Journal of Thermal Engineering
https://jten.yildiz.edu.tr/
https://doi.org/10.47481/jten.0078

RESEARCH ARTICLE

Performance evaluation of an improved international electro-technical commission based thermal modeling of power transformers under factory testing conditions

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Abstract

Power transformers play a vital role in power systems, from the generation of electrical energy through transmission and distribution to end consumers. They are often loaded near rated-load conditions during operation. This leads to increased losses and a rise in temperature in the power transformers. The thermal performance of power transformers is a critical factor influencing operational reliability and insulation life, yet standard International Electro technical Commission-based models often assume a constant ambient temperature, limiting their predictive accuracy under real operating conditions. The objective of this research is to develop an improved International Electro technical Commission-based thermal model that incorporates time-varying ambient temperature effects during transformer-type testing. The research method includes exponential equations that are validated against stepped-load data from a 5 MVA transformer, where the ambient temperature ranged between 27°C and 32°C during the experimentation. A comparative analysis showed that the improved model reduced the mean absolute error for oil temperature rise from 3.15% to 2.04%, and for winding temperature rise from 2.30% to 1.88%. Similarly, root-mean-square error and mean percentage error decreased by 30–40%, indicating a consistent improvement in predictive accuracy across metrics. These findings indicate that incorporating ambient temperature variability enables the model to more accurately reproduce both steady-state conditions and transient heating and cooling behavior, thereby aligning more closely with physical expectations. Inference from the results suggests that the improved model offers a scientifically rigorous yet computationally efficient alternative to more complex data-driven approaches. The novelty of this work lies in bridging the gap between oversimplified, constant-ambient International Electro technical Commission-based thermal models and computationally intensive methods, thereby providing a standards-consistent framework with enhanced realism. The outcomes have direct implications for transformer manufacturers, enabling more reliable type testing; for utilities, enabling improved insulation life assessment and overload management; and for standards developers, recommending integration of dynamic ambient effects into standard guidelines.

Keywords: Power transformer, thermal modeling, international electro-technical commission standard, ambient temperature, type test

Cite this article as: Mehta, V., & Vajpai, J. (2026). Performance evaluation of an improved international electro-technical commission based thermal modeling of power transformers under factory testing conditions. Journal of Thermal Engineering, 12(6), 1966–1974. https://doi.org/10.47481/jten.0078

1. Introduction

Power transformers play a role in the entire power system, stepping up and down voltage levels at different stages from the generating end to the utility terminals. With increasing demand on the load side, power transformers must operate near or below critical loading conditions. This leads to a rise in temperature inside the power transformers. The rise in temperature is further enhanced by ambient temperature, especially during hot summers. Hence, the design of modern power transformers needs to be modified to improve their thermal performance.

During the testing phase, power transformers undergo various tests in factories before commissioning. These tests include type and routine tests. The temperature-rise test is a general test that every power-transformer manufacturer undergoes. The maximum temperature rise and heat transfer capability are assessed during this test. This test also ensures that the insulation used in the transformers can withstand thermal

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Submitted: 15 July 2025; **Accepted:** 20 November 2025

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University, İstanbul, Türkiye

stresses. The competence of the cooling system is also assessed during the temperature rise test. Since this test is performed on the factory premises, the external temperature is kept almost constant. The effects of other major influencing parameters, such as solar irradiation and wind flow, are not considered. The work presented in this paper considers the influencing parameters under factory-operated conditions by developing improved thermal models that are compared with the practical observations taken during the experiment. To gain further insight, the present work surveys progress in field applications and difficulties associated with power-transformer temperature-rise type tests.

