and L. Wang, "Analyzing problems of distribution transformer service areas based on customer-side data mining," in *Proc. IOP Conf., Mater. Sci. Eng.*, vol. 768, Mar. 2020, Art. no. 062033, doi: 10.1088/1757-899X/768/6/062033.

[2] J. Singh, S. Singh, and A. Singh, "Distribution transformer failure modes, effects and criticality analysis (FMECA)," *Eng. Failure Anal.*, vol. 99, pp. 180–191, May 2019, doi: 10.1016/j.engfailanal.2019.02.014.

[3] A. R. Sedighi, A. Kafiri, M. R. Sehhati, and F. Behdad, "Life estimation of distribution transformers using thermography: A case study," *Measurement*, vol. 149, Jan. 2020, Art. no. 106994, doi: 10.1016/j.measurement.2019.106994.

[4] M. Pourakbari-Kasmaei, F. Mahmood, M. Krbal, L. Pelikan, J. Orságová, P. Toman, and M. Lehtonen, "Evaluation of filtered spark gap on the lightning protection of distribution transformers: Experimental and simulation study," *Energies*, vol. 13, no. 15, p. 3799, Jul. 2020, doi: 10.3390/en13153799.

[5] R. Strzelecki, W. Matelski, R. Malkowski, V. Tomasov, L. Wolski, and A. Krahel, "Distribution transformer with multi-zone voltage regulation for smart grid system application," in *Proc. IEEE 6th Int. Conf. Energy Smart Syst. (ESS)*, Apr. 2019, pp. 132–137, doi: 10.1109/ESS.2019.8764193.

[6] A. Vinogradov, A. Vinogradova, and V. Bolshev, "Analysis of the quantity and causes of outages in LV/MV electric grids," *CSEE J. Power Energy Syst.*, vol. 6, no. 3, pp. 537–542, Sep. 2020, doi: 10.17775/CSEEJPES.2019.01920.

[7] R. Madavan and S. Balaraman, "Failure analysis of transformer liquid—Solid insulation system under selective environmental conditions using Weibull statistics method," *Eng. Failure Anal.*, vol. 65, pp. 26–38, Jul. 2016, doi: 10.1016/j.engfailanal.2016.03.017.

[8] S. M. Agah and H. A. Abyaneh, "Distribution transformer loss-of-life reduction by increasing penetration of distributed generation," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 1128–1136, Apr. 2011, doi: 10.1109/TPWRD.2010.2094210.

[9] H. Pezeshki, P. J. Wolfs, and G. Ledwich, "Impact of high PV penetration on distribution transformer insulation life," *IEEE Trans. Power Del.*, vol. 29, no. 3, pp. 1212–1220, Jun. 2014, doi: 10.1109/TPWRD.2013.2287002.

[10] H. Nafisi, "Investigation on distribution transformer loss-of-life due to plug-in hybrid electric vehicles charging," *Int. J. Ambient Energy*, pp. 1–7, Jan. 2019, doi: 10.1080/01430750.2018.1563816.

[11] Q. Ye, R. Mo, and H. Li, "Impedance modeling and DC bus voltage stability assessment of a solid-state-transformer-enabled hybrid AC–DC grid considering bidirectional power flow," *IEEE Trans. Ind. Electron.*, vol. 67, no. 8, pp. 6531–6540, Aug. 2020, doi: 10.1109/TIE.2019.2937039.

[12] B. Zhou, J. Yan, D. Yang, X. Zheng, Z. Xiong, and J. Zhang, "A regional smart power grid distribution transformer planning method considering life cycle cost," in *Proc. 4th Int. Conf. Intell. Green Building Smart Grid (IGBSG)*, Sep. 2019, pp. 612–615, doi: 10.1109/IGBSG.2019.8886277.

[13] S. Karmakar, A. Dutta, and H. Kalathiripi, "Investigation of the effect of high voltage impulse stress on transformer oil by infrared spectroscopy," in *Proc. Int. Conf. High Voltage Eng. Technol. (ICHVET)*, Feb. 2019, pp. 1–5, doi: 10.1109/ICHVET.2019.8724336.

[14] S. Forouhari and A. Abu-Siada, "Application of adaptive neuro fuzzy inference system to support power transformer life estimation and asset management decision," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 25, no. 3, pp. 845–852, Jun. 2018, doi: 10.1109/TDEI.2018.006392.

