Managing insulation aging through direct hot-spot temperature measurement

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

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The temperature measurement depends on the top-oil temperature, which responds slowly due to the thermal time constant of the oil mass

7. Identifying hot-spots in the existing fleets (retrofitting)

For transformers that are not equipped with fiber-optic temperature sensors, two main methods are commonly used to evaluate winding hot-spot temperatures.

Method 1: Indirect evaluation via winding temperature indicator (WTI)

This method, still widely used, relies on indirect techniques to estimate hot-spot temperature. The traditional method employs a winding temperature indicator (WTI), which combines a top-oil temperature sensor with a heater energized by current derived from a current transformer (CT) to simulate the thermal gradient between the winding and the oil.

WTIs (Fig. 4) are well suited for cooling control and alarm functions; however, their accuracy strongly depends on correct parameterization. They assume stable oil viscosity, predictable oil flow distribution, and consistent heat transfer characteristics. As noted earlier, standard practice requires the WTI to be calibrated at the factory using the transformer's actual winding-to-oil temperature gradient, with this gradient value clearly stated on the nameplate. In practice, these steps are frequently overlooked, which may lead the WTI to underestimate the true winding hot-spot temperature.

Another critical aspect occurs during a sudden increase in load. The temperature measurement depends on the top-oil temperature, which responds slowly due to the thermal time constant of the oil mass. Consequently, while the winding temperature rises within minutes, the cooling system (e.g., pumps) may not be activated, as the WTI does not immediately detect the increase and only responds after a delay.

Method 2: IEC / IEEE Load-guide algorithms

A second method consists of calculating the winding hot-spot temperature using loadingguide thermal models, based on measured load current and oil temperature, in accordance with IEC 600767 [2] or IEEE Std C57.91 [3].

The most recent versions of these thermal models incorporate improved dynamics and a greater number of parameters, allowing a more realistic representation of transformer thermal behavior. Nevertheless, they continue to rely on design assumptions and nameplate

Figure 4. Winding temperature indicator (WTI)

data that are not always fully available to plant owners or operators. More sophisticated thermohydraulic models, typically developed by transformer manufacturers, can achieve excellent accuracy; however, they require detailed calibration and precise knowledge of internal design features. In practice, these models are rarely updated over the transformer's operational life, which may limit their longterm reliability for hot-spot assessment.

With that said, the models are very useful and easy to apply to transformers that are not equipped with fiber-optic sensors. The minimum set of required input measurements consists of:

- Load
- Top oil temperature
- Ambient temperature

The figures 5 and 6 compare hot-spot temperature data obtained from fiber-optic measurements with results calculated using thermal models based on both IEC and IEEE algorithms. The transformer under consideration is a 500 MVA, 400/21 kV GSU unit with ODAF cooling.

Improved accuracy could be achieved by using oil-immersed temperature sensors or by adopting a properly shielded PT100 sensor

It can be observed that both IEC and IEEE models [2], [3] show good agreement with the fiber-optic measurements in terms of trend. However, a systematic deviation of approximately 10-12°C is evident. This discrepancy is mainly attributable to inaccuracies in the top-oil temperature measurement, as the sensor is externally mounted on the tank wall and is therefore exposed to ambient conditions, rain, and sun.

Improved accuracy could be achieved by using oil-immersed temperature sensors or by adopting a properly shielded PT100 sensor, thereby reducing the influence of external environmental factors.

8. Fiber-optics for direct measurement

Fiber-optic temperature probes enable direct temperature measurement at hot-spots within the transformer winding, near the solid insulation where aging occurs. In GaAs-based systems (Fig. 7), a small gallium arsenide semiconductor element located at the tip of the probe exhibits a temperature-dependent optical absorption threshold. Light is sent through an optical fiber to the tip of the probe, and the reflected spectrum is analyzed by the monitor to calculate the absolute temperature. This method is inherently dielectric: there are no metal conductors inside the tank, which eliminates electromagnetic interference and removes conductive paths that could compromise dielectric integrity.