The thermal models of power transformer are presently constructed according to International Electro-technical Commission IEC60076-7 standard [4] using heat transfer studies for determining the temperature of oil and winding. The IEC60076-7 standard guide recommends a method based on exponential equations suitable for modeling the thermal aspects of power transformers under test, which are operated with stepped loads while the outdoor ambient temperature is kept nearly constant. Institute of Electrical and Electronics Engineers (IEEE) C57.12.00 standard [9] covers various tests, including resistance, polarity, ratio, no-load loss, impedance, dielectric, temperature, short-circuit, audible sound level measurements, and calculated data, offering a comprehensive standard for conducting these assessments in transformer evaluation. IEEE C57.168 standard [10] offers comprehensive insights by covering test methodologies, result interpretation guidance and strategies to navigate common testing pitfalls, enhancing the efficiency of transformer evaluations.

W. H. Tang et. al. [1] have used the genetic algorithm for calculating various thermal parameters of power transformers and also compared it with the real-time temperature readings. Till present, the thermal model for type test has only been used by D. Susa et. al. [2], whose findings are relevant to this research work and is considered as major reference for the validation of methodology and data analysis technique by comparison of results. The model as presented in the research paper of D. Susa et. al. [2] has been validated by comparison with the experimental results. However, their work typically assumes constant ambient conditions during testing, which do not reflect real-world factory or field environments. Even modest variations in ambient temperature significantly influence cooling dynamics, leading to systematic deviations of 3-4°C in IEC-based predictions. Numerical and AI-based models can address this limitation but require high computational effort and lack the transparency and standards consistency of IEC formulations.

O. A. Amoda et. al. [3] have developed the thermal models which are based on IEEE standards for the determination of various temperature inside a power transformer. A. Mamizadeh and I. Iskender [5] have proved that the thermal models for an indoor and an outdoor power transformer differ from each other. H. Neubert et. al. [6] have presented thermal model of a current transformer by considering the heating effect in Finite Element Method (FEM). M. Kim el. al. [7] have improved the performance of the existing radiators inside the power transformer and also done the design optimization of the cooling arrangement systems. P. Li et. al. [8] have proposed a technique to find the rise in temperature of a power transformer using ANSYS software and compare the obtained results with the testing dataset. L. Zhang et. All. [11] have proposed a fuzzy set theory-based calculation of temperature rise of a power transformer to identify the overload risk factors. V. Mehta and J. Vajpai [12] have presented an enhanced IEC-based thermal model for outdoor power transformers that integrates external environmental factors such as wind and solar radiation. The study demonstrates improved accuracy and predicting top-oil and hot-spot temperature behavior under varying operating conditions. F. T. Yuan et al. [13] have developed a coupled magnetic thermal fluid multi physics finite-element model, then uses support vector regression and neural networks to invert winding hot-spot temperature from external measurements with ≤8% error.

M. Shi et. al. [14] have considered magnetic and hysteresis effects for analyzing losses and temperature values in a power transformer, whereas Y. Zhang et. al. [15] have analyzed the performance of a power transformer to get thermal and overall electromagnetic profile of a power transformer. Q. Duan et. al. [16] have developed a dynamic thermal model of a power transformer that is installed in the grid system of a renewable power station. R. Kumar et. al. [17] and J. Lee et. al. [28] have employed computational fluid dynamics along with machine learning in order to develop thermal models of power transformers for the prediction of thermal faults. B. Wang et. al. [18] have modeled the IEC based thermal model of transformer oil temperature.

