

Managing insulation aging through direct hot-spot temperature measurement

Benefits of gallium arsenide-based fiber-optic sensing for transformer winding hot-spot monitoring



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1. Introduction

Power transformers are increasingly operated close to their project design limits. A key contributing factor is the growing integration of renewable energy sources into power grids, which results in higher load variability and places additional pressure on utilities to meet increasingly stringent Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) targets. Under these conditions, winding hot-spot temperature becomes one of the most critical parameters influencing insulation aging, residual life assessment, and overall operational risk management.

Historically, temperature control was based on strict compliance with nameplate ratings, referring exclusively to the maximum permissible current.

It was later recognized that this approach was inadequate and could introduce risks under high ambient temperature conditions while, conversely, unnecessarily restricting transformer operation under overload conditions at low ambient temperatures.

To address these limitations, alarm systems were introduced that correlated maximum oil temperature with load, thereby simulating the trend of the winding maximum temperature.
Subsequently, overload criteria were defined by specifying precise load–duration limits applicable to all units, regardless of environmental conditions.

Further studies on the thermal aging of oil-impregnated paper insulation led to a more scientific approach, highlighting the strong dependence of insulation aging on temperature. Regulatory standards attempted to address this issue by introducing the concept of the winding hot-spot temperature, imposing maximum allowable limits through a calculation linked to the average winding temperature, historically the only parameter measurable during temperaturerise tests.

This approach is also subject to limitations, as each transformer shows unique thermal behavior and it is therefore not possible to define universally valid parameters for all designs.

Current standards have evolved further by introducing transformer thermal models that depend on the specific type of transformer.

Direct measurement of hot spots using Gallium Arsenide-based fiber-optic probes, as formalized in the IEC 60076-2 standard [1], eliminates model uncertainty, improves the effectiveness of factory acceptance tests (FATs), and provides the real-time data necessary for condition-based maintenance of transformers. This article examines the evolution of real-time operation and maintenance, explains why hot-spot measurement is important during FATs and in-service, compares indirect determination approaches, and quantifies the technical and economic benefits.

2. Evolution of plant management with realtime command and control systems

Ongoing challenges within the global supply chain are compelling transformer manufacturers to further optimize material selection, loss performance, and equipment footprint. At the same time, end-users increasingly require highly reliable, high-performance transformer solutions capable of accommodating variable load profiles, harmonic distortion, and complex environmental operating conditions.

This evolution represents not only a shift in transformer design philosophy, but also a progressive reduction of the traditional design safety margins historically embedded in transformer specifications. Consequently, the adoption of advanced monitoring, diagnostics, and asset management solutions becomes essential to ensure reliable operation, effective risk control, and sustained asset performance throughout the transformer life cycle.

As a result, power transformers are increasingly operated near their thermal limits, particularly during periods characterized by renewable energy intermittency or peak demand conditions. Under these operating regimes, winding hot-spot temperature assumes a decisive role: it can no longer be regarded solely as a design-stage parameter, but must instead be treated as a critical operational variable requiring accurate and continuous monitoring.

Overload management, cooling system performance, and loadshedding strategies are directly dependent on the accuracy with which the transformer's thermal state is assessed. A conservative evaluation of the available thermal margin enables more effective and flexible grid operation, whereas an overly optimistic thermal assessment accelerates insulation aging and significantly increases the likelihood of unplanned dielectric failures.

Digital monitoring systems can respond on time scales ranging from seconds to minutes; however, their effectiveness is fundamentally dependent on the accuracy and representativeness of the input measurements. Consequently, advances in operational control naturally drive the adoption of measurement techniques that reflect the transformer's true limiting condition, namely the winding hot-spot temperature within the insulation system. Transformer load guides [2], [3] explicitly correlate permissible loading with hot-spot temperature and associ-

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ated insulation lifeloss concepts, while temperaturerise standards acknowledge that direct fiber-optic measurements can significantly enhance reliability when thermal emulation models are subject to uncertainty. Direct hot-spot detection therefore constitutes an enabling technology for realtime transformer operation, allowing traditionally static nominal ratings to be converted into dynamically managed thermal capacity.

