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**RESEARCH PAPER**

# A method for estimating the remaining life of power transformers considering loading, hotspot temperature, and oil assessment

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**Abstract.** Power transformers face significant aging issues, which threatens their reliability and service life. This research aims to develop an accurate method for predicting the remaining lifespan of transformers. Current studies highlight the inadequacy of existing approaches in determining transformer lifespan, which is affecred by the degradation of paper insulation through furan compounds and hotspot temperatures. This method adheres to the CIGRE D1 738 (2018) standard, which converts furan concentration into Degree of Polymerization (DPest) as an indicator of paper insulation condition. The methodology involves analyzing oil test data and operational temperature to estimate the remaining life of the transformer. This research not only aims to improve the accuracy of paper insulation assessments but also integrates sustainability principles. The goal is to optimize the use of existing transformers, reduce premature replacements, and conserve material and energy resources. By minimizing unexpected failures, this research contributes to reducing industrial waste and environmental impact. Furthermore, this approach aligns with practices that support economic and social sustainability. Extending the lifespan of critical devices can lower maintenance costs while ensuring a reliable and sustainable energy supply. The proposed method provides a comprehensive framework for predicting transformers longevity.

**Keywords:** Transformer; Paper insulation condition; Hotspot temperature; Remaining life

## 1. Introduction

Power transformers are critical components of electrical networks, with some units operating beyond their intended service life (Kaliappan & Rengaraj, 2021; Prasojo et al., 2021). The limited lifespan of transformers raises significant concerns about potential failures and their associated impacts (Islam et al., 2023). This research aims to accurately predict the remaining life of power transformers, thereby preventing failures of aging units and mitigating associated risks.

One major issue linked to a shorter service life is the generation of hazardous waste from degraded transformer oil, which contains toxic, non-biodegradable compounds (Rashed et al., 2022). Frequent replacements also accelerate the consumption of natural resources required for manufacturing new equipment, placing additional pressure on ecosystems. Moreover, improper disposal and recycling of old transformer components can contribute to air and water pollution.

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Extending the service life of transformers through effective maintenance and accurate condition assessments not only prevents failures but also minimizes environmental impact by reducing waste and conserving resources (Adekunle et al., 2023; Liang et al., 2024).

The aging of insulation systems is significantly influenced by electrical, thermal, mechanical, and environmental stresses (CIGRE A2 - 761, 2019; Prasojo et al., 2017; Prihantiny et al., 2021). Irreversible structural changes in paper insulation contribute to its degradation (Hydroelectric Research and Technical Services Group, 2005; Prihantiny et al., 2021), making it a key factor in studying transformer life expectancy.

The oxidation of transformer oil at high temperatures and moisture levels leading to acid formation, which accelerates paper insulation degradation (Aciu et al., 2020; CIGRE 494, 2012; CIGRE D1 – 738, 2018; Prasojo, Kurniawan, et al., 2023). Paper degradation involves depolymerization and the production of furan compounds (CIGRE 494, 2012; CIGRE D1 - 738, 2018; Thiviyanathan et al., 2020). The degree of polymerization serves as a key indicator for assessing the condition of paper insulation and estimating the remaining lifespan of the transformer (CIGRE Brochure 323, 2007; CIGRE D1 - 738, 2018). Previous research (Prasojo, Kurniawan, et al., 2023; Prasojo, Safarina, Duanaputri, Hakim, et al., 2023; Prasojo, Safarina, Duanaputri, Kurniawan, et al., 2023) has extensively examined paper insulation conditions using oil test parameter evaluations. Analyzing gas and physical parameters is crucial for assessing the health and performance of transformer systems. Gases such as carbon monoxide (CO), carbon dioxide ($CO_2$), hydrogen ($H_2$), methane ($CH_4$), acetylene ($C_2H_2$), ethylene ($C_2H_4$), and ethane ($C_2H_6$) provide insights into insulation degradation (Diwyacitta et al., 2017). Elevated CO and $H_2$ levels may indicate damage, while increased $CH_4$ and $C_2H_2$ levels often signal overheating or insulation failure. Physical parameters, including moisture content, surface voltage, acidity level, and temperature, also play essential role in transformer condition assessments. High moisture levels weaken insulation performance, while elevated acidity levels indicate oil degradation (Prasojo, Safarina, Fiqh, et al., 2023). Monitoring these parameters is essential for early detection of potential issues and effective maintenance planning, helping to extend transformer lifespan and enhance electrical system reliability.