A thermal model is proposed by Q. Lin et. al. [19] for determining eddy losses, which is further validated for harmonic loads by Y. Cao et. al [20]. V. Mehta and J. Vajpai [21] have modelled the power transformer using IEEE standard and bon graph approach by considering external conditions. A moisture mitigation technique was presented by M. Bukhari et. al. [22]. S. Shafaei et. al. [23] have analyzed the thermal circuit of a power transformer by using nanoparticle-based oils. Y. Liu et. al. [24] have gathered the field data for designing a dynamic thermal model, and M. Akram et. al. [25] have incorporated a radiative cooling system for the top oil temperature model. Another contribution from H. Cho et. al. [26] have focused on forced oil cooling system modeling under intermittent renewable generation. U. Saeed et. al. [27] have analyzed the effect of high frequency ripple currents from power electronic converters on transformer thermal aging. S. Xu et. al. [29] have used the technique of deep learning in order to predict the hot spots inside the power transformer. H. Deng et. al. [30] have modeled the convection circuit of a power transformer. Transformer thermal behavior with recent advancements has been presented by F. Bhatti et. al. [31] and P. Ranjan et. al. [32] have presented a hybrid model including variation in load. X. Zhao et. al. [33] have examined a multi-layer network method for accelerated hotspot temperature estimation. Together, these works reveal that the integration of advanced numerical, data-driven, and hybrid physics-informed methods is shaping the future of thermal modeling of transformers under modern power system challenges. The most recent article by Z. S. Rabeeah et al. [34] have investigated the thermal and hydraulic performance of a double-pipe heat exchanger enhanced with open-cell copper foam baffles. The results emphasize the growing role of porous metal structures in improving heat exchanger design while balancing performance against pressure drop penalties. A. Rubaye et al. [35] have proposed integrating a gas turbine with a LiBr absorption refrigeration system to mitigate performance losses at high ambient temperatures. Their work highlights the effectiveness of waste-heat-driven absorption cooling compared to conventional intake air cooling methods. A. Azzawi et al. [36] analyzed the performance of a solar-assisted double-effect absorption refrigeration system in Iraq, showing that using LiBr-water working pairs with optimized solar collector areas significantly improved and reduced dependency on electrical cooling.

The literature review has provided insights and motivation for designing new and improved thermal models of power transformers. Research gaps have been identified in the lack of consideration of ambient temperature effects, indicating an opportunity to modify IEC-based thermal models. Therefore, there is a need for a computationally efficient, standards-consistent model that integrates dynamic ambient conditions into IEC thermal formulations. The findings presented in this paper have practical and cross-sectoral implications. For transformer manufacturers, the improved model provides a more reliable tool for validating factory-type tests, ensuring that test results reflect real-world ambient conditions rather than idealized assumptions. For utilities and system operators, more accurate prediction of oil and winding temperatures improves estimation of winding temperatures, prediction of insulation life, and risk-informed overload management. Such improvements can directly translate into extended asset life and reduced maintenance costs, which are central concerns for the power sector.

For the research community, this work demonstrates that IEC-based models, traditionally viewed as oversimplified, can be enhanced to approach the predictive fidelity of advanced FEM or data-driven methods while maintaining computational simplicity. This positions the improved IEC model as a strong candidate for integration into digital twin platforms and real-time monitoring systems in which fast, accurate, and interpretable models are essential. Finally, from a standards and policy perspective, the results suggest that future revisions of IEC testing guidelines should explicitly account for ambient variability, given its measurable impact on transformer thermal response. Such revisions would benefit the wider community by harmonizing test practices with field-representative conditions, leading to safer and more efficient operation of critical grid assets.

The present study develops such a model, validates it against experimental type-test data obtained from a 5-MVA transformer, and demonstrates its superiority over the conventional IEC model in terms of accuracy and dynamic response. An attempt was made in this research to include the time-varying ambient temperature in the thermal model during a type test performed under factory conditions at Dusad Transformers & Switchgears Pvt. Ltd., Pali, India, on a 5MVA power transformer.

The objectives are to formulate an enhanced IEC-compliant exponential model, validate its performance against stepped-load experimental data from a 5 MVA transformer under real factory conditions, and quantitatively compare its predictive accuracy with that of the conventional IEC model using statistical indices such as mean absolute error (MAE), root mean square error (RMSE), and mean percentage error (MPE).The originality of this work lies in bridging the gap between oversimplified IEC models and computationally intensive alternatives by providing a novel, ambient-aware IEC formulation. Unlike earlier studies, this model incorporates real-time ambient variability while remaining compliant with IEC exponential equations, thereby offering scientific novelty and industrial applicability.

