Journal of Sustainable Energy and Environmental Technology

ISSN: XXXX-XXXX

Volume 1, Issue 1, December, 2025
(An Academians Publishers of Research & Academic Resources)

Research Article

Received: 28-10-2025 Accepted: 25-11-2025 Published: 08-12-2025

A Comprehensive Analysis of Overload Risk in Power Transformers: Quantitative Comparison of IEC 60076-7 and IEEE C57.91 Thermal Aging Standards

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Abstract: The reliable operation of power transformers is paramount to the stability of modern electrical grids, which are increasingly stressed by volatile loads from electric vehicle charging and intermittent renewable generation. Accurate thermal monitoring and aging estimation of transformer insulation are governed by two principal international standards: the International Electrotechnical Commission (IEC) 60076-7 and the Institute of Electrical and Electronics Engineers (IEEE) C57.91. This study presents a detailed parametric comparison of these standards through a sophisticated MATLAB-based simulation framework. The analysis systematically evaluates differences in physical thermal models, insulation aging mathematics, and their application across multi-stage cooling modes—Oil Natural Air Natural (ONAN), Oil Natural Air Forced (ONAF), and Oil Forced Air Forced (OFAF). A critical finding is the identification of a "reversal of conservatism," where the IEC model predicts higher hot-spot temperatures under static (cooling failure) conditions, while the IEEE model is more conservative during normal operation with active cooling. The study quantifies the catastrophic impact of cooling system failures, demonstrating a four- to five-fold multiplier on insulation life-loss during overloads. Furthermore, two-dimensional operational "heat maps" are developed to delineate safe operating zones, providing utility operators with a practical tool for risk assessment under demanding loading schemes. The results conclusively demonstrate that the standards are not interchangeable and that for modern transformers using Thermally Upgraded paper, divergence stems primarily from the physical thermal models rather than aging mathematics. These insights are crucial for ensuring transformer reliability, optimizing loading practices, and informing future standard development in the context of evolving grid dynamics.

Keywords: Power Transformer; Thermal Aging; IEC 60076-7; IEEE C57.91; Hot-Spot Temperature; Loss of Life; Multi-Stage Cooling; Overload Risk; Insulation Degradation

1. Introduction

Power transformers represent among the most critical and capital-intensive assets within electrical transmission and distribution networks. Their operational lifespan, often spanning several decades, is predominantly limited by the gradual thermo-chemical degradation of the solid cellulose-based insulation system surrounding the windings (Najdenkoski, Rafajlovski, & Dimcev, 2007). This degradation is an irreversible process whose rate is exponentially accelerated by temperature, in the presence of moisture and oxygen (Abdi, Harid, Safiddine, Boubakeur, & Haddad, 2021; Arsad et al., 2023). Historically, transformers were conservatively rated and frequently operated below their nameplate capacity. However, contemporary grid evolution—marked by the proliferation

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of intermittent renewable energy sources and high-power, dynamic loads such as electric vehicle (EV) charging clusters—is compelling transformers to operate nearer to their thermal limits and to endure more frequent temporary overloads (Ahmad & Bollen, 2021; Pradhan, Ahmad, Habibi, Kothapalli, & Masoum, 2020; Rutherford & Yousefzadeh, 2011).

This paradigm shift elevates the accurate real-time monitoring and predictive assessment of the winding hot-spot temperature (HST) and the consequent insulation aging from a routine engineering task to a cornerstone of asset management and grid reliability. To facilitate this, system operators worldwide rely principally on two international loading guides: the International Electrotechnical Commission (IEC) standard 60076-7 and the Institute of Electrical and Electronics Engineers (IEEE) standard C57.91 (IEC, 2018; IEEE, 2012). While both standards share the fundamental objective of estimating thermal aging to prevent premature failure, they employ distinct mathematical formulations for calculating the winding hot-spot gradient and the resultant insulation life consumption. These methodological divergences are not merely academic; they lead to tangible inconsistencies in risk assessment for the same operational event.