This study proposes a method to determine the remaining lifespan of transformers based on the CIGRE D1 – 738 (2018) standard. The method converts furan content into the Degree of Polymerization to evaluate paper insulation (Cheim et al., 2012; Mtetwa, 2009). The use of CIGRE D1 - 738 (2018) is essential for addressing transformer aging, as it provides a comprehensive framework for assessing aging conditions. This standard employs a data-driven approach to analyze aging markers, such as furanic compounds, offering valuable insights into insulation degradation and transformer life estimation. By modeling cellulose aging kinetics and considering oxygen and moisture levels in the insulation system, CIGRE D1 - 738 (2018) supports transformer managers develop effective life extension strategies. The standard also encourages the evaluation decommissioned units to refine reliable aging models and improve life management decisions. This approach aims to enhance transformer condition assessments and facilitate accurate lifespan predictions, ultimately reducing maintenance costs and ensuring stable energy supply. Understanding transformer conditions allows for better maintenance planning, extending equipment lifespan and preventing premature replacements. This not only saves costs and supports economic and environmental sustainability by minimizing waste and conserving resources (Ariannik et al., 2020; PLN, 2014).

## 2. Method

The flowchart in Figure 1 illustrates the process of determining the remaining life of a transformer based on the condition of its paper insulation, which is evaluated to support maintenance and operational decisions. This study uses test data from five 150 kV transformers in East Java and Bali. The secondary data includes oil test results (2FAL) and historical data such as load and temperature. The relationship between furan compounds, load, and temperature plays a crucial role in assessing the reliability of paper insulation in transformers and can assist in estimating the remaining lifespan of the equipment. Furan compounds, such as 2FAL, serve as indicators of insulation material degradation, arising as products of cellulose breakdown. When a transformer operates under high load, the temperature tends to rise, and if it exceeds the safe maximum threshold, the degradation of insulation accelerates. Consequently, this may lead to a decline in the reliability of the paper insulation, increasing the risk of transformer failure and significantly reducing its operational lifespan.

### 2.1 Data Preparation

The first step is to convert the results of the 2FAL test into DPest. In this study, the conversion of 2FAL to DPest is performed using Equation (1) from Stebbins (PLN, 2014), as the solid insulation of transformers in the East Java and Bali Regional Unit utilizes Thermally Upgraded Paper. The Equation (1) is as follows:

$$\text{DPest} = \frac{\log(\text{2FAL} \times 0.88) - 4.51}{-0.0035} \qquad (1)$$

The second data preparation step is calculating the hotspot temperature to proceed with the calculations for determining remaining life of transformer. The hotspot temperature can be calculated using the ambient temperature and top oil temperature with the following Equation (2) (IEC 60076-7, 2005):

$$\theta h(t) = \theta a + \Delta\theta or \,.\left[\frac{1 + R\,.\,K^2}{1 + R}\right]^x + \text{H gr}\,K^y \qquad (2)$$

These include ($\theta a$), which represents the ambient temperature surrounding the transformer. The temperature difference ($\Delta\theta or$) between the top oil temperature and the ambient temperature.