2. Methodology

Increases or decreases in the temperature inside a power transformer due to the step changes in load follow exponential rise or fall curves. Therefore, the step change in load is implemented by keeping the current constant during each time step. The exponential equation method enables power transformer manufacturers to calculate heat transfer parameters through testing. The steady state response of the relative increase in the oil temperature is shown by an exponential function $f_1(t)$ as follows [4]:

$$f_1(t) = 1 - \exp^{-\frac{t}{t_a \tau_o}} \tag{1}$$

Similarly, the relative increase in the winding temperature over oil temperature is shown by the following exponential function $f_2(t)$ [4].

$$f_2(t) = t_b(1 - \exp^{-\frac{t}{t_c \tau_w}}) - (t_b - 1)(1 - \exp^{-\frac{t}{\tau_w / t_c}}) \tag{2}$$

Also, the exponential function $f_3(t)$ designates the relative fall in the oil temperature over ambient temperature is shown by [4]:

$$f_3(t) = \exp^{-\frac{t}{t_a \tau_o}} \tag{3}$$

The load is varied as a constant value across the terminals of the power transformer during the testing phase. Two cases are possible: the load's value is greater than in the previous cycle, or the load's value is smaller than in the previous cycle. In the first case, the oil and winding temperatures rise; in the second case, their values fall.

The rise in the oil temperature $T_o(t)_{rise}$ in the power transformer with the increasing step of applied load is given by [4]:

$$T_o(t)_{rise} = T_a + \Delta T_{oi} + \left\{ \Delta T_{or} \left[\frac{1 + LF^2 \alpha}{1 + \alpha} \right]^x - \Delta T_{oi} \right\} f_1(t) \tag{4}$$

Similarly, the rise in the winding temperature $T_w(t)_{rise}$ with increasing step of applied load is [4]:

$$T_w(t)_{rise} = T_o(t)_{rise} + \Delta T_{wi} + \{\Delta T_{wr} LF^y - \Delta T_{wi}\} f_2(t) \tag{5}$$

The fall in the oil temperature inside power transformer with decreasing step of load is [4]:

$$T_o(t)_{fall} = T_a + \Delta T_{or}\left[\frac{1 + LF^2\alpha}{1+\alpha}\right]^x + \left\{\Delta T_{oi} - \Delta T_{or}\left[\frac{1 + LF^2\alpha}{1+\alpha}\right]^x\right\} f_3(t) \tag{6}$$

Similarly, the fall in the winding temperature $T_w(t)_{fall}$ with the decreasing step of applied load is [4]:

$$T_w(t)_{fall} = T_o(t)_{fall} + \Delta T_{wr} LF^y \tag{7}$$

Equations (4)-(7) are more easily explained using Figure 1. It shows the increase and decreases of load and the governing for temperature rise and fall. Figure 1(a) demonstrates exponential thermal behavior: as load increases, winding and oil temperatures both rises, but at different rates and to different magnitudes. Winding temperature is more sensitive and responds more quickly, whereas oil temperature lags owing to its greater thermal inertia. These dynamics are crucial because winding temperature largely determines insulation aging and transformer lifetime.

(a) Increasing load **(b)** Decreasing load

Figure 1. Increasing and decreasing of load and the guiding equations of temperature rise and fall

Similarly, Figure 1(b) illustrates the cooling behavior of the transformer winding and oil temperatures following a load reduction. When the load decreases, both the winding and oil temperatures exhibit exponential decay toward a lower equilibrium value. The winding cools more quickly than the oil due to its smaller thermal time constant and lower thermal inertia, while the oil, with greater thermal mass, dissipates heat more slowly and lags in response. This difference in cooling dynamics highlights the fundamental thermal characteristics of transformer components and is central to accurately modeling transient behavior, predicting winding temperatures, and assessing insulation life under varying load conditions.