[15] M. Rebolini, C. A. Serafino, E. Savorelli, M. Tozzi, and A. Salsi, "TERNA fleet management of power transformers: Through fault current monitoring to plan proper maintenance," *CIRED-Open Access Proc. J.*, vol. 2017, no. 1, pp. 1512–1515, Oct. 2017, doi: 10.1049/oap-cired.2017.1356.

[16] J. Sun, S. Zhang, Z. Xu, C. Wu, X. Yu, Y. Qiu, and Z. Gao, "Oil-paper insulation characteristic and maintenance measures of oil-immersed transformer in cold environment," in *Proc. IEEE 19th Int. Conf. Dielectric Liquids (ICDL)*, Jun. 2017, pp. 1–5, doi: 10.1109/ICDL.2017.8124667.

[17] J. Jalbert, E. M. Rodriguez-Celis, O. H. Arroyo-Fernández, S. Duchesne, and B. Morin, "Methanol marker for the detection of insulating paper degradation in transformer insulating oil," *Energies*, vol. 12, no. 20, p. 3969, Oct. 2019, doi: 10.3390/en12203969.

[18] Y. Zhang, Y. Li, S. Li, H. Zheng, and J. Liu, "A molecular dynamics study of the generation of ethanol for insulating paper pyrolysis," *Energies*, vol. 13, no. 1, p. 265, Jan. 2020, doi: 10.3390/en13010265.

[19] M. Rafiq, L. Chengrong, and Y. Lv, "Effect of Al_2O_3 nanorods on dielectric strength of aged transformer oil/paper insulation system," *J. Mol. Liquids*, vol. 284, pp. 700–708, Jun. 2019, doi: 10.1016/j.molliq.2019.04.041.

[20] L. Wanninayaka, C. Edirisinghe, S. Fernando, and J. R. Lucas, "A mathematical model to determine the temperature distribution of a distribution transformer," in *Proc. Moratuwa Eng. Res. Conf. (MERCon)*, Jul. 2019, pp. 462–467, doi: 10.1109/MERCon.2019.8818872.

[21] N. Abu Bakar and A. Abu-Siada, "A new method to detect dissolved gases in transformer oil using NIR-IR spectroscopy," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 24, no. 1, pp. 409–419, Feb. 2017, doi: 10.1109/TDEI.2016.006025.

[22] Z. Zhong, S. Tang, G. Peng, and Y. Zhang, "A novel quantitative spectral analysis method based on parallel BP neural network for dissolved gas in transformer oil," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Oct. 2016, pp. 1979–1983, doi: 10.1109/APPEEC.2016.7779840.

[23] V. A. Thiviyanathan, P. J. Ker, Y. S. Leong, M. Z. B. Jamaluddin, and L. H. Mun, "Detection of 2FAL furanic compound in transformer oil using optical spectroscopy method and verification using morse oscillation theory," *IEEE Access*, vol. 8, pp. 76773–76779, 2020, doi: 10.1109/ACCESS.2020.2989432.

[24] S. Tang, G. Peng, and Z. Zhong, "Quantitative spectral analysis of dissolved gas in transformer oil based on the method of optimal directions," in *Proc. 35th Chin. Control Conf. (CCC)*, Jul. 2016, pp. 4425–4429, doi: 10.1109/ChiCC.2016.7554041.

[25] H. Cui, A. Abu-Siada, S. Li, and S. Islam, "Correlation between dissolved gases and oil spectral response," in *Proc. 1st Int. Conf. Electr. Mater. Power Equip. (ICEMPE)*, May 2017, pp. 28–32, doi: 10.1109/ICEMPE.2017.7982046.

[26] R. M. Arias Velásquez and J. V. Mejía Lara, "Corrosive sulphur effect in power and distribution transformers failures and treatments," *Eng. Failure Anal.*, vol. 92, pp. 240–267, Oct. 2018, doi: 10.1016/j.engfailanal.2018.05.018.

[27] Z. Zheng, S. Duan, X. Qiu, D. Zhang, Z. Zheng, and R. Song, "Research on error analysis and reduction measures of transformer loss overall measurement system," in *Proc. IEEE Sustain. Power Energy Conf. (iSPEC)*, Nov. 2019, pp. 500–504, doi: 10.1109/iSPEC48194.2019.8975236.