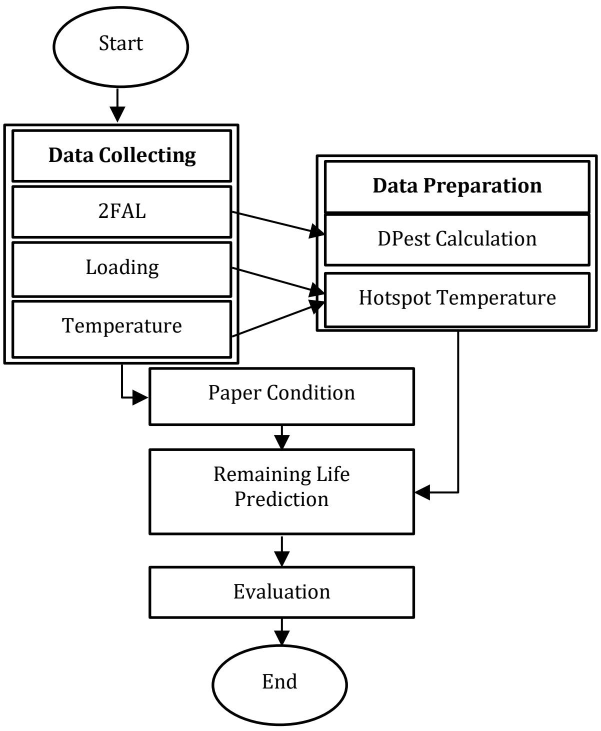


**Figure 1.** Flowchart for determining the remaining life transformer

Additionally, (R) which denotes the ratio of measured losses to no-load losses, and (K) representing the load per unit. The equation incorporates variables like ($x$), the exponent of oil properties, (H) the hotspot factor, (gr) indicating the temperature rise from winding, and ($y$) the winding exponent. These parameters collectively contribute to the accurate estimation of the hotspot temperature (IEC 60076 – 7, 2005).

### 2.2 Paper condition

To determine the condition of paper insulation from the furan (2FAL) value that has been converted to DPest, refer to Table 1. In determining DPest, furan testing is conducted first, as furans form due to thermal effects caused by excessive load and temperature influences on the transformer (Duanaputri et al., 2023). Therefore, load and temperature significantly affect the determination of paper insulation condition. Data from the Meteorology and Geophysics Agency show that the average ambient temperature in Indonesia is approximately 30°C (IEC 60354, 1991).

One of the primary factors affecting transformer operational condition is high temperature, which can accelerate insulation aging and shorten the transformer's lifespan. Monitoring winding and top oil temperatures can diagnose transformer condition and provide indications to reduce the risk of catastrophic damage to the cooling system, preventing operational emergencies (CIGRE A2 - 761, 2019). The hotspot temperature rise limit specified in the literature is 80°C (110°C – 30°C) for IEEE and 78°C (98°C – 20°C) for IEC 60076-2.

### 2.3 Remaining life

In determining the remaining life of a transformer, it can be calculated based on the DP value and predicted parameters influenced directly by high temperature caused by excessive load (Kanumuri et al., 2020; Syadad, 2019). This affects the mechanisms of paper insulation and hot spot spacing in cellulose materials, leading to accelerated aging of paper insulation (CIGRE A2 - 761, 2019; CIGRE D1 - 738, 2018). To calculate the remaining lifespan of the transformer, Equation (3) can be used.

$$\text{Remaining Life } = \frac{\frac{1}{DPt} - \frac{1}{DPo}}{A \,.\, 24 \,.\, 365} \,.\, e^{\frac{E_A}{RT}} (\text{year}) \tag{2}$$

Where, DPt is the estimated age value of the transformer in use, DPo is the end-of-life value of the transformer, R is the molar gas constant (8.314 J/mol/K), T is the hotspot temperature (K), EA is the activation energy (KJ/mol), and A is the environmental-dependent constant.

### 2.4 Transformer recommendation

Regardless of whether the condition of the transformer paper insulation is found to be good or bad after furan analysis, maintenance of the paper insulation should still be conducted according to the recommendations in Table 2**.** Transformer condition should also be monitored by assessing the loading and hotspot temperature values. If the hotspot temperature exceeds the standard limits, it indicates abnormal transformer performance and will shorten its operational lifespan.

**Table 1.** Transformer condition based on DPest value (Source: CIGRE A2 - 761 (2019))

| Parameter | Condition | | |
|---|---|---|---|
| | **Good** | **Fair** | **Poor** |
| DPest from 2FAL | >800 | 500 – 800 | <500 |

## 3. Result and discussion

### 3.1. Test parameter data

The assessment of paper insulation condition from transformer oil testing results using the furan analysis method, applied to five transformers, as examples of subjects analyzed, can be observed Table 3. The assessment of paper insulation condition using furan is considered accurate because furan compounds directly adhere to cellulose paper. Therefore, if the DPest value is sufficiently high, the reliability of the paper insulation is also relatively low.