3. The evolution of maintenance through realtime information

Maintenance strategies have undergone a parallel evolution, transitioning from predominantly time-based approaches toward condition and riskbased maintenance frameworks. Historically, utilities have relied on periodic oil sampling programs, primarily based on dissolved gas analysis (DGA), supplemented by scheduled visual inspections, conservative replacement or refurbishment strategies, and periodic electrical testing. Electrical test results were typically evaluated through comparative analysis between factory acceptance tests (FAT), site acceptance tests (SAT), and subsequent in-service inspections. While these practices remain technically sound, they are increasingly inadequate for transformer fleets characterized by aging assets, constrained human resources, and stringent reliability requirements. The growing availability of continuous online monitoring—including online DGA, oil moisture measurement, bushing diagnostics, onload tapchanger (OLTC) monitoring, partial discharge detection, vibration analysis, and thermal measurements—enables a more comprehensive understanding of asset condition. Such data streams support trend analysis, early anomaly detection, and riskinformed decisionmaking, allowing maintenance activities to be more precisely targeted and better aligned with the actual operating condition of the transformer.

The critical factor is not the mere accumulation of large volumes of data, but the capability to convert raw measurements into actionable indicators, such as asset health indices, failure risk metrics, and estimates of remaining useful life. In this context, winding hot-spot temperature is a pivotal variable, as it directly links operational decisions to the rate of insulation aging. A transformer may be subjected to thousands of thermal cycles and transient overload events over its service life; the resulting cumulative loss of life exhibits a strongly nonlinear dependence on temperature. Consequently, maintenance planning approaches that fail to adequately account for uncertainty in hot-spot temperature assessment may lead to misaligned prioritization of assets—prompting unnecessary interventions on units in satisfactory condition while failing to identify accelerated aging in thermally stressed transformers.

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4. Transformer monitoring: Maintenance 4.0

Transformer monitoring is a cornerstone of what many utilities refer to as "Maintenance 4.0": a digital, connected approach in which equipment data is continuously collected, contextualized, and transformed into operational and maintenance decisions. In modern architecture, sensors inside and outside the transformer provide time-synchronized measurements, while edge devices perform validation and first-level analysis. The data is then transmitted to centralized platforms for asset dashboards, fleet analytics, and AI-powered diagnostics. The goal is twofold: to detect incipient failures early and to optimize the economic utilization of the asset.

Power transformers are subject to a variety of failure mechanisms, many of which are thermally accelerated, including cellulose depolymerization of the paper insulation, oxidation of the insulating oil, the formation of vapor bubbles under conditions of elevated temperature and moisture, and localized overheating resulting from degradation of the cooling system. For these mechanisms, the winding hot-spot temperature represents the governing or "bottleneck" variable, as it occurs at the location of maximum thermal stress within the solid insulation system.

Second, hot-spot temperature monitoring provides an effective means of quality control for production consistency. Manufacturing or assemblyrelated issues—such as partially blocked cooling ducts, spacer delamination, or deviations in winding assembly—can manifest as abnormal hot-spot temperature distributions, even when bulk oil or average winding temperatures remain within acceptable limits.

Third, direct hot-spot measurements enable improved calibration of winding temperature indicators (WTIs) and digital hot-spot simulation models, which subsequently govern cooling system activation and alarm thresholds. By anchoring these indirect or model-based systems to measured thermal behavior, the overall reliability of temperature-based control and protection functions is enhanced.

The IEC 600762 standard provides specific guidance on the application of optical fiber temperature sensors and recommends a minimum number of sensors

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as a function of the transformer's rated power and cooling arrangement [1] (see Tab. 1).

The IEEE 1538a standard provides additional guidance on the placement and use of fiber-optic temperature sensors for testing applications [6]. Together, these standards establish a robust technical basis for incorporating fiber-optic hot-spot measurements as contractual acceptance criteria during factory acceptance testing (FAT).

If the objective is limited to temperature monitoring during operation, monitoring could be restricted to the winding with the poorest heat dissipation. Typically, regulations or tertiary windings are not considered.

5. The importance of hot-spot monitoring during FAT

Factory acceptance tests (FATs)—as well as type-approval tests for newly developed transformer designs—represent the first opportunity to verify compliance of the thermal design with contractual specifications and applicable standards. Conventional temperature-rise tests, as defined in IEC 600762 [1] and IEEE C57.12.90 [5], determine the average winding temperature rise by resistance measurements and the top-oil temperature rise using installed sensors.

However, the limiting thermal criterion for insulation integrity is the local winding hot-spot temperature, which cannot be directly measured using traditional test methods. This introduces a critical blind spot: a transformer may comply with average temperature-rise limits while still experiencing excessive local temperatures at specific hot-spot locations. Such localized overheating may result from restricted oil flow paths, unanticipated stray losses, or manufacturingrelated deviations, none of which are necessarily reflected in bulk or average temperature measurements.