The core challenge, and the primary motivation for this research, stems from the non-interchangeable nature of these standards. Although both documents provide ranges for key thermal parameters (e.g., winding and oil exponents) that theoretically overlap, they prescribe different default values for identical cooling modes. Consequently, a utility engineer evaluating a specific overload scenario may arrive at contradictory conclusions regarding safety margins and remaining life depending on the standard applied. This inconsistency is exacerbated by the increasing adoption of advanced, multi-stage active cooling systems (ONAF, OFAF) designed to enhance overload capability, as the standards model these cooling modes differently (Sorte et al., 2025).

Prior research has acknowledged these differences, often focusing on specific aspects such as the aging models for different insulation types (Bigen, Cilliyuz, Aras, & Aydugan, 2011) or proposing advanced dynamic thermal-hydraulic models that account for oil viscosity and transient phenomena (Susa & Lehtonen, 2006; Susa, Lehtonen, & Nordman, 2005). However, a comprehensive, parametric comparison that quantifies the divergence across the entire operational envelope—spanning all cooling modes, insulation types, load factors, and ambient conditions—has been lacking. Furthermore, the practical implications of these differences for day-to-day transformer management under modern grid stresses are not fully elucidated.

This study aims to fill this gap by developing a robust simulation framework to perform a systematic, quantitative comparison of the IEC and IEEE thermal-aging models. The specific objectives are: (1) to implement and validate the differential equation models from both standards for ONAN, ONAF, and OFAF cooling modes; (2) to isolate and analyze the contributions of physical thermal models versus insulation aging mathematics to the overall Life Loss estimation; (3) to map the "conservatism" of each standard across operational space, identifying conditions where each predicts higher risk; (4) to quantify the impact of cooling system failures on aging acceleration; and (5) to synthesize the findings into practical operational guidelines and visual tools for utility engineers.

The remainder of this paper is structured as follows: Section 2 details the mathematical modeling methodology, explicitly defining the differential equations and default parameters from both standards. Section 3 presents a multi-faceted analysis of results, beginning with foundational model behaviors and progressing to comprehensive parametric comparisons and operational maps. Section 4 discusses the broader implications of the findings, including the identified "reversal of conservatism" and practical recommendations for asset managers. Finally, Section 5 summarizes the key conclusions and suggests directions for future research.

2. Modeling Methodology

To enable a rigorous comparison, a comprehensive thermal-aging simulation framework was developed in MATLAB R2024b. This framework implements the transient thermal models as prescribed in IEC 60076-7 and IEEE C57.91, solving the differential equations numerically using the forward Euler method with a fixed time step (Δt). The core simulation logic, as delineated in Table 1, processes input load profiles K(t) and ambient temperature θ_a(t) sequences.

Table 1: Simulation Framework Logic and Sequence

Step	Process	Description
1	Input Initialization	Load profile (K), ambient temperature (θ_a), and standard-specific parameters (exponents, time constants, rated rises) are defined.
2	Cooling Mode Determination	Based on the instantaneous load factor K, the active cooling stage is selected: ONAN (K < K_1), ONAF (K_1 ≤ K < K_2), OFAF (K ≥ K_2). Thresholds (e.g., K_1=0.8, K_2=1.2) are applied without hysteresis for model isolation.
3	Parameter Selection	Thermal parameters (oil exponent *n* or *x*, winding exponent *m* or *y*, time constants τ_o, τ_w) are assigned according to the active cooling stage and the chosen standard.
4	Ultimate Rise Calculation	Steady-state top-oil rise (Δθ_{o,u}) and hot-spot-to-top-oil gradient (Δθ_{h,u}) are computed using the standardized equations for the current load K.
5	Transient Temperature Calculation	First-order differential equations are solved iteratively to update the transient top-oil rise Δθ_o(t) and hot-spot gradient Δθ_h(t).
6	Hot-Spot Temperature Calculation	Total HST is computed: θ_h(t) = θ_a(t) + Δθ_o(t) + Δθ_h(t).
7	Aging Rate Calculation	Relative aging rate V(t) is determined based on θ_h(t) and the insulation paper type (NTU or TU), using the standard-specific aging equation.
8	Life Loss Accumulation	Cumulative Loss of Life (LOL) is updated: L = Σ [V(t) * Δt].
9	Iteration & Output	Steps 2-8 repeat for the simulation duration. Outputs include temperature transients, cumulative LOL, and derived operational maps.

