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Thermal Model for Transformer Lifetime Prediction Using Simulation Method

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Abstract:
This paper presents simulation technique for life assessment of the insulation of the power transformer. Load and ambient temperatures are two important factors that influence the hot spot of transformers. The transformer hot spot temperature is one of the most critical parameter in determining the life of transformer paper insulation. The simulation (Matlab Software Package) is based on related international standards as the IEC 60076-7:2005 loading guide method. Load and ambient temperatures of the transformer obtain from General Electrical Company and meteorology office of Libya are used as the input for the simulation together with transformer parameters from heat run test. Hottest spot temperature and loss-of-life are calculated. Lifetime of transformer is predicted.

Keywords: Hot-spot temperature, power transformer, top-oil temperature, loss of life.

الملخص
تقدم هذه الورقة تقنية محاكاة لتقييم عمر عزل المحولات الكهربائية. تعتبر درجة الحرارة المحيطة للمحول والحمل هم عاملان مهمان يؤثران على نقاط الحرارة الساخنة بالمحولات. وتعد درجة حرارة النقطة الساخنة للمحول هي العامل الأهم في حساب عمر ورق العازل للمحول. تعتمد المحاكاة باستخدام برنامج(2013ماتلاب) على المعايير الدولية ذات الصلة كطريقة دليل التحميل (2005: 7- 60076CEI). الحمل ودرجة الحرارة المحيطة للمحول المقابلة له، أخذت من الشركة العامة للكهرباء ومكتب الأرصاد الجوية في ليبيا والتي تم استخدامهم كدخل للمحاكاة مع قيم المعاملات الناتجة من اختبار العملي الحراري للمحول. يتم حساب درجة حرارة النقطة الأكثر سخونة والفاقد في العمر. كما تم حساب وتوقع العمر الافتراضي للمحول.

الكلمات المفتاحية: حرارة نقطة التسخين، محول القدرة، ارتفاع قمة الزيت الحرارية، الفاقد في العمر.

Introduction

Power transformers constitute the largest capital investment in transmission and distribution substations, underscoring their critical role in power system reliability and economic performance. Their outages can cause severe disruptions and incur significant financial penalties due to service interruptions and maintenance costs. Given their high initial costs and operational importance, effective condition monitoring of transformers is imperative to maximize return on investment and minimize lifecycle costs. Among various parameters affecting transformer performance and longevity, the hot-spot temperature is a decisive factor, as it directly governs insulation aging, loss of efficiency, and overall operational reliability [1, 2].

The hot-spot temperature in a transformer is influenced by various factors, including ambient temperature, transformer design (such as winding configurations), cooling methods, and instantaneous load. Excessively high hot-spot temperatures can lead to exponential insulation degradation, significantly shortening the transformer's life span and increasing the risk of catastrophic failure. In most designs, the hot-spot is typically located near the top of the winding due to thermal gradients. The traditional method for estimating hot-spot temperature involves summing the ambient temperature, the top-oil temperature rise in the tank, and the hot-spot-to-top-oil temperature gradient. While this approach is straight forward, it often lacks the accuracy required to accommodate dynamic operating conditions and unique transformer designs [2, 3].

There are two primary approaches to determining the hot-spot temperature: direct measurement and thermal modeling.

Direct Measurement method employs fiber-optic temperature sensors strategically placed at anticipated hot-spot locations within the transformer windings. The sesensors are embedded between the insulated conductor and spacers, transmitting temperature dataviaoptical fiber sto external monitoring systems. This approach offers unparalleled precision and real-time monitoring, making it particularly suitable for high-value or critical transformers where exact thermal management is essential. However, direct measurement has limitations—primarily the high cost of sensors and installation, which can make large-scalead option impractical, especially for retrofitting existing transformers. Additionally, accurately identifying the hot-spot location for sensor placement remains an engineering challenge. As a result, direct measurement is typically reserved for transformers in strategic or high-priority installations [4, 5, 6].