During FATs, where no fiber-optic sensors are installed, the hot-spot temperature is indirectly estimated by extrapolation of the winding resistance decay curve.

First, the transformer is energized under short circuits and heated at total losses to determine the oil temperature rise above the cooling medium temperature (total loss injection stage). The transformer is then kept for one hour at rated load to stabilize the winding and hot-spot temperatures (rated current injection stage). At the end of this period, the load and short circuit are rapidly disconnected to measure the winding resistance, which is proportional to the average winding temperature (hot resistance measurement stage). The winding resistance is subsequently measured at one-minute intervals to record the decay curve, representing the winding cooling behavior following load removal.

The hot-spot temperature is indirectly derived from the highest winding resistance value, ideally measured at the instant of load shutdown. In practice, a short but unavoidable time delay is required to remove the short circuit and initiate the resistance measurement. This delay must be minimized and is typically limited to less than 2 minutes for transformers below 100 MVA, and less than 3 minutes for transformers below 500 MVA (the IEC and IEEE standards define this time in 4 minutes).

Once the decay curve has been recorded (see example in Fig. 1), the winding resistance at the moment of shutdown is extrapolated using equations provided in both IEC and IEEE standards.

From the extrapolated resistance value, the average winding temperature is calculated, and the winding-to-oil gradient is determined.

The final hot-spot value rise $\Delta\theta h$ is then calculated, in accordance with Eq. 1, by adding the top-oil temperature rise $\Delta\theta o$ to the winding gradient g multiplied by the hot-spot factor H (typically in a 1.1-1.3 range):

Eq. 1: $\Delta\theta h = \Delta\theta o + H \times g$

Several factors may lead to differences in the final hot-spot temperature estimation, including:

- Excessive time delay between load disconnection and resistance measurement, leading to underestimation of the winding temperature;
- Selection of the extrapolation function for the decay curve;
- Arbitrary inclusion or exclusion of the first winding test result
- Use of a default H factor rather than a design-specific value;
- Inaccuracies in the cold resistance measurement: the winding temperature calculation relies on a reference value measured prior to the test (cold

Table 1. Example from IEC 60076-2:2011 Annex E (Table E.1): recommended minimum number of fiber-optic sensors for Three-phase transformers

Rated power (MVA)	Cooling system	Total	Central phase HV	Central phase LV	Each lateral phase HV	Each lateral phase LV
≥ 100	All systems	8	2	2	1	1
20 to < 100	ON…/OF…	6	1	1	1	1
20 to < 100	OD…	8	2	2	1	1

resistance). If this value is incorrect or measured at a temperature different from that assumed, the final temperature estimate may be significantly affected. For example, ambient temperature is sometimes used as a substitute for winding temperature, which may differ by up to 5 °C.

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Fig. 2 shows the application of the IEC extrapolation curve during the FAT of a 60 MVA 132/33 kV grid transformer. The curves are done by using the three different oil decay functions (constant, linear and exponential) as described in IEC 60076-2 Annex C.2. Despite the method is correct, the use of three different extrapolation curves can result in different estimated shutdown values. In this case, the OEM selected the green curve (constant oil decay), corresponding to a winding temperature rise of 48 K, while the curves that use linear or exponential oil decay would have indicated a rise close to 50 K.

Based on the selected curve, the calculated hot-spot temperature rise was 66.5 K.