### 3.2. Result of transformer remaining life calculation

The hotspot temperature cannot be directly measured but can be calculated using the ambient temperature, top oil temperature, and load. Calculating the hotspot temperature involves Equation (2) with coefficients defined by the IEC 60076-7 (2005) standard.

Based on the remaining life calculation in Table 4. Transformer 1 has the shortest remaining lifespan of 2.4 years. This is due to its highest hotspot temperature of 107.13 K. Conversely, Transformer 2 has the longest remaining lifespan of 18.3 years, as its hotspot temperature is the lowest at 90.84 K. This difference is attributed to the condition of the paper insulation and the higher loading conditions, which cause the transformer to work harder and generate more heat. This accelerates the aging rate of the paper insulation and reduces the transformer's remaining life.

### 3.3. Transformer maintenance

Based on the remaining lifespan calculation of the transformer presented in Table 4, it is evident that transformers are more susceptible to aging when acids mix with high temperatures

**Table 2.** Recommendations for paper condition based on Furan testing (Source: Hydroelectric Research and Technical Services Group (2005), CIGRE Brochure 323 (2007))

| Recommendations | Category |
|---|---|
| Normal furan concentration, continue routine testing. | Good |
| If furan concentration exceeds normal limits, check for paper samples contaminated by moisture levels, acids, and other compounds. Also, inspect operational temperatures and design, as well as the insulation oil filters. | Fair |
| High furan concentration: conduct internal investigation to assess transformer paper insulation condition, consider replacing transformer paper. If replacement is not feasible, consider replacing the transformer itself. | Poor |

**Table 3.** Data parameters for transformer remaining life

| Trafo | 2FAL | DPest | Load (pu) | Ambient temperature (°C) | Ambient temperature for nominal load (°C) | Top oil temperature (°C) |
|---|---|---|---|---|---|---|
| 1 | 1684 | 383 | 0.77 | 32 | 30 | 53 |
| 2 | 68 | 781 | 0.58 | 33 | 30 | 58 |
| 3 | 1184 | 426 | 0.66 | 30 | 30 | 53 |
| 4 | 274 | 608 | 0.59 | 34 | 30 | 50 |
| 5 | 83 | 756 | 0.61 | 30 | 30 | 58 |

**Table 4.** Results of transformer remaining life

| Trafo | Hotspot temperature (K) | Remaining life (years) |
|---|---|---|
| 1 | 107.13 | 2.4 |
| 2 | 90.84 | 18.3 |
| 3 | 93.60 | 9.9 |
| 4 | 88.80 | 16.9 |
| 5 | 91.50 | 3.3 |

and moisture levels, leading to oil degradation. Without regular maintenance, this condition can significantly reduce the reliability of the paper insulation. Therefore, it is crucial to ensure that the transformer loading does not exceed the maximum value of 0.80 pu, as outlined in IEC 60354 (1991). Additionally, the operating temperature of the transformer must remain within the limits set by IEC 60076-14, with a maximum normal hotspot temperature of 98°C. By adhering to these standards, transformers can operate normally and achieve a longer service life.

## 4. Conclusion

Furan compounds are important indicators for measuring the aging of transformer paper insulation due to electrical, thermal, and mechanical stresses. By utilizing the concentration of furan (2FAL) to determine the Degree of Polymerization (DP), the condition of the insulation can be effectively monitored. Research findings show that high levels of furan in transformer oil accelerate insulation aging and indicate that the transformer is nearing the end of its service life, especially at high hotspot temperatures and low DP estimates. This research supports sustainability by providing an accurate method to extend the life of transformers, thereby reducing the need for early replacements and the use of new resources. Routine maintenance based on furan and DP testing, along with efficient cooling systems, helps maintain transformer performance, reduces waste and environmental impact, and lowers operational and maintenance costs, ultimately contributing to the stability of a reliable and sustainable energy supply.