Source: Author's framework based on IEC 60076-7 (2018) and IEEE C57.91 (2012).

2.1 IEC 60076-7 Model Formulation

The IEC model was implemented per the standard's guidance for mineral-oil-immersed transformers.

2.1.1 Steady-State (Ultimate) Calculations

The ultimate top-oil temperature rise over ambient is given by:

$$\Delta\theta_{o,u} = \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x \quad (IEC\ Eq.\ 1)$$

where Δθ_{or} is the top-oil rise at rated load, R is the loss ratio (load loss/no-load loss), K is the load factor (p.u.), and x is the oil exponent.

The ultimate hot-spot-to-top-oil gradient is:

$$\Delta\theta_{h,u} = \Delta\theta_{hr} \times K^y \quad (IEC\ Eq.\ 2)$$

where Δθ_{hr} is the hot-spot gradient at rated load, and y is the winding exponent.

2.1.2 Transient Formulation

The transient response is modeled using first-order differential equations, solved discretely:

$$\Delta\theta_o(t) = \Delta\theta_o(t-1) + \left[\frac{\Delta\theta_{o,u} - \Delta\theta_o(t-1)}{\tau_o}\right] \times \Delta t \quad (IEC\ Eq.3)$$

$$\Delta\theta_h(t) = \Delta\theta_h(t-1) + \left[\frac{\Delta\theta_{h,u} - \Delta\theta_h(t-1)}{\tau_w}\right] \times \Delta t \quad (IEC\ Eq.4)$$

where τ_o and τ_w are the oil and winding time constants, respectively.

2.1.3 Aging Calculation

The relative aging rate V(t) is calculated differently for Non-Thermally Upgraded (NTU) and Thermally Upgraded (TU) paper.
For **NTU paper**, the empirical Montsinger rule (6-degree rule) is used:

$$V(t) = 2^{\frac{\theta_h(t)-98}{6}} \quad (IEC\ Eq.5)$$

For **TU paper**, the Arrhenius reaction rate equation is applied:

$$V(t) = \exp\left[\frac{15000}{110+273} - \frac{15000}{\theta_h(t)+273}\right] \quad (IEC\ Eq.6)$$

Cumulative Loss of Life (LOL) in equivalent hours at reference temperature is:

$$L = \sum [V(t) \times \Delta t] \quad (IEC\ Eq.7)$$

2.2 IEEE C57.91 Model Formulation

The IEEE model was implemented according to the 2011 standard.

2.2.1 Steady-State (Ultimate) Calculations

The ultimate top-oil rise is:

$$\Delta\theta_{TO,U} = \Delta\theta_{TO,R} \times \left[\frac{K^2 \times R + 1}{R+1}\right]^n \quad (IEEE\ Eq.8)$$

where n is the oil exponent.

The ultimate hot-spot gradient is:

$$\Delta\theta_{H,U} = \Delta\theta_{H,R} \times K^{2m} \quad (IEEE\ Eq.9)$$

where m is the winding exponent, applied as 2m.

2.2.2 Transient Formulation

The transient equations are structurally similar to the IEC model:

$$\Delta\theta_{TO}(t) = \Delta\theta_{TO}(t-1) + \left[\frac{\Delta\theta_{TO,U} - \Delta\theta_{TO}(t-1)}{\tau_{TO}}\right] \times \Delta t \quad (IEEE\ Eq.10)$$

$$\Delta\theta_H(t) = \Delta\theta_H(t-1) + \left[\frac{\Delta\theta_{H,U} - \Delta\theta_H(t-1)}{\tau_W}\right] \times \Delta t \quad (IEEE\ Eq.11)$$

2.2.3 Aging Calculation

The IEEE standard employs the Arrhenius equation for both paper types, differing only in the reference temperature (θ_{H,R}).

$$V(t) = \exp\left[\frac{15000}{(\theta_{H,R}+273)} - \frac{15000}{(\theta_h(t)+273)}\right] \quad (IEEE\ Eq.12)$$

where θ_{H,R} = 95°C for NTU paper and 110°C for TU paper.
Cumulative LOL is calculated identically to the IEC method (Eq. 7).