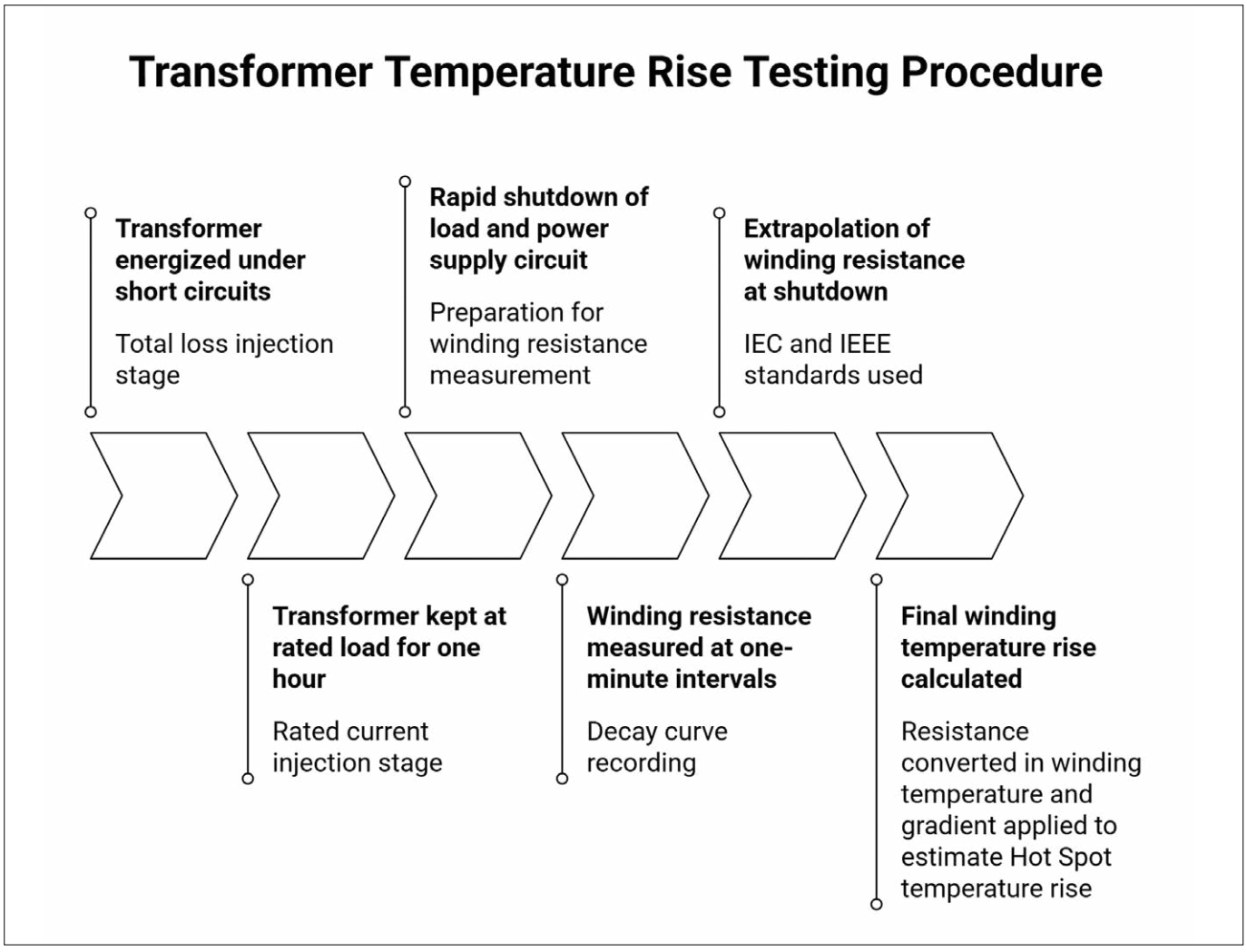
During the same temperature rise test, fiber-optic sensors were also monitored, with the following results:

- In the same phase of the winding resistance test (central phase) a maximum temperature rise was measured at 101.8 K, which corresponds to a Hot-spot rise above ambient of 71 K, which is 4.5K higher than the calculated value
- In another phase, the hot-spot temperature rise was measured at 75 K

These results demonstrate that, due to the inherent uncertainties in the indirect calculation method, the actual hot-spot temperature may differ significantly from the estimated value – by up to 10 °C in some cases.

In addition, it should be noted that winding temperature indicators (WTIs) are not always properly configured. Although WTIS should be calibrated by adjusting resistance values to match the gradient obtained from FAT results or thermal design calculations, in practice they often reach site installations with factory default settings. This further contributes

Figure 1. Transformer temperature rise testing procedure



The hot-spot temperature is indirectly derived from the highest winding resistance value, ideally measured at the instant of load shutdown

to inaccuracies in hot-spot temperature estimation during operation.

Direct measurement of winding hot-spot temperature during FATs using fiber-optic sensors fundamentally overcomes these limitations. First, it enables direct validation of the thermal model applied during the design review. Even small deviations of a few degrees Celsius are significant, as insulation aging acceleration is highly temperature sensitive; an underestimation of approximately 6–7 °C can double the calculated aging rate (see Section 6).