[28] M. Djamali, S. Tenbohlen, E. Junge, and M. Konermann, "Real-time evaluation of the dynamic loading capability of indoor distribution transformers," *IEEE Trans. Power Del.*, vol. 33, no. 3, pp. 1134–1142, Jun. 2018, doi: 10.1109/TPWRD.2017.2728820.

[29] C. Lu, J. Gong, X. Qian, K. Jin, and Y. Wang, "Study on load loss measurement of distribution transformer with different short connection parts and test intervals," in *Proc. IEEE Sustain. Power Energy Conf. (iSPEC)*, Nov. 2019, pp. 2566–2568, doi: 10.1109/iSPEC48194.2019.8975284.

[30] A. Z. Khan, "Transformer failures, causes & Impact," in *Proc. Int. Conf. Data Mining, Civil Mech. Eng. (ICDMCME)*, Bali, Indonesia, Feb. 2015, pp. 49–52, doi: 10.15242/IIE.E0215039.

[31] R. Godina, E. Rodrigues, J. Matias, and J. Catalão, "Effect of loads and other key factors on oil-transformer ageing: Sustainability benefits and challenges," *Energies*, vol. 8, no. 10, pp. 12147–12186, Oct. 2015, doi: 10.3390/en81012147.

[32] J. Liu, X. Fan, Y. Zhang, H. Zheng, and C. Zhang, "Condition prediction for oil-immersed cellulose insulation in field transformer using fitting fingerprint database," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 27, no. 1, pp. 279–287, Feb. 2020, doi: 10.1109/TDEI.2019.008442.

[33] I. A. Chera Anghel and E. Gatman, "Transformer lifetime management by analyzing the content of furan and gas dissolved in oil," in *Proc. E3S Web Conf.*, vol. 112, Aug. 2019, Art. no. 04004, doi: 10.1051/e3sconf/201911204004.

[34] A. M. Emsley and G. C. Stevens, "Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled transformers," *IEE Proc.-Sci., Meas. Technol.*, vol. 141, no. 5, pp. 324–334, Sep. 1994, doi: 10.1049/ip-smt:19949957.

[35] *IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators*, IEEE Standard C57.91-2011 (Revision of IEEE Standard C57.91-1995), 2012, pp. 1–123, doi: 10.1109/IEEESTD.2012.6166928.

[36] R. Islam and Z. H. Mahmood, "Characterization of transformer oil for breakdown voltage, transmittance & heat dissipation capability," in *Proc. 2nd Int. Conf. Green Energy Technol.*, Sep. 2014, pp. 54–58, doi: 10.1109/ICGET.2014.6966661.

[37] R. Moxley and A. Guzmán, "Transformer maintenance interval management," Schweitzer Eng. Lab., Pullman, WA, USA, Tech. Rep., 2005.

[38] Z. Li, K. Wu, C. Cheng, and C. Li, "Breakdown characteristics of oil-paper interface in converter transformer," in *Proc. 2nd Int. Conf. Electr. Mater. Power Equip. (ICEMPE)*, Apr. 2019, pp. 535–539, doi: 10.1109/ICEMPE.2019.8727282.

[39] *IEEE Guide for the Reclamation of Mineral Insulating Oil and Criteria for Its Use*, IEEE Standard C57.637-2015 (Revision IEEE Standard 637-1985), 2015, pp. 1–38, doi: 10.1109/IEEESTD.2015.7328235.

[40] R. A. Abd El-Aal, K. Helal, A. M. M. Hassan, and S. S. Dessouky, "Prediction of transformers conditions and lifetime using furan compounds analysis," *IEEE Access*, vol. 7, pp. 102264–102273, 2019, doi: 10.1109/ACCESS.2019.2931422.

[41] S. G. Patki, S. G. Patil, and J. S. Wadhwa, "Assessing remnant life of transformer based on furan content in transformer oil and degree of polymerization of solid insulation," in *Proc. 15th Nat. Power Syst. Conf. (NPSC)*, IIT Bombay, India, Dec. 2008, pp. 1–4.

[42] A. Moradnouri, M. Hajiaghapour-Moghimi, and M. Vakilian, "A framework for economic and low harmonic loss distribution transformer selection based on ecodesign directive," in *Proc. Int. Power Syst. Conf. (PSC)*, Tehran, Iran, Dec. 2019, pp. 19–24, doi: 10.1109/PSC49016.2019.9081493.

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