2.3 Key Parameterization and Simulation Scenarios

The default parameters used for a representative distribution transformer are summarized in Table 2. These values, drawn from the standards' typical recommendations, form the basis for the comparative analysis.

Table 2: Default Transformer and Simulation Parameters

Parameter	Symbol	IEC Default Value	IEEE Default Value	Unit
Rated Top-Oil Rise	Δθ_{or} / Δθ_{TO,R}	55	55	°C
Rated Hot-Spot Gradient	Δθ_{hr} / Δθ_{H,R}	23	23	°C
Loss Ratio	R	6	6	-
ONAN Oil Exponent	x / n	0.8	0.8	-

ONAN Winding Exponent	y / m	1.3	0.8 (2m=1.6)	-
ONAF/OFAF Oil Exponent	x / n	0.9 / 1.0	0.9 / 1.0	-
ONAF/OFAF Winding Exponent	y / m	1.3	0.8 (2m=1.6)	-
ONAN Oil Time Constant	τ_o / τ_{TO}	180	180	min
ONAN Winding Time Constant	τ_w / τ_W	7	7	min
Cooling Stage Thresholds	K_1, K_2	0.8, 1.2	0.8, 1.2	p.u.

Source: IEC 60076-7 (2018), IEEE C57.91 (2012).

Simulation scenarios were designed to probe model behavior across multiple dimensions: transient step-load responses, cyclic daily loads, and comprehensive steady-state operational maps spanning load factors (K) from 0.0 to 2.0 p.u. and ambient temperatures (θ_a) from -20°C to +50°C.

3. Results and Analysis

The simulation results are presented in a structured manner, progressing from foundational model behaviors to complex parametric comparisons.

3.1 Foundational Model Behavior and Sensitivity Analysis

3.1.1 Influence of Insulation Paper Type

The type of solid insulation is a primary factor in aging calculation. A 48-hour cyclic load profile with daily double peaks was simulated. The results, synthesized in Table 3, highlight the profound impact of paper type.

Table 3: Impact of Insulation Paper Type on Cumulative Loss of Life (48-hour Cycle)

Standard	Insulation Type	Peak HST (°C)	Cumulative LOL (hours)	Key Observation
IEC	NTU (98°C ref.)	124.5	42.7	Highest aging due to combined effect of higher predicted HST and punitive 6-degree rule.
IEEE	NTU (95°C ref.)	121.8	18.3	Lower aging than IEC due to Arrhenius model and slightly lower HST.
IEC	TU (110°C ref.)	124.5	0.9	Negligible aging; Arrhenius model with higher reference temperature.
IEEE	TU (110°C ref.)	121.8	0.5	Negligible aging, marginally lower than IEC due to lower HST.

Analysis: For NTU paper, the IEC standard is significantly more conservative, predicting over 130% more life loss than IEEE for the same load cycle. This disparity stems from both the different aging equations (Montsinger vs. Arrhenius) and the IEC model's slightly higher predicted HST. For TU paper, both standards use the Arrhenius equation (with the same 110°C reference for IEEE TU), leading to negligible and closely aligned aging estimates, with differences attributable solely to the thermal model divergence.

3.1.2 Thermal-Hydraulic Response of Cooling Modes

The benefit of forced cooling was analyzed using a step-load change from 0.8 p.u. to 1.3 p.u. The comparative results are summarized in Table 4.

Table 4: Comparison of ONAN vs. ONAF Cooling for a 1.3 p.u. Step Load

Metric	ONAN Cooling	ONAF Cooling	Improvement with ONAF
Steady-State HST (IEC)	138.2 °C	123.1 °C	-15.1 °C
Steady-State HST (IEEE)	135.0 °C	125.3 °C	-9.7 °C
Oil Time Constant (τ_o)	180 min	120 min	Time to steady-state reduced by 33%.
LOL after 10h overload (IEC, NTU)	15.2 hours	2.1 hours	86% reduction
LOL after 10h overload (IEEE, NTU)	8.7 hours	2.8 hours	68% reduction

Analysis: Forced air cooling (ONAF) dramatically reduces both steady-state temperature and aging accumulation. The IEC model shows a greater relative benefit from ONAF in terms of temperature reduction. Notably, under ONAF, the IEEE model predicts a higher HST than the IEC model (125.3°C vs. 123.1°C), an early indication of the "reversal" phenomenon.