Thermal modeling, on the other hand, provides a scalable and cost-effective alternative, particularly in applications where budget constraints make direct measurement unfeasible. This method involves computational simulations of a transformer's thermal behavior based on standardized methodologies such as IEEE Standard C57.19 (1995) and IEC Standard 1991. These standards offer simplified, empirically validated frameworks for estimating hot-spot temperatures using key parameters like historical loading profiles, ambient temperature data, and transformer design specifications. While thermal modeling relies on assumptions that introduce some degree of uncertainty, it has gained widespread acceptance due to its practicality and accuracy in real-world operational scenarios. Additionally, the integration of advanced computational tools—such as finite element analysis and data-driven approaches—has further improved the predictive capability of thermal models [7, 8, 9, 16,17].

The choice between direct measurement and thermal modeling depends on the specific application. Direct measurement is preferred for new installations where cost is justifiable and precision is critical, while thermal modeling is better suited for existing transformers or situations where affordability and scalability are key considerations. Emerging advancements in sensor technology and computational methods—such as real-time monitoring systems integrated with IoT and AI—are bridging the gap between these approaches, creating hybrid solutions that enhance accuracy and applicability.

Effectively understanding and managing hot-spot temperatures in power transformers is essential to ensuring their reliability, efficiency, and longevity. While direct measurement provides unmatched accuracy, it is cost-prohibitive for wide spread use. Conversely, thermal modeling offers a practical and scalable alternative. As monitoring technologies and computational techniques continue to evolve, the future of transformer thermal management will likely see significant advancements, contributing to enhanced reliability and sustainability in power systems.

Transformer thermal model

In this study, the thermal model outlined in IEC 60076-7 (Revision 2005) [4]. It was used to calculate the transformer's hot-spot temperature. This model represents the latest thermal modeling standard within the IEC framework, incorporating advancements and research conducted by Pierce [4,5]. It provides a reliable and robust method for estimating temperature rise in transformers under dynamic loading conditions.

A. Top-Oil Temperature

The top-oil temperature is a critical parameter in transformer thermal modeling, representing the average oil temperature at the top of the transformer tank. The governing differential equation for top-oil temperature rise is given as follows [2, 10, 11, 16]:

$$\left[\frac{1+K^2R}{1+R}\right]^x (TOR_R) = k_{11}\tau_0 \frac{dTO}{dt} + (TO - TA)(1)$$

K is the transformer load in (pu), R is the ratio of load loss to no-load loss, x and k11 are thermal constant, TO is top oil temperature, TA is ambient temperature, τo is oil time constant and TORR is top oil rise at rated load [6,12 and 13]. The equation 1 captures the thermal dynamics of oil under varying load and environmental conditions.

B. Hot-Spot Temperature Rise

The hot-spot temperature rise (HSR) is modeled as the sum of two differential equations:

$$HSR = HSR_1 \ - \ HSR_2 \qquad (2)$$

The first and second components are governed by the following differential equations (3) and (4):

$$k_{21}K^y(HSR_R) = k_{22}\tau_w \frac{dHSR_1}{dt} + HSR_1 \qquad (3)$$

$$(\mathrm{k}_{21} - 1)\mathrm{K}^y(\mathrm{HSR_R}) = \frac{\tau_0}{\mathrm{k}_{22}} \frac{\mathrm{dHSR_2}}{\mathrm{dt}} + \mathrm{HSR_2} \qquad (4)$$

τw is winding time constant, HSRR is hotspot temperature rise at rated load, k22 and y are thermal constant.