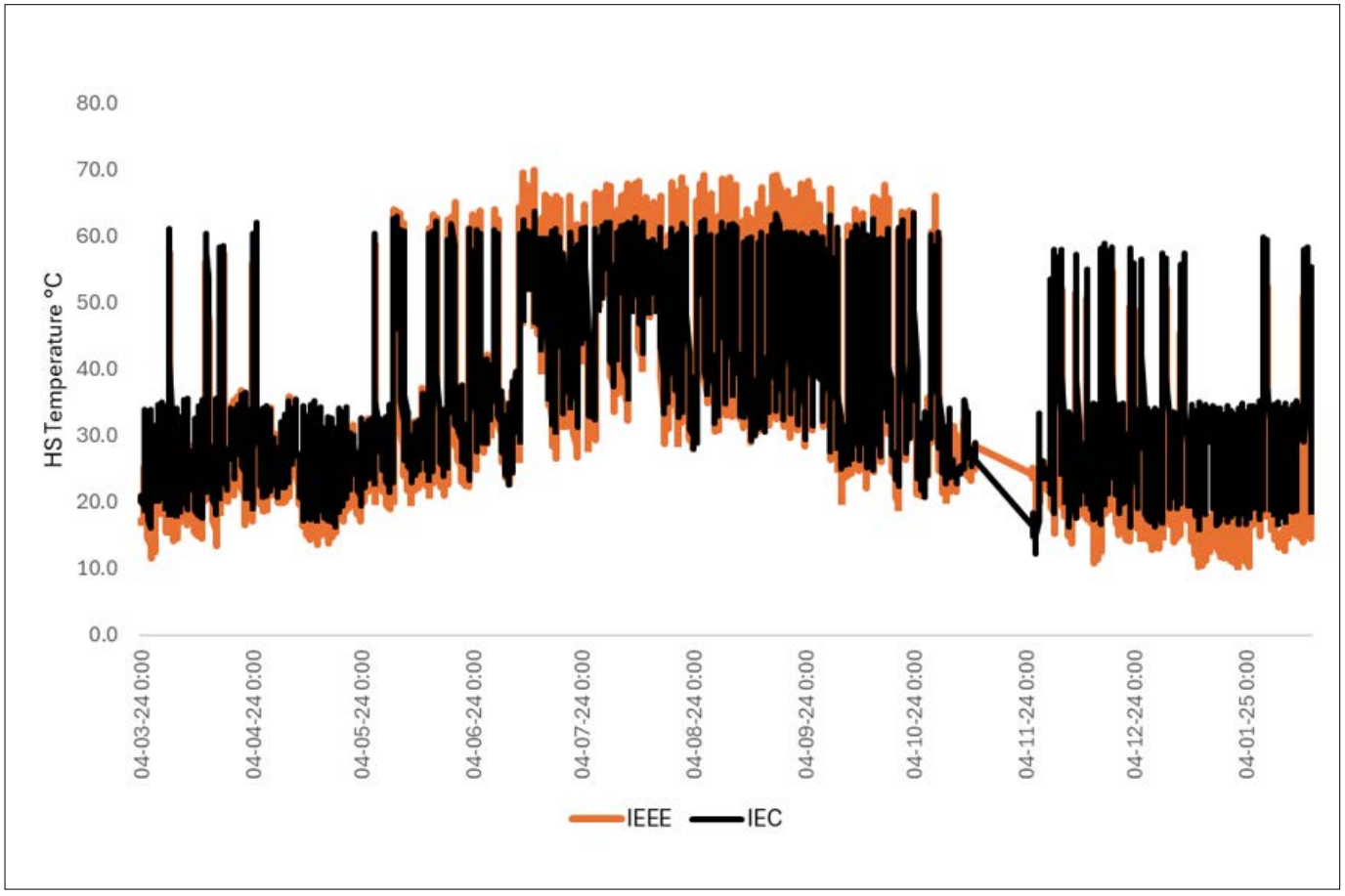

Figure 5. IEC and IEEE models

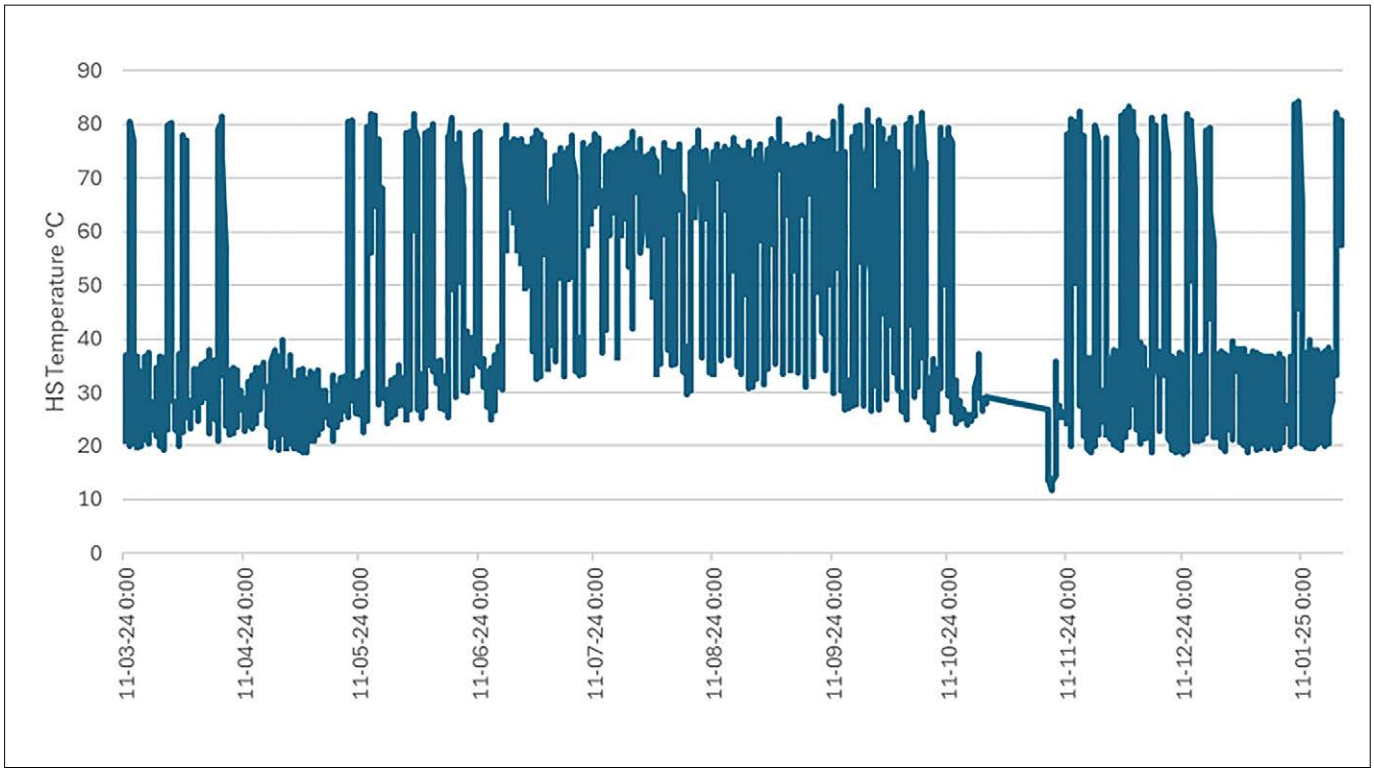

Figure 6. Fiber optic monitoring data

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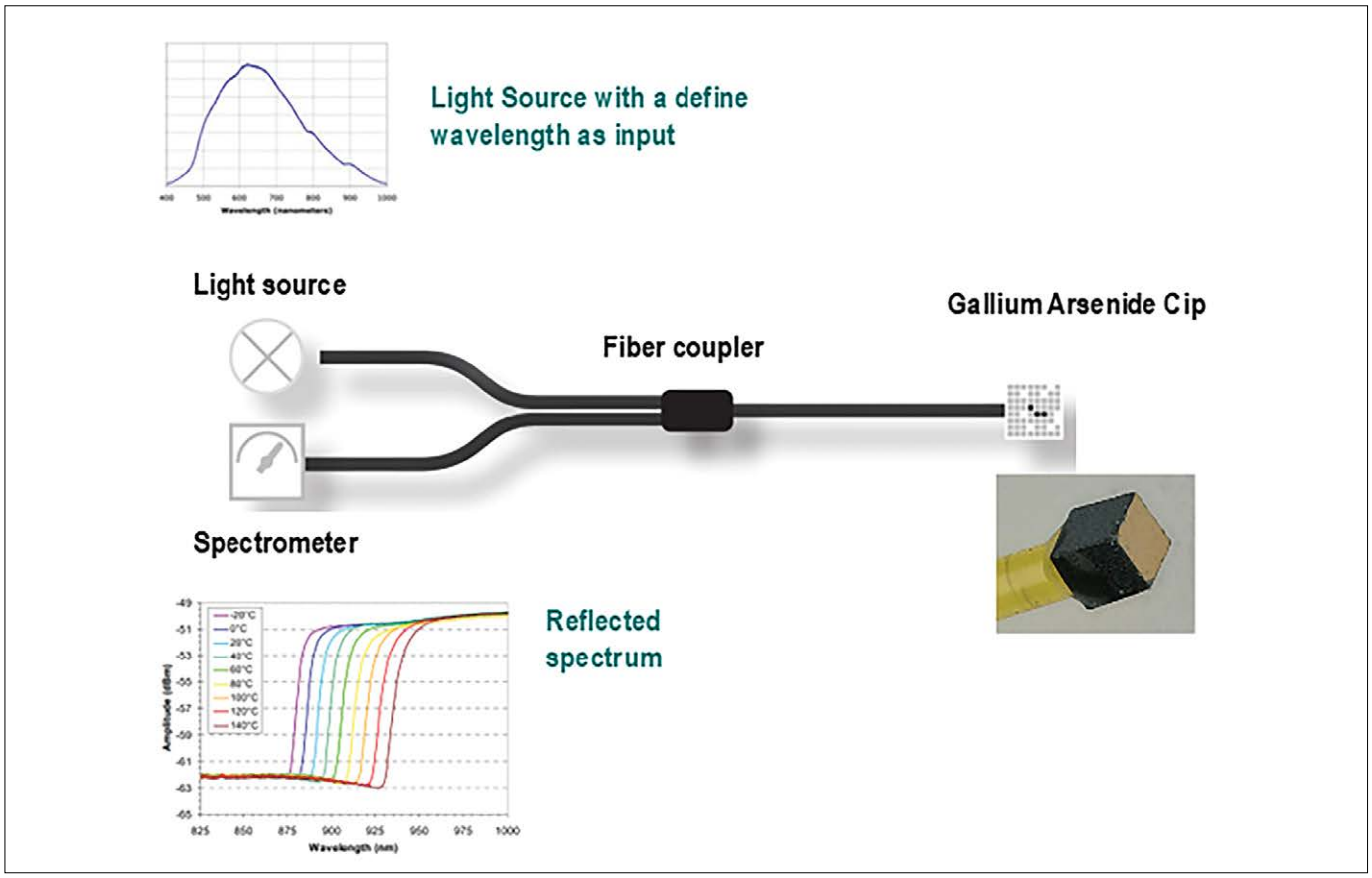

Figure 7. Gallium Arsenide based fiber-optic technology

In practical applications, fiberoptic temperature probes are typically integrated into radial spacers, winding support discs, or dedicated insulating components

Direct temperature measurement eliminates the uncertainty associated with thermal emulation methods. In practical terms, it is considered drift-free, as the measured physical quantity is the semiconductor bandgap, which does not require periodic recalibration when operated within its specified conditions. In addition, optical fibers are chemically inert and can be safely routed within solid insulation structures without affecting dielectric performance.