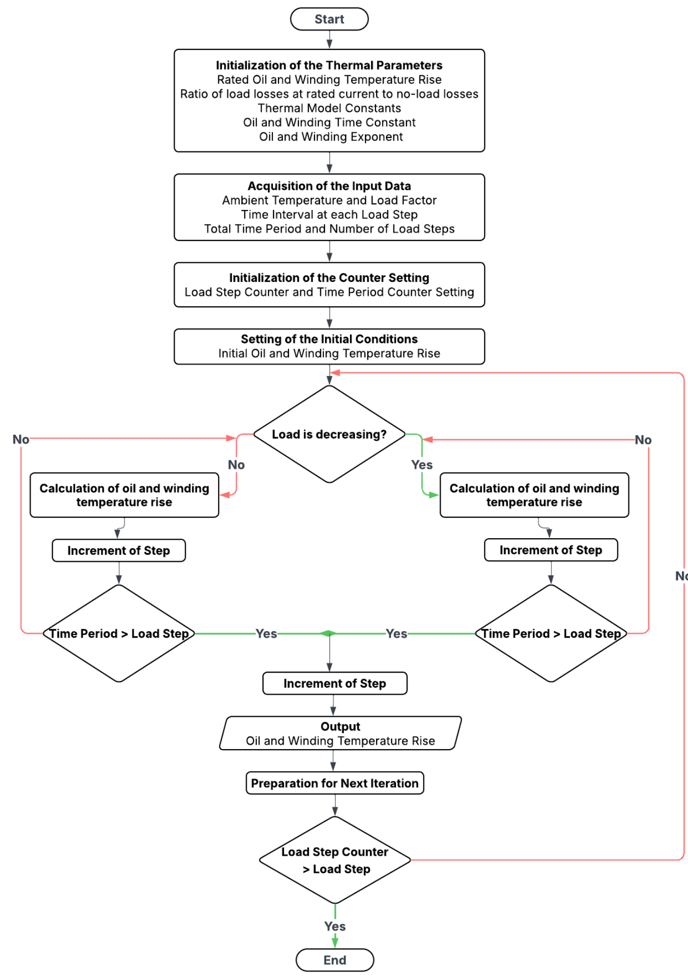


Figure 2. Flow chart of IEC based exponential equation method

To ensure that a power transformer meets the customer's design specification and expectations, it must undergo the testing procedure and other necessary tests (type tests) during the manufacturing process. Figure 2 shows the flowchart of IEC-based exponential-equation method for developing a computational model. It shows the step-by-step procedure for designing a thermal model of a power transformer using the IEC-based exponential-equation method. First, all input data, including rated values of oil and winding temperature, the ratio of load to no-load losses, various constants of the thermal model, time constants, and values of exponents, were considered. The next step is to acquire data on ambient temperature and load factors at one-minute intervals during experimentation in the factory. Furthermore, proper solver parameters are selected by initializing the counters. The initial conditions for oil and winding temperature rise during the type test are reported. To permit intermittent cooling, each increasing load step is followed by a decreasing load step, and the current during each load step is kept constant.

The next step involves determining whether the load step is increasing or decreasing, and a decision is then made using equations (4) and (5) to calculate the oil and winding temperature rise. If the load factor LF is less than 1, equations (6) and (7) are used to determine the decreases in oil and winding temperatures. During both the increasing and decreasing load steps, the values of oil and winding temperature rise are recorded every minute by increasing the counter setting. At each load step, when the value of the counter becomes greater than the set interval, the counter is increased to determine the oil and winding temperature rise during the next interval. In the next iteration, the load step is checked again to determine whether it is an increasing or decreasing function. The process is repeated until the oil and winding temperature-rise values at each minute are determined using an exponential-equation-based thermal model designed according to the IEC standard.

The methodology as explained in this section is first implemented and validated by designing the thermal models as proposed by D. Susa et. al.[2]. In the next section, the validated, improved thermal model is applied to a power transformer under factory conditions.

3. Results and discussions

This section analyses and compares the performance and accuracy of the designed, improved thermal model to practical readings obtained through observations, with the aim of evaluating the validity and applicability of the model in real-world scenarios. Figure 3 shows the experimental setup for the type test on the factory premises.

Figure 3. Experimental set up

The findings of this comparative analysis will provide insights into possible further improvements to the models and identify potential modifications. The recommended thermal parameters of the power transformer under consideration, on which this type test has been performed, are shown in Table 1.