C. Hot-Spot Temperature

The hot-spot temperature (HS) is calculated as the sum of the top-oil temperature and the hot-spot temperature rise, which given by [14, 15 and 16]:

$$\mathrm{HS} = \mathrm{TO} + \mathrm{HSR} \qquad (5)$$

D. Transformer Loss of Life.

The loss of life of a transformer is derived from the hot-spot temperature using the following equation:

$$2^{\frac{(\mathrm{HS}-98)}{6}} = \frac{\mathrm{dL}}{\mathrm{dt}} \qquad (6)$$

Simulation MODEL

The transformer thermal model developed in this study was implemented in MATLAB/Simulink to simulate the dynamic behavior of top-oil temperature rise, hot-spot temperature rise, and transformer life degradation under varying operating conditions. This model is based on the thermal framework outlined in IEC 60076-7 (Revision 2005) and utilizes the Runge-Kutta method for numerical computations. The simulation spans a full 24-hour period, divided into 1440-minute increments, allowing for a detailed analysis of the transformer's time-dependent thermal response.

A. Top-Oil Temperature Rise Model.

The top-oil temperature refers to the temperature of the oil at the upper part of the transformer tank, where heat accumulation and dissipation are most significant

The block diagram of the top-oil temperature rise model, shown in Figure 1, illustrates the relationship between key inputs—such as transformer load and ambient temperature—and the model's governing parameters. This component serves as the foundation for further calculations related to hot-spot temperature and transformer aging.

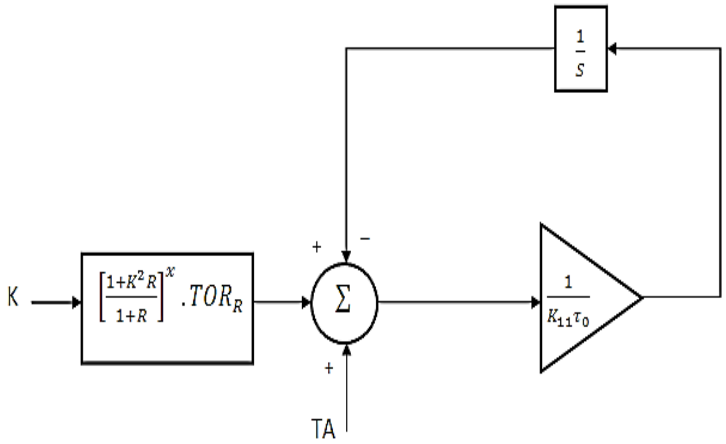

Figure 1: Block diagram of top oil rise model.

B. Hot-Spot Temperature Rise Model.

The hot-spot temperature rise is a crucial parameter that directly impacts the aging of transformer insulation and over all system reliability. The thermal model breaks down the hot-spot temperature rise into two distinct components, each corresponding to different heat transfer mechanisms within the windings(HSR1 - HSR2).
Block diagrams illustrating these two components are provided in Figures 2 and 3, while their combined effect is shown in Figure 4.

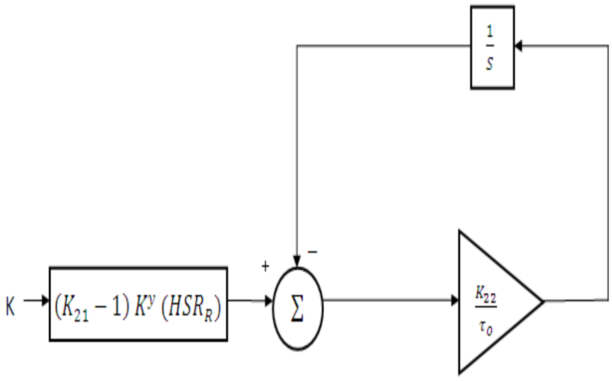

Figure 2: Block diagram of HSR1 model.