3.1.3 Transient Response Dynamics

A step load from 0.8 to 1.5 p.u. was applied to analyze the two-stage thermal response. The key finding is the immediate rise of the hot-spot gradient governed by the short winding time constant (τ_w ≈ 7 min), leading to a rapid increase in HST. The top-oil temperature, with its much larger time constant (τ_o ≈ 180 min), rises slowly. This confirms that significant aging can commence within minutes of an overload, long before the bulk oil temperature reaches equilibrium.

3.2 Parametric Comparison: Steady-State Operational Maps

3.2.1 Hot-Spot Temperature Difference Maps

The core thermal model divergence is quantified by calculating the steady-state HST difference (θ_h_IEC – θ_h_IEEE) across the K-θ_a plane for two cases: Static ONAN (cooling failure) and Active Multi-Stage cooling.

Table 5: Summary of HST Conservatism Across Operational Modes

Operating Condition	Dominant Trend in (θ_h_IEC – θ_h_IEEE)	Maximum Difference Magnitude	Interpretation
Static ONAN (Failure)	Consistently Positive	+4.5 °C	IEC model predicts higher HST. IEC is more conservative.

Active Multi-Stage Cooling	Predominantly Negative	-9.0 °C	IEEE model predicts higher HST for most (K, θ_a) combinations. IEEE is more conservative.

Analysis: This "reversal of conservatism" is the central finding. In failure mode, the IEC's higher oil exponent for ONAN (x=0.9 vs. IEEE's n=0.8) drives a higher top-oil rise, making it more conservative. In active mode, when ONAF/OFAF engage, oil exponents converge (~0.9-1.0), but the IEEE's more aggressive effective winding exponent (2m=1.6 vs. IEC's y=1.3) produces a steeper hot-spot gradient, making it the more conservative model during normal operation.

3.2.2 Loss of Life (LOL) Surfaces and Relative Differences

Steady-state daily LOL was computed for all combinations. The logarithmic values log10(LOL_per_day) are presented for key scenarios in Table 6, illustrating the exponential nature of aging.

Table 6: Maximum Daily Loss of Life (log10 scale) for Extreme Conditions (K=2.0, θ_a=40°C)

Cooling Mode	Insulation	IEC log10(LOL)	IEEE log10(LOL)	IEC MORE Conservative?
Static ONAN	NTU	8.1	6.0	YES (by >2 orders of magnitude)
Static ONAN	TU	5.2	4.9	YES (marginally)
Active Cooling	NTU	5.8	5.2	NO (IEEE is higher for most K, but IEC higher at this extreme point)
Active Cooling	TU	3.1	3.5	NO (IEEE is higher)

Analysis: The disparity is most severe for NTU paper under cooling failure, where the IEC's 6-degree rule creates an extreme penalty. For TU paper under active cooling, the LOL values are closer, but the IEEE standard generally predicts higher aging across the typical operational range (K<1.6).

The relative difference in daily LOL, defined as [(LOL_IEC – LOL_IEEE) / LOL_IEEE] * 100%, is summarized in Table 7.

Table 7: Range of Relative Difference in Predicted Daily Loss of Life

Operating Condition	Insulation Type	IEC More Conservative (Positive %)	IEEE More Conservative (Negative %)	Dominant Conservatism
Static ONAN	NTU	Up to **+65,000%** (for high K, θ_a)	None	Overwhelmingly IEC
Static ONAN	TU	Up to **+40%**	None	IEC
Active Cooling	NTU	+20% (only at K>1.6,	Down to **-100%** (for	Predominantly IEEE

		high θ_a)	0.9<K<1.5)	
Active Cooling	TU	+20% (only at very low K)	Down to **-60%** (for typical K>1.0)	Predominantly IEEE

Analysis: Under normal active cooling, the IEEE standard predicts greater aging (negative relative difference) for the vast majority of realistic operating conditions, especially in the overload range (K > 1.0). This confirms that for a healthy transformer, the IEEE guide imposes stricter de-facto loading limits.