The load factor LF varies in accordance with the IEC loading guide, with each increasing step followed by a subsequent reduction in load. During each time interval, the load current was kept constant and throughout the duration of test, the ambient temperature was varied between 27°C to 32°C. This test started at 10:30 AM with a unit step (LF=1).

Table 1. Thermal parameter of the power transformer

Thermal Parameter	Value
ΔT_{or}	30°C
ΔT_{wr}	25°C
ΔT_{oi}	0°C
ΔT_{hi}	0°C
α	7
τ_o	210 mins
τ_w	10 mins
k_a	0.5
k_b	2.0
k_c	2.0
x	0.8
y	1.3

The last incremental load factor, 1.7, was reached at 10:15PM. The time and corresponding load factor are shown in Table 2, and its graphical illustration is shown in Figure 4.

Table 2. Load steps of the power transformer under type test condition

Time Period (in mins)	Load Factor
0 – 205	1.0
205 – 370	0.5
370 – 490	1.4
490 – 680	0.4
680 – 705	1.7

The results from the improved thermal model, which is based on an IEC temperature-rise test, are now compared with the experimental observations from the laboratory. The comparison of the results obtained from the standard and modified IEC-based thermal models and the practical observations during the test has been shown graphically in Figures 5 and 6. Figure 5 compares the experimental oil temperature rise with predictions from the standard and improved IEC models under stepped-load conditions.

The experimental data demonstrate a nonlinear heating profile, with faster rises during initial load increments and slower asymptotic approaches toward thermal equilibrium at higher loads. The standard IEC model systematically underestimates oil temperature rise during high-load intervals (e.g., at LF = 1.4 between 490-680 minutes), with deviations up to 4°C. This discrepancy arises because the conventional IEC model assumes fixed ambient conditions, which oversimplifies the heat dissipation dynamics.

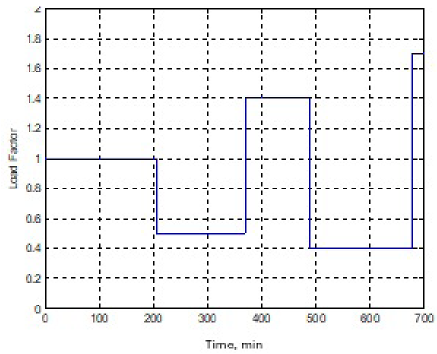


Figure 4. Load steps of power transformer under type test conditions

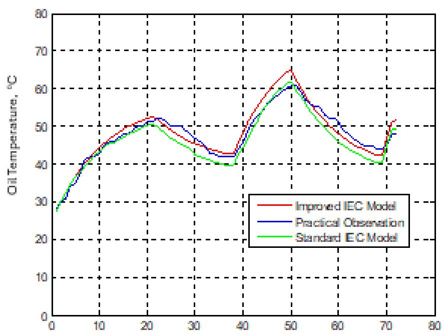


Figure 5. Oil temperature rise from IEC based thermal model (type test)

Oil temperature rise is highly sensitive to ambient-oil gradients, and even modest variations in ambient (27-32°C during the test) significantly affect convection-driven cooling rates. By contrast, the improved IEC model tracks the experimental curve more closely across both heating and cooling phases. Importantly, the improved model better reproduces the time constant of the oil cooling process; this improvement is particularly evident during load reductions (e.g., at 205-370 minutes, LF = 0.5). This suggests that incorporating ambient variability allows the model to dynamically adjust the effective heat transfer coefficient, producing a more physically realistic representation of thermal inertia.