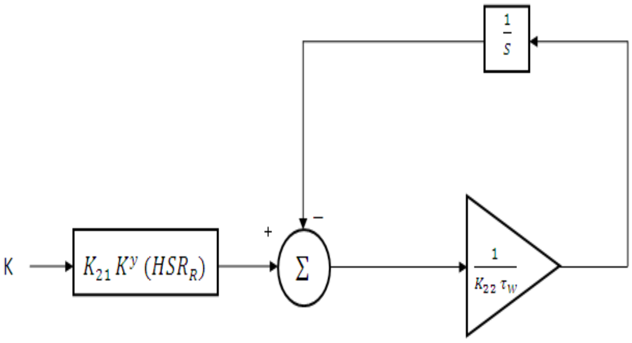

Figure 3: Block diagram of HSR2 model.

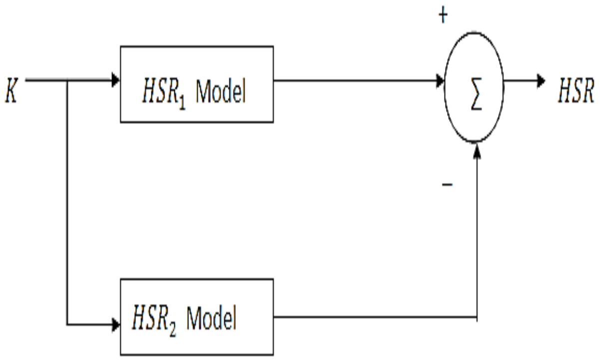

Figure 4: Block diagram of the sum of two differential hotspot equations.

C. Hot-Spot Temperature Model

The hot-spot temperature is determined by adding the hot-spot temperature rise, and top-oil temperature rise.
The block diagram of the hot-spot temperature model, shown in Figure 5, provides a structured representation of how these parameters are combined into a single, actionable thermal metric.

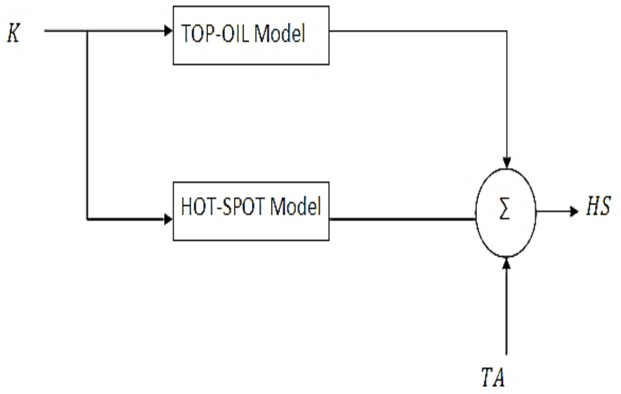

Figure 5: Block diagram of Hotspot temperature model.

D. Loss-of-Life Model

The loss-of-life model estimates the cumulative thermal aging of the transformer over the simulation period. Using the calculated hot-spot temperature, the model predicts the rate of insulation degradation and translates this into an equivalent "loss of life" metric. This provides a quantifiable measure of the impact of thermal stresses on the transformer's lifespan.

The block diagram of the loss-of-life model, shown in Figure 6, integrates the thermal data into a comprehensive aging analysis. This output is particularly valuable for assessing the long-term reliability of the transformer and optimizing its operational management.

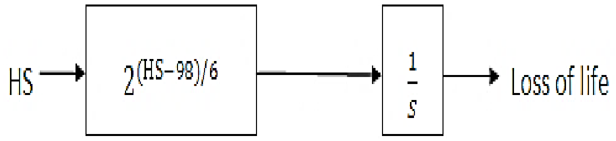

Figure 6: Block diagram of loss-of-life model.

The simulation workflow begins with the initialization of thermal constants, rated values, and time constants. Input variables, such as load profiles and ambient temperature, are fed into the model as time-series data to simulate realistic operating conditions. The Runge-Kutta method is then used to iteratively solve the thermal equations over the 24-hour period.

The key outputs of the simulation include:

Top-oil temperature profile: Tracks the dynamic changes in oil temperature, providing insights into heat dissipation and accumulation.