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## References

Aciu, A. M., Nitu, M. C., Nicola, M., Nicola, C. I., & Lazarescu, F. (2020). Complementary analysis of the degree of polymerization based on chemical markers 2-furaldehyde and methanol using the fuzzy logic. *2020 21st International Symposium on Electrical Apparatus & Technologies (SIELA), Bourgas, Bulgaria. 1-6.* https://doi.org/10.1109/SIELA49118.2020.9167088

Adekunle, A. A., Oparanti, S. O., & Fofana, I. (2023). Performance Assessment of Cellulose Paper Impregnated in Nanofluid for Power Transformer Insulation Application: A Review. *Energies*. 16(4). 2002. https://doi.org/10.3390/en16042002

Ariannik, M., Razi-Kazemi, A. A., & Lehtonen, M. (2020). An approach on lifetime estimation of distribution transformers based on degree of polymerization. *Reliability Engineering and System Safety*, *198*. 106881. https://doi.org/10.1016/j.ress.2020.106881

Cheim, L., Platts, D., Prevost, T., & Xu, S. (2012). Furan analysis for liquid power transformers. *IEEE Electrical Insulation Magazine*, *28*(2), 8–21. https://doi.org/10.1109/MEI.2012.6159177

CIGRE 494. (2012). Furanic compounds for diagnosis. CIGRÉ. https://www.e-cigre.org/publications/detail/494-furanic-compounds-for-diagnosis.html

CIGRE A2 - 761. (2019). Condition Assessment of Power Transformers. https://www.e-cigre.org/publications/detail/761-condition-assessment-of-power-transformers.html

CIGRE Brochure 323. (2007). Ageing of Cellulose in Mineral-Oil Insulated Transformers. CIGRÉ. https://www.e-cigre.org/publications/detail/323-ageing-of-cellulose-in-mineral-oil-insulated-transformers.html

CIGRE D1 - 738. (2018). Ageing of Liquid Impregnated Cellulose for Power Transformers. CIGRÉ. https://www.e-cigre.org/publications/detail/738-ageing-of-liquid-impregnated-cellulose-for-power-transformers.html

Diwyacitta, K., Prasojo, R. A., Suwarno, & Gumilang, H. (2017). Effects of loading factor in operating time on dielectric characteristics of transformer oil. *2017 International Conference on High Voltage Engineering and Power Systems (ICHVEPS), Denpasar, Indonesia.* 335-339. https://doi.org/10.1109/ICHVEPS.2017.8225968

Duanaputri, R., Prasojo, R. A., & Safarina, L. (2023). The Influence of Load on the Oil Index for Treatment