Second, direct hot-spot monitoring provides a powerful quality control tool for assessing manufacturing consistency. Abnormal hot-spot temperature distributions can reveal partially blocked cooling ducts, spacer displacement, or assembly-related deviations, even when average winding or oil temperatures remain within acceptable limits.

Third, measured hot-spot data significantly improve the calibration of WTIs and digital hot-spot thermal models, which govern cooling system control and alarm thresholds during transformer operation. By anchoring these control functions to measured thermal behavior, the reliability of temperaturebased protection and control strategies is substantially enhanced.

Several factors may lead to differences in the final hot-spot temperature estimation

6. Hot-spot temperature monitoring: A key factor in transformer performance and maintenance

During operation, hot-spot temperature monitoring delivers measurable benefits across three closely interrelated domains:

- Insulation life management,
- Operational flexibility,
- Risk reduction.

The influence of temperature on the aging of solid insulation has been well established since the early 1980s [4], and these principles were subsequently formalized in IEC 60076-7 [2]. As cellulose based paper insulation is exposed to elevated temperatures, it undergoes progressive depolymerization, resulting in a gradual loss of mechanical strength and dielectric integrity.

IEC 600767 defines insulation aging by reference to the service life of paper subjected to a constant temperature of 98 °C [2]. This value corresponds to the assumed winding hot-spot temperature at rated load, based on an average winding temperature rise of 65 K above an ambient temperature of 20 °C, together

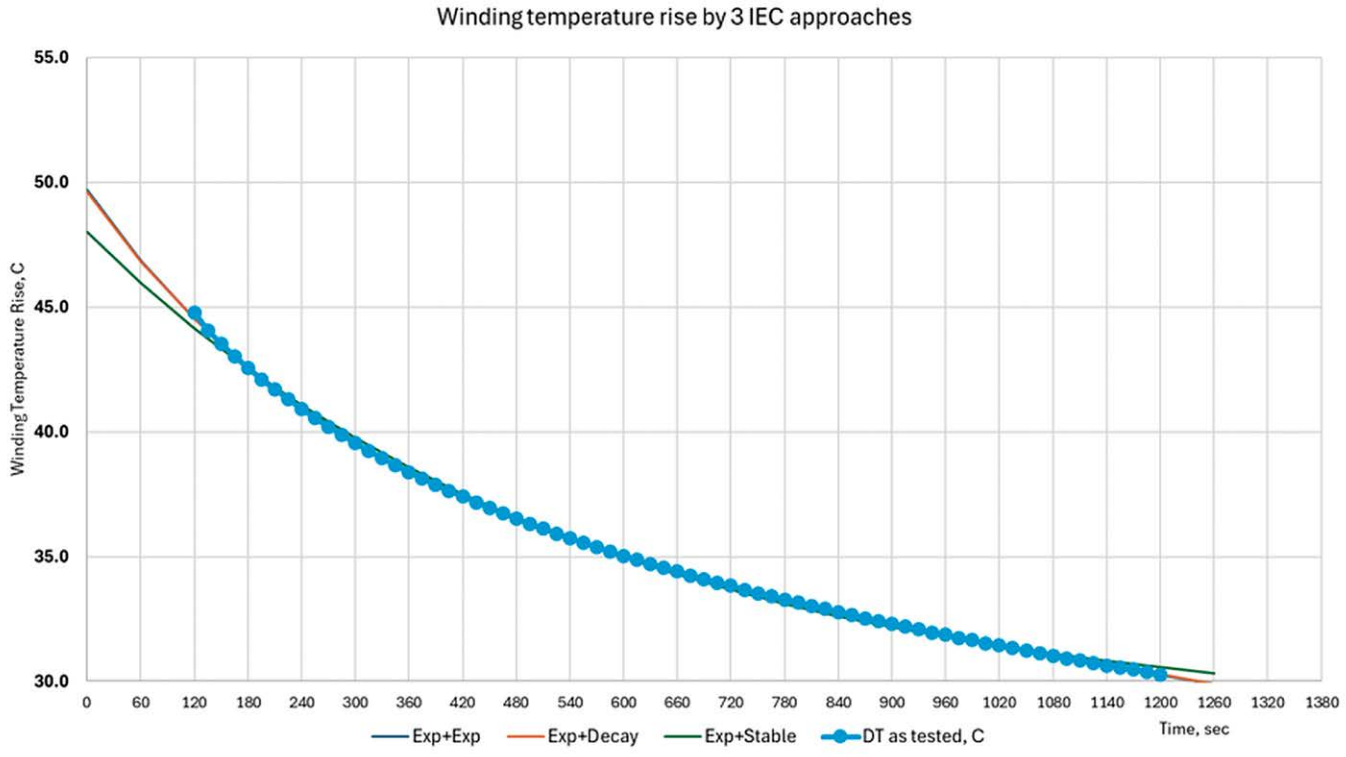


Figure 2. Winding temperature rise

with an additional hot-spot gradient of approximately 13 K* between the average winding temperature and the local hot-spot temperature.