Hot-spot temperature profile: Captures the peak thermal conditions within the transformer, highlighting potential risks of overheating.

Loss-of-life estimation: Quantifies the thermal aging of the transformer insulation, offering actionable data for maintenance planning.

Transform under Study

The transformer under study is a three-phase 20 MVA, 66/11 kV ONAN (Oil Natural Air Natural) cooling transformer. This type of transformer is widely used in power systems due to its reliability and efficient heat dissipation. The heat run test data for the transformer is summarized in Table 1, which provides essential parameters for thermal modeling and simulation.

Table 1: Transformer heat run test data.

Top oil temperature rise at rated load	50
Hot spot temperature rise at rated load	55
R (ratio of load loss/ no load loss)	6.5
Top oil time constant, min	210
Winding time constant, min	7
y exponent	.16
x exponent	0.8
K11	0.5
K21	2.0
K22	2.0

Daily Load and Ambient Temperature Profiles

The thermal behavior of the transformer was analyzed using daily load and ambient temperature profiles, both sampled at 60-minute (one-hour) intervals. The load profile, provided by the General Electrical Company of Libya, reflects typical operational patterns, capturing the variations in transformer loading throughout 24-hours period. The ambient temperature data, sourced from the Meteorology Office of Libya, illustrates the hourly fluctuations influencing transformer heat dissipation.

Figure 7 depicts the daily load profile for the 20 MVA, 66/11 kV ONAN transformer, recorded at one-hour intervals. The transformer load exhibits notable variations over the day, with periods of higher demand during peak operational hours. These fluctuations directly impact the thermal performance of the transformer, influencing both the top-oil and hot spot temperature rises

Figure 8 shows the corresponding daily ambient temperature profile, also sampled at one-hour intervals. The ambient temperature follows a typical diurnal pattern, peaking during midday and decreasing during the night. This profile plays a significant role in determining the rate of heat dissipation from the transformer to its surroundings.

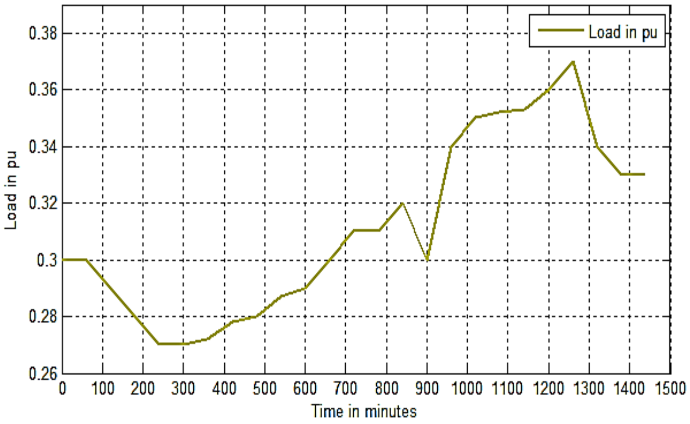

Figure 7: Daily load profiles for the 20MVA, 66/11KV transformer.

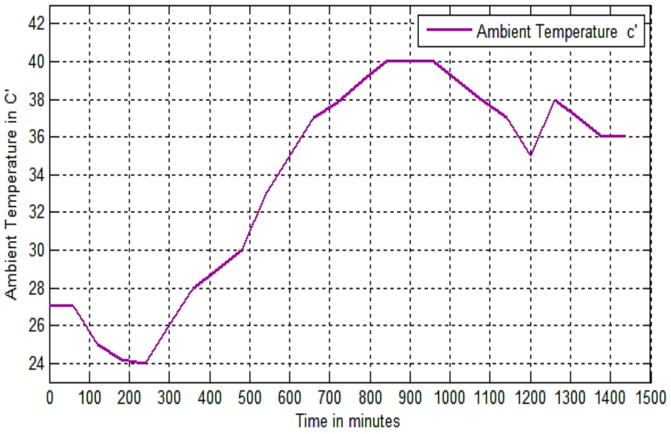

Figure 8: Daily ambient temperature for the 20MVA, 66/11KV transformer.