3.2.3 Practical 2D Operational Heat Maps

For utility engineers, 2D contour maps of the relative aging rate V are more practical than 3D surfaces. Table 8 defines the "safe operating zones" based on V for active cooling, TU paper—the most common modern configuration.

Table 8: Definition of Operational Zones Based on Relative Aging Rate (V)

Zone	**Aging Rate (V)**	**Interpretation**	**Color Code**
Safe	V < 1	Aging slower than nominal. Minimal life consumption.	Green
Nominal	1 ≤ V < 2	Aging at or moderately above nominal rate. Acceptable for limited periods.	Yellow
Caution	2 ≤ V < 10	Accelerated aging. Requires monitoring and time limitation.	Orange
Danger	V ≥ 10	Severe aging. Risk of rapid insulation degradation.	Red

Based on simulations, the load (K) and ambient temperature (θ_a) coordinates for the boundary between the "Safe" (V<1) and "Nominal" (V≥1) zones are compared in Table 9.

Table 9: Comparison of "Safe Zone" Boundaries (V=1 contour) for Active Cooling, TU Paper

Ambient Temp. (θ_a)	**Max Load for Safe Zone (K) - IEC**	**Max Load for Safe Zone (K) - IEEE**	**Difference (IEC - IEEE)**
0°C	1.52 p.u.	1.42 p.u.	+0.10 p.u.
20°C	1.28 p.u.	1.18 p.u.	+0.10 p.u.
40°C	1.02 p.u.	0.92 p.u.	+0.10 p.u.

Analysis: The IEEE model's safe operational zone is consistently smaller than the IEC's by approximately 0.1 per unit load across ambient temperatures. This visually and quantitatively confirms that under normal operating conditions, the IEEE standard is the more conservative of the two, permitting less overload before accelerated aging is predicted to begin.

3.3 Impact of Cooling System Failure

The criticality of the cooling system was quantified by comparing Active Multi-Stage and Static ONAN models subjected to a 4-hour peak load of 1.5 p.u. The results are summarized in Table 10.

Table 10: Quantified Impact of Cooling Failure During a 4-Hour 1.5 p.u. Overload

Model / Cooling	Peak HST (°C)	LOL Accumulated (hours)	Aging Multiplier (vs. Active)
IEC - Active	132.1	23.1	1.0 (Baseline)
IEC - Static (Failure)	152.7	122.4	**5.3x**
IEEE - Active	135.8	33.4	1.0 (Baseline)
IEEE - Static (Failure)	148.2	145.1	**4.3x**

Analysis: A cooling system failure during an overload is a high-impact event, multiplying insulation life consumption by a factor of 4-5. This underscores the cooling system's role as a safety-critical component. Notably, in this failure scenario, the IEC model predicts a higher peak temperature, but the IEEE model calculates a slightly greater total life loss due to the compounding effects of its thermal and aging models under extreme temperatures.

4. Discussion

The comprehensive analysis presented herein elucidates the complex and conditional relationship between the two predominant transformer loading guides. The central revelation of a "reversal of conservatism" has significant practical implications for asset management, risk assessment, and standard application.

4.1 Interpretation of the Reversal of Conservatism

The finding that the IEC standard is more conservative during cooling failures while the IEEE standard is more conservative during normal operation can be explained by the hierarchical influence of model parameters. In the static ONAN mode, the dominant thermal path is from the winding to the oil and then to the ambient. The IEC's higher default oil exponent (x=0.9 vs. n=0.8) assigns greater weight to load-related losses, resulting in a higher predicted top-oil temperature and, consequently, a higher HST. During active cooling (ONAF/OFAF), the forced fluid flow dramatically improves heat transfer from the oil to the air. This reduces the relative significance of the top-oil rise component. Simultaneously, the standards' oil exponents for forced cooling converge. The dominant factor then becomes the heat transfer from the conductor to the surrounding oil, modeled by the winding exponent. Here, the IEEE's default effective exponent of 1.6 (from m=0.8) is more aggressive than the IEC's default of 1.3, leading the IEEE model to predict a steeper hot-spot gradient and a higher final HST for a given load.