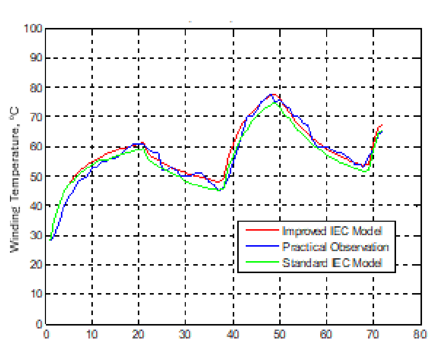
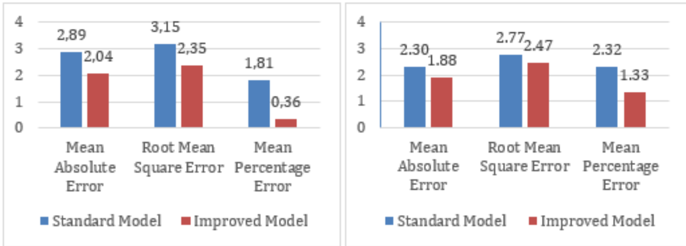


Figure 6. Winding temperature rise from IEC based thermal model (type test)

Figure 6 presents the measured winding temperature rise compared with predictions from the standard and improved IEC models. Similar to oil, the winding thermal response shows clear exponential characteristics, but with faster transients due to the lower thermal time constant of copper compared with oil. The standard IEC model again shows delayed response during transient load changes, failing to capture the sharper heating gradients following load increases (e.g., LF=1.0 at 370- 490 mins). Deviations between the model and experimental results peak at approximately 3°C. This lag is due to the model's fixed treatment of ambient conditions, which neglects the direct coupling among winding losses, oil temperature, and ambient temperature fluctuations. The improved IEC model demonstrates markedly better alignment with the experimental winding profile. Notably, the improved model preserves the relative phase relationship between oil and winding thermal behavior, predicting faster winding heating during load steps and slower cooling during load reductions, in agreement with physical expectations. An accurate representation of transient winding behavior is critical because the winding temperature rise primarily determines insulation aging and transformer lifetime.

Comparable findings were reported by Susa et al. [4], who validated IEC based models under constant ambient conditions but observed systematic offsets in high load regimes. The present results extend their framework, demonstrating that accounting for ambient fluctuations materially improves the fidelity of oil temperature predictions. Susa et al. [4] also emphasized the importance of accurately capturing oil and winding temperature gradients under varying load conditions. The present results reinforce this conclusion by demonstrating that a relatively simple IEC-based enhancement — the explicit inclusion of time-varying ambient temperature — can produce winding predictions comparable in accuracy to more computationally demanding data-driven approaches.

The MAE, RMSE, and MPE have also been determined for both oil and winding temperature-rise values obtained from the standard and improved thermal models, as shown in Figure 7. The bar chart clearly illustrates the consistent performance improvements exhibited by the improved IEC model across all error indices. For oil temperature rise, the MAE decreased from 2.89% (standard IEC) to 2.04% (improved IEC), while the RMSE decreased from 3.15% to 2.35%. Similarly, the MPE was lowered from 1.81% to 0.36%. For winding temperature rise, the MAE improved from 2.30% to 1.88%, and the RMSE from 2.77% to 2.47%, while the MPE decreased from 2.32% to 1.33%.



(a) Oil temperature rise **(b)** Winding temperature rise

Figure 7. Different errors of improved and standard thermal models

The graphical comparison emphasizes not only the magnitude but also the consistency of error reduction, with the improved model delivering superior accuracy in both oil and winding predictions. Notably, the larger gains observed in error metrics for oil reflect the model's enhanced ability to capture the greater thermal inertia of oil under variable ambient conditions. These findings are in line with the observations of Susa et al. [4], who noted higher deviations when constant ambient IEC models were applied. However, the present model achieves these improvements within the computationally efficient IEC framework, underscoring its novelty and industrial relevance.

In this manner, the designed thermal model as presented in this paper helps ensuring the reliability and suitability of the power transformers for the intended application. Buyers of power transformers can verify that the transformers meet both industry standards and the buyers' specific technical and performance requirements. Inspecting the power transformer on factory premises by undergoing a type test also allows them to identify specific customization requirements.

It should be noted that the spread of transformer oil requires time to adjust its speed to correspond to increases in load. Even though the time constants for the oil and winding of a power transformer are unique to each unit, their values can be determined to maintain consistent loss and cooling settings until steady state is achieved.