Simulation Results

The simulation results for the transformer under study provide comprehensive insights into its thermal behavior over a 24-hour period. Key parameters such as the top-oil temperature rise (TO), winding hot-spot temperature rise (HSR), hot-spot temperature (HS), and cumulative loss of life were analyzed to evaluate the transformer's performance and aging under dynamic loading and ambient temperature conditions. The figures below highlight the temporal variations and interdependence of these parameters.

A. Top-Oil Temperature Rise

Figure 9 illustrates the daily variation in the top-oil temperature rise. At the start of the day, the top-oil temperature is elevated (~50°C), potentially due to residual heat from previous operational conditions. Following a brief decline, the temperature stabilizes before rising steadily, peaking around 1000 minutes (~16–17 hours) due to increased loading and higher ambient temperatures. A gradual decline is observed during the evening hours, aligning with lower loads and cooler ambient temperatures.

These fluctuations underscore the direct relationship between load, ambient conditions, and the thermal behavior of the transformer oil. The stable temperature ranges observed during off-peak periods demonstrate the efficiency of the cooling system, while the midday peak highlights the need for careful load management during high-demand periods to prevent excessive thermal stress.

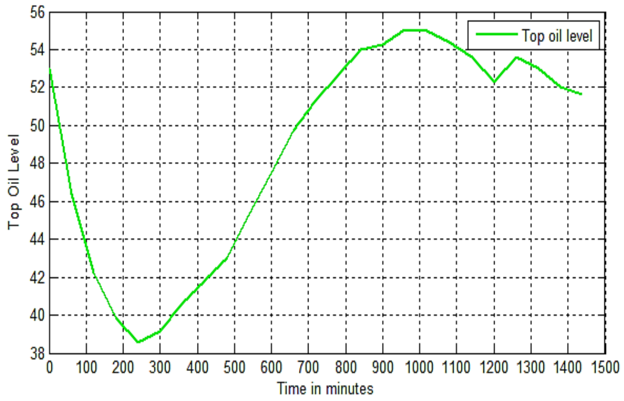

Figure 9: Daily top oil temperature rise for the 20MVA, 66/11KV transformer.

B. Winding Hot-Spot Temperature Rise

The winding hot-spot temperature rise, presented in Figure 10, exhibits similar trends to the top-oil temperature but with slightly lower amplitudes. The initial drop from approximately 14.3°C reflects the winding's thermal adjustment to fluctuating loading conditions. A steady increase begins around 400 minutes, first peaking at 12.3°C during the late afternoon. And second peaking at 14.8°C begging of night. The gradual decline toward the end of the simulation reflects the transformer's thermal recovery during periods of reduced loading.

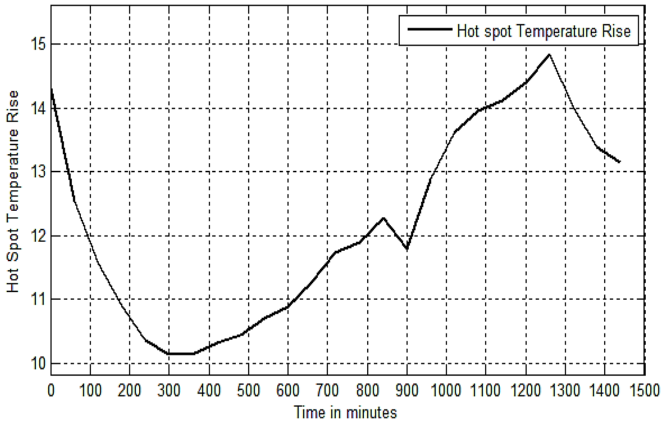

Figure 10: Daily winding hotspot temperature rise for the 20MVA, 66/11KV transformer.