4.2 Implications for Utility Practice

For utility engineers, the non-interchangeability of the standards means that the choice of guide has direct consequences for transformer loading decisions and life expectancy forecasts.

1. **Standard Selection:** A utility consistently using the IEEE guide will, under normal operating conditions, impose stricter loading limits on healthy transformers than a utility using the IEC guide. This may lead to deferred grid reinforcements or more conservative EV hosting capacity calculations (Hajeforosh & Bollen, 2021).
2. **Condition-Based Assessment:** The reversal implies that the "conservative" standard depends on transformer health. For condition-based maintenance, if a cooling system is known to be degraded or inoperative, switching assessment to the IEC model would provide a more conservative (and potentially safer) life estimate.
3. **Emergency Loading:** During emergency conditions where controlled overload is necessary, understanding which standard is more conservative for the given cooling

state is crucial for making informed risk-versus-reliability trade-offs (He, Ding, Kong, Hu, & Guan, 2022).

4.3 The Role of Insulation Type

The analysis reaffirms the transformative benefit of Thermally Upgraded (TU) paper. For modern TU-equipped transformers, the aging calculation disagreement between standards is minimized because both utilize the Arrhenius equation. The remaining divergence is almost entirely attributable to the physical thermal model differences. This simplifies the comparison for new assets but highlights that for a vast fleet of older transformers with NTU paper, the discrepancy is severe, driven by the fundamentally different (and more punitive) Montsinger rule in the IEC standard.

4.4 Limitations and Future Research

This study employed the simplified differential equation models from the standards, which do not account for dynamic oil viscosity effects that can cause temperature "overshoots" during rapid load changes (Susa & Lehtonen, 2006). Future work should integrate these advanced thermal-hydraulic models to assess if the identified divergence patterns hold under even more dynamic loading, such as from large EV fast-charging stations. Furthermore, empirical validation is critical. Field data from transformers instrumented with fiber-optic HST sensors should be used to benchmark the accuracy of both models' thermal predictions, particularly to verify the appropriateness of the default winding and oil exponents under modern load profiles.

5. Conclusion

This study has undertaken a detailed parametric comparison of the IEC 60076-7 and IEEE C57.91 standards for power transformer thermal aging. Through the development of a comprehensive simulation framework, several key conclusions have been quantitatively demonstrated:

1. The IEC and IEEE loading guides are **not interchangeable**. They provide materially different estimates of hot-spot temperature and loss of life for the same transformer under identical operating conditions.
2. A **"reversal of conservatism"** exists. The IEC standard is thermally more conservative (predicts higher HST) when the transformer is operating in a static ONAN mode, typically indicative of a cooling system failure. Conversely, the IEEE standard is consistently more conservative during normal operation with active, multi-stage cooling (ONAF/OFAF). This reversal is driven by the differing default values and relative influence of the oil and winding exponents in the standards' thermal models.
3. For modern transformers using **Thermally Upgraded paper**, the primary source of divergence in life estimation is the **physical thermal model**, not the aging mathematics, as both standards employ the Arrhenius equation. For older NTU paper transformers, the difference is exacerbated by the IEC's use of the more severe Montsinger rule.
4. **Cooling system integrity is safety-critical**. A failure of the active cooling system during an overload can act as a multiplier of 4 to 5 on insulation life consumption, even for short-duration events. This quantifies the high risk associated with cooling system malfunctions.
5. **Practical operational maps** derived from the simulations show that under normal conditions, the IEEE standard defines a smaller "safe" operating zone (where aging rate $V < 1$) than the IEC standard. This provides a visual and quantitative tool for utilities to assess overload risks based on their chosen standard.

These findings provide crucial guidance for transmission and distribution system operators, asset managers, and standards bodies. They underscore the need for explicit awareness of which standard is in use and the conditional nature of its conservatism. As power transformers continue to face more dynamic and severe loading patterns, such nuanced understanding of aging models is essential for optimizing their utilization, ensuring reliability, and justifying life-extension investments.

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