Recommendations. *Sixth International Conference on Vocational Education and Electrical Engineering (ICVEE)*. 102-108. https://doi.org/10.1109/ICVEE59738.2023.10348208
Hydroelectric Research and Technical Services Group. (2005). *Transformers: Basics, Maintenance, and Diagnostics*.
IEC 60076-7. (2005). Loading guide for oil-immersed power transformers. In *International Electrotechnical Commission* (Vol. 12). www.iec.ch/online_news/justpub
IEC 60354. (1991). *Loading guide for oil-immersed power transformers*. www.iec.ch/searchpub
Islam, N., Khan, R., Das, K. S., Sarker, K. S., Islam, M. Md., Akter, M., & Muyeen, S. M. (2023). Power transformer health condition evaluation: A deep generative model aided intelligent framework. *Electrical Power Systems Research*, *218*. 109201. https://doi.org/https://doi.org/10.1016/j.epsr.2023.109201
Kaliappan, G., & Rengaraj, M. (2021). Aging assessment of transformer solid insulation: A review. *Materials Today: Proceedings*, *47*, 272–277. https://doi.org/10.1016/j.matpr.2021.04.301
Kanumuri, D., Sharma, V., & Rahi, O. P. (2020). *Remaining Life Assessment of Solid Insulation in Power Transformer Using Fuzzy Inference System (FIS)*. 37–45. https://doi.org/10.1007/978-981-15-0633-8_5
Liang, Z., Fang, Y., Cheng, H., Sun, Y., Li, B., Li, K., Zhao, W., Sun, Z., & Zhang, Y. (2024). Innovative Transformer Life Assessment Considering Moisture and Oil Circulation. *Energies*, *17*(2). 429. https://doi.org/10.3390/en17020429
Mtetwa, N. Sidwell (2009). *Accuracy of Furan Analysis in Estimating the Degree of Polymerization in Power Transformers*. Master Thesis. Faculty of Engineering and the Built Environment, University of the Witwatersrand.
Prasojo, R. A., Diwyacitta, K., Suwarno, & Gumilang, H. (2017). Transformer paper expected life estimation using ANFIS based on oil characteristics and dissolved gases (Case study: Indonesian transformers). *Energies*, *10*(8). 1135. https://doi.org/10.3390/en10081135
Prasojo, R. A., Kurniawan, I., Dakhlan, D. F., Sudarmaja, I., Praditama, W. F., & Safarina, L. (2023). Assessment of Power Transformer Solid Insulation Condition Using a Composite Index: A Case Study of UIT-JBM Population. *2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*. https://doi.org/10.1109/ICHVEPS58902.2023.10257430
Prasojo, R. A., Safarina, L., Duanaputri, R., Hakim, M. F., Ridzki, I., & Kurniawan, I. (2023). An Evaluation and Correlation Study of Oil and Solid Insulation in Power Transformers using Composite Index Considering Operating Age. *International Journal on Electrical Engineering and Informatics*, *15*(4), 549–562. https://doi.org/10.15676/ijeei.2023.15.4.4
Prasojo, R. A., Safarina, L., Duanaputri, R., Kurniawan, I., Yulianto, E., & Suwarno. (2023). Assessing Transformer Insulation Aging through Oil Treatment Index: A Comparative and Correlation Study of 150 kV Power Transformers. *International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*. 40-45. https://doi.org/10.1109/ICHVEPS58902.2023.10257397
Prasojo, R.A., Safarina, L., Fiqh, A., Islam, P., Duanaputri, R., Mieftah, M., & Yulianto, E. (2023). Implementasi Metode Scoring Matrix dalam Menentukan Indeks Kondisi Minyak Isolasi pada Transformator Daya 150 kV. *ELPOSYS: Jurnal Sistem Kelistrikan*, *10*(1).
Prasojo, R. A., Setiawan, A., Suwarno, Maulidevi, N. U., & Soedjarno, B. A. (2021). Development of Power Transformer Remaining Life Model Using Multi-Parameters. *2021 IEEE International Conference on the Properties and Applications of Dielectric Materials (ICPADM), Johor Bahru, Malaysia*. 99-102. https://doi.org/10.1109/ICPADM49635.2021.9493928
PLN (2014). *Transformator Tenaga*.
Rashed, A. K., Mansour, D. E. A., Rezk, A., & Ghali, M. (2022). Effect of Oxidation of Aged Power Transformer Insulating Oil on UV-Vis Spectra. *2022 IEEE 21st International Conference on Dielectric Liquids (ICDL), Sevilla, Spain*. 1-4. https://doi.org/10.1109/ICDL49583.2022.9830922
Prihantiny, R.S., Wahjudi, D., & Yulianto, P. (2021). *Pengaruh Kondisi Isolasi Dielektrik Terhadap Kehandalan Transformator Tenaga*. *22*(2), 81–94. https://doi.org/10.53810/jt.v22i2.426
Syadad, R. (2019). *Perkiraan Umur Transformator Tenaga di Gardu Induk Banyudono Berdasar Variasi Pembebanan*. Undergraduate dissertation. Teknik Elektro. Universitas Muhammadiyah Surakarta.
Thiviyanathan, V. A., Ker, P. J., Leong, Y. S., Jamaluddin, M. Z. Bin, & Mun, L. H. (2020). Detection of 2FAL Furanic Compound in Transformer Oil Using Optical Spectroscopy Method and Verification Using Morse Oscillation Theory. *IEEE Access*, *8*, 76773–76779. https://doi.org/10.1109/ACCESS.2020.2989432