The relatively minor fluctuations compared to the top-oil temperature indicate the thermal inertia of the winding and the transformer's ability to maintain stable operating conditions. Nonetheless, the midday peak reinforces the need for load redistribution strategies to minimize prolonged exposure to elevated winding temperatures, which could accelerate insulation degradation.

C. Hot-Spot Temperature

The overall hot-spot temperature, shown in Figure 11, combines the effects of top-oil temperature rise, winding hot-spot temperature rise, and ambient temperature. The curve begins at a high initial value (~67°C) and stabilizes around 50°C during the early hours of the day. As loading and ambient temperatures increase, the hot-spot temperature rises, peaking near 68°C around 1000 minutes. The gradual decline in the evening aligns with reduced load and cooling effects, stabilizing at 65°C by the end of the simulation.

This parameter is critical for assessing the thermal aging of the transformer's insulation, as elevated hot-spot temperatures during peak periods significantly contribute to cumulative aging. Effective load and cooling management are essential to ensure the transformer operates within safe thermal limits.

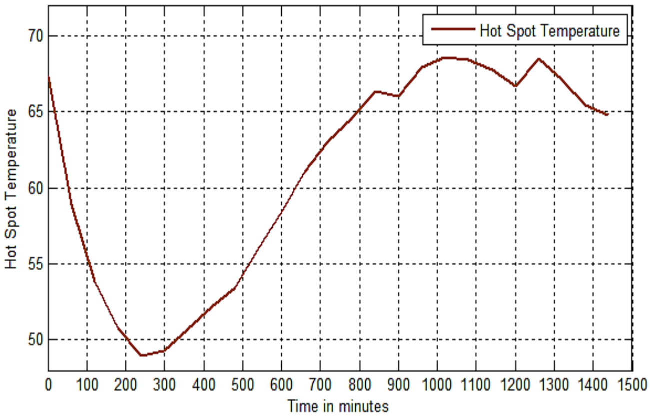

Figure 11: Daily hotspot temperature for the 20MVA, 66/11KV transformer.

D. Loss of Life

Figure 12 highlights the cumulative loss of life for the transformer over the 24-hour simulation period. The curve exhibits an exponential trend, with minimal increments during low-load periods and significant increases during peak demand hours. The total loss of life reaches approximately 25 minutes by the end of the day.

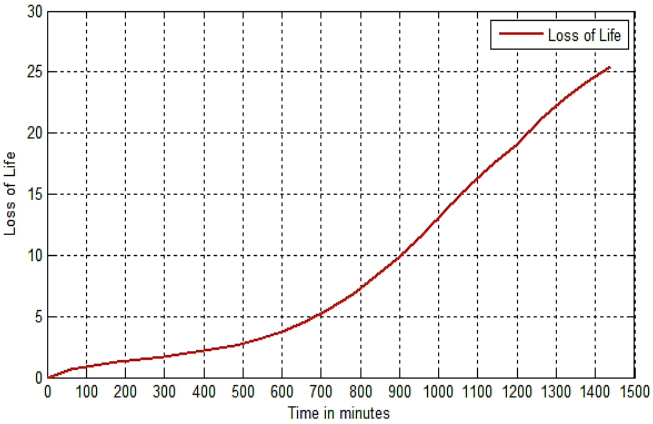

Figure 12: Daily loss of life for the 20MVA,66/11KV transformer.

The steepest rise in loss of life occurs between 800 and 1400 minutes, coinciding with the hot-spot temperature peak. This exponential behavior reflects the nonlinear relationship between insulation aging and temperature, emphasizing the critical importance of minimizing thermal stress during high-demand periods.

Lifetime Estimation for Transformer

To evaluate the transformer's reliability over an extended period, a 30-day load and ambient temperature profile was extracted from historical operational data. The same simulation methodology from the previous section was applied to determine the hot-spot temperature and insulation loss of life for each dataset, with the results systematically presented in Table 2. This analysis specifically considers the daily peak ambient temperature and maximum load as the primary influencing factors.