4. Conclusion

This study sets out to develop and validate an improved IEC-based thermal model that incorporates time-varying ambient temperature effects during transformer type testing. The objective was achieved by reformulating the IEC exponential equations to dynamically account for ambient variability while retaining compliance with standards. In this way, the research bridges the gap between simplified standards-based models and resource-intensive advanced simulations. The model was applied to stepped-load experimental data from a 5 MVA transformer, and its predictions were compared with those of the standard International Electro technical Commission formulation. The experimental observations of the transformer temperature and load profiles were collected on the factory premises of Dusad Transformers & Switchgears Pvt. Ltd. in Pali, India. The load was changed in such a way that it affected the temperature in the power transformer. The results obtained from the model and from the experimental observations are shown graphically. The improved thermal model demonstrated consistent error reductions of 30-40%, lowering the mean absolute error from 2.89% to 2.04% for the oil temperature rise and from 2.30% to 1.88% for the winding temperature rise. The Root Mean Square Error and Mean Percentage Error also decreased significantly, confirming that accounting for ambient variability enhances both absolute and relative prediction accuracy. Importantly, the improved model reproduced the dynamic heating and cooling transients more faithfully than the standard International Electro technical Commission formulation, aligning closely with experimental time constants. The results suggest that, during the temperature-rise test, the effect of ambient temperature also needs to be considered to obtain precise test results that help consumers operate power transformers within the specified thermal limits.

The findings have direct practical implications. For transformer manufacturers, the improved thermal model offers a more reliable framework for type test validation under realistic factory conditions. For utilities, the model supports more accurate hot-spot prediction, insulation life assessment, and overload risk evaluation. From a standards perspective, the improvements demonstrated suggest that dynamic ambient effects should be considered in future revisions of the International Electro Technical Commission testing guidelines. In conclusion, this work contributes both scientifically and practically: it enhances the rigor of International Electro technical Commission-based thermal models and provides the transformer industry with a method that is accurate, computationally efficient, and directly applicable to real-world testing environments.

Further, improvement can be achieved by developing dynamic thermal models that account for changes in the internal properties of transformer oil. It is also necessary to upgrade existing temperature monitoring systems and introduce new instrumentation schemes to measure design parameters and improve thermal modeling. In conclusion, the major recommendation of this work is to improve thermal models of power transformers in accordance with current standards by including key influencing parameters as inputs.

Author contributions statement

Vinit Mehta: Conceptualization, methodology, investigation, data curation, formal analysis, writing original script, visualization and project administration. Jayashri Vajpai: Supervision, validation, review and editing, interpretation of results and overall guidance throughout the research.

Conflict of interests

The authors declare that they have no known financial interests, personal relationships or competing interests that could have appeared to influence the work reported in this paper.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that no generative AI or AI- assisted technologies were used in the writing, editing, analysis or preparation of this manuscript.

Nomenclature

IEC	International Electro technical Commission
IEEE	Institute of Electrical and Electronics Engineers
LF	Load Factor
MAE	Mean Absolute Error
MPE	Mean Percentage Error
RMSE	Root Mean Square Error
T_a	Ambient Temperature (°C)
$T_o(t)_{rise}$	Rise in Oil Temperature (°C)
$T_o(t)_{fall}$	Fall in Oil Temperature (°C)
$T_w(t)_{fall}$	Fall in Winding Temperature (°C)
$T_w(t)_{rise}$	Rise in Winding Temperature (°C)
t_a, t_b and t_c	Thermal Constants
x	Oil Exponent
y	Winding Exponent
α	Ratio of Load Losses to the No Load Losses
τ_o	Oil Time Constant (min)
τ_w	Winding Time Constant (min)
ΔT_{oi}	Initial Oil Temperature Rise (°C)
ΔT_{wi}	Initial Winding Temperature Rise (°C)
ΔT_{or}	Rated Oil Temperature Rise (°C)
ΔT_{wr}	Rated Winding Temperature Rise (°C)

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