**Note: According to the applicable standards, the temperature rise limit of 13 K is considered valid for transformers with a capacity of up to 50 MVA. However, the application of this generalized assumption may introduce a potential loss of accuracy, as it does not fully account for designspecific and operational differences among transformer types.*

The corresponding reference thermal aging diagram is shown in Fig. 3.

Bibliography

[1] IEC 60076-2, *Temperature Rise for Liquid-Immersed Transformers*, International Electrotechnical Commission, 2011.

[2] IEC 60076-7:2005, *Loading Guide for Oil-Immersed Power Transformers*, International Electrotechnical Commission, 2005.

[3] IEEE C57.91, *IEEE Guide for Loading Mineral-Oil-Immersed Transformers*, IEEE.

[4] A. W. Lowson, J. A. Simmons, J. Gale, *Thermal Aging of Cellulose Paper Insulation*, IEEE Transactions on Electrical Insulation, vol. EI-12, pp. 61–66, 1977.

[5] IEEE C57.12.90, *IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers*, IEEE.

[6] IEEE 1538a-2015, *IEEE Guide for Determination of Maximum Temperature Rise for Liquid-Immersed Transformers*, IEEE, 2015.

[7] CIGRE Technical Brochure 659, *Transformer Thermal Modelling*, CIGRE, 2016.

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Abnormal hot-spot temperature distributions can reveal partially blocked cooling ducts, spacer displacement, or assembly-related deviations, even when average winding or oil temperatures remain within acceptable limits

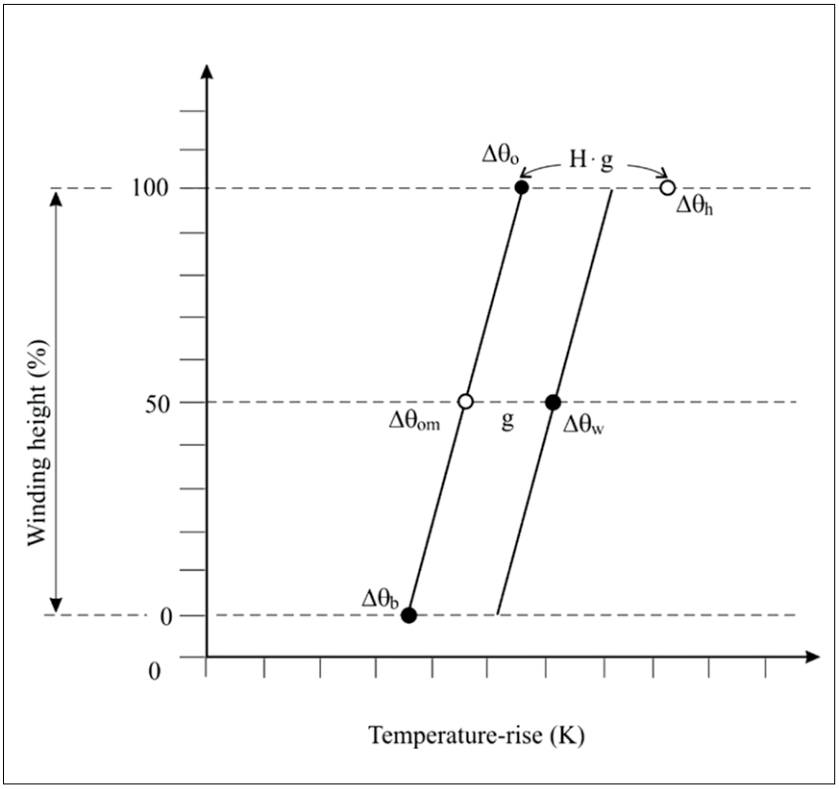
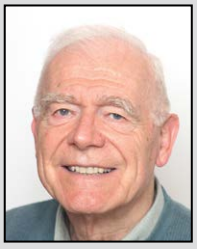


Figure 3. Simplified guidelines for calculating the hot-spot

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