According to Table 2, the transformer's annual loss-of-life expectancy is calculated to be 3,899.16 minutes, equivalent to 64.986 hours per year. The transformer's remaining lifespan is estimated based on the assumption that the annual loading profile remains consistent throughout its operational period.

For insulation life assessment, the Degree of Polymerization (DP) = 200 is adopted as the end-of-life threshold in accordance with IEEE standards. This threshold corresponds to an expected insulation lifespan of 150,000 hours under nominal full-load conditions for a transformer designed to IEEE specifications. However, in high-reliability applications where strict operational control is required, an alternative end-of-life criterion based on 25% retention of tensile strength may be considered, reducing the insulation lifespan to 135,000 hours under full-load conditions. Based on these aging models and assuming a steady rate of thermal wear over the years, the estimated lifespan of the transformer is:

- If 25% of tensile strength (135,000 hours) is used as the end-of-life benchmark: ~2,077 years
- If degradation is measured based on a Degree of Polymerization (DP) of 200: ~2,308 years

Table 2: Loss of life profile.

DATA	MAX. ambient temperature (C^0)	Peak load (pu)	Loss of life (minute)
1	24	0.355	4.29
2	25	0.355	5.12
3	28	0.33	6.03
4	37	0.33	17.5
5	28	0.339	7.28
6	25	0.328	5.57
7	26	0.33	5.45
8	28	0.339	6.39
9	36	0.356	12.97
10	35	0.357	14.26
11	32	0.32	8.56
12	30	0.33	7.78
13	33	0.337	9.75
14	36	0.339	12.76
15	38	0.34	16.57
16	42	0.354	26.18
17	40	0.354	24.5
18	43	0.396	36.78
19	34	0.35	11.64
20	36	0.355	11.72
21	28	0.35	7.58
22	25	0.33	5.45
23	26	0.33	5.68
24	28	0.33	5.57
25	31	0.358	8.48
26	35	0.33	12.79
27	29	0.355	7.88
28	27	0.33	6.15
29	28	0.355	7.39
30	27	0.338	6.86

However, it's important to note that these projections focus solely on thermal stress as the primary cause of aging. Other factors like moisture buildup, oxidation, partial discharges, and dielectric breakdown—things that can speed up insulation wear—aren't included in these estimates. If those issues come into play, the transformer may need maintenance or replacement much sooner.

This reinforces the importance of real-time thermal monitoring, proactive load management, and predictive maintenance to slow down aging and extend the transformer's lifespan. By using advanced thermal diagnostics and condition-based maintenance (CBM), power companies can improve reliability, cut long-term costs, and enhance the stability of the power grid.

Conclusion

Power transformers are essential to power systems, ensuring stability and reliability. Their performance directly impacts overall system operations, with the health of transformer insulation playing a crucial role in determining lifespan. Insulation degradation is primarily influenced by temperature and exposure time, making thermal performance a key factor to monitor and optimize.

This study explored the relationship between transformer hot-spot temperature and load, as defined by IEC standards, and used this understanding to model thermal behavior. The thermal model, based on the latest IEC 60076-7 standards, was implemented in MATLAB/Simulink to accurately calculate the hot-spot temperature and cumulative loss of life.

The results demonstrated that the model effectively predicts transformer hot-spot temperature and insulation aging. Additionally, lifetime estimations based on DP = 200 and 25% tensile strength retention provided reliable projections, aligning well with standard insulation aging models.

Simulation findings highlighted the importance of managing thermal stress through load optimization and cooling enhancements to maintain long-term reliability.

Overall, this study confirms the practicality and accuracy of IEC thermal models for predicting transformer lifespan. The results provide valuable insights for power utilities looking to improve transformer operation, implement predictive maintenance strategies, and enhance system reliability.

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