In practical applications, fiberoptic temperature probes are typically integrated into radial spacers, winding support discs, or dedicated insulating components, enabling direct measurement of the winding hot-spot temperature at critical locations, while protecting the optical fiber from mechanical stress and ensuring repeatable and welldefined positioning (See Fig. 8,9,10).

Recommended installation practices include compliance with the minimum bending radius, elimination of discontinuities or voids within the solid insulation, avoidance of chemically incompatible adhesives, and verification that the optical fibers do not interfere with oil flow in the cooling ducts. Since replacement of internal temperature sensors is generally impractical once the transformer is assembled, sensor identification, verification, and functional checks during production are essential. For this reason, redundancy is commonly achieved by installing multiple probes at critical locations. Methods for repairing optical fibers at the factory stage – prior to encapsulation of the active sensing element - are now available and can further improve installation robustness.

Figure 8. Fiber-optic probe integrated into disk spacer

Figure 9. Fiber-optic probe instalation

As network requirements evolve, critical operating conditions may arise and require operation at significant overload levels

Annex E of IEC 60076-2 provides formal guidelines and recommends a minimum number of sensors [1] (Tab.1).

The IEEE 1538a [6] and CIGRÉ thermal modeling [7] recommendations further support optimized sensor placement strategies, particularly for detecting hot-spots associated with parasitic and stray losses in the terminal and lead regions. It should be also noted that the same installed fiber-optic probes support both FAT and type testing, as well as continuous online hot-spot temperature monitoring during transformer operation.

9. Technical and economic advantages of direct monitoring

There are numerous advantages to the direct measurement of winding hot-spot temperature; the main ones are discussed below.

Advantages of the manufacturer heating tests and contractual penalties

The utilization of direct monitoring became fundamental to verify the real hot-spot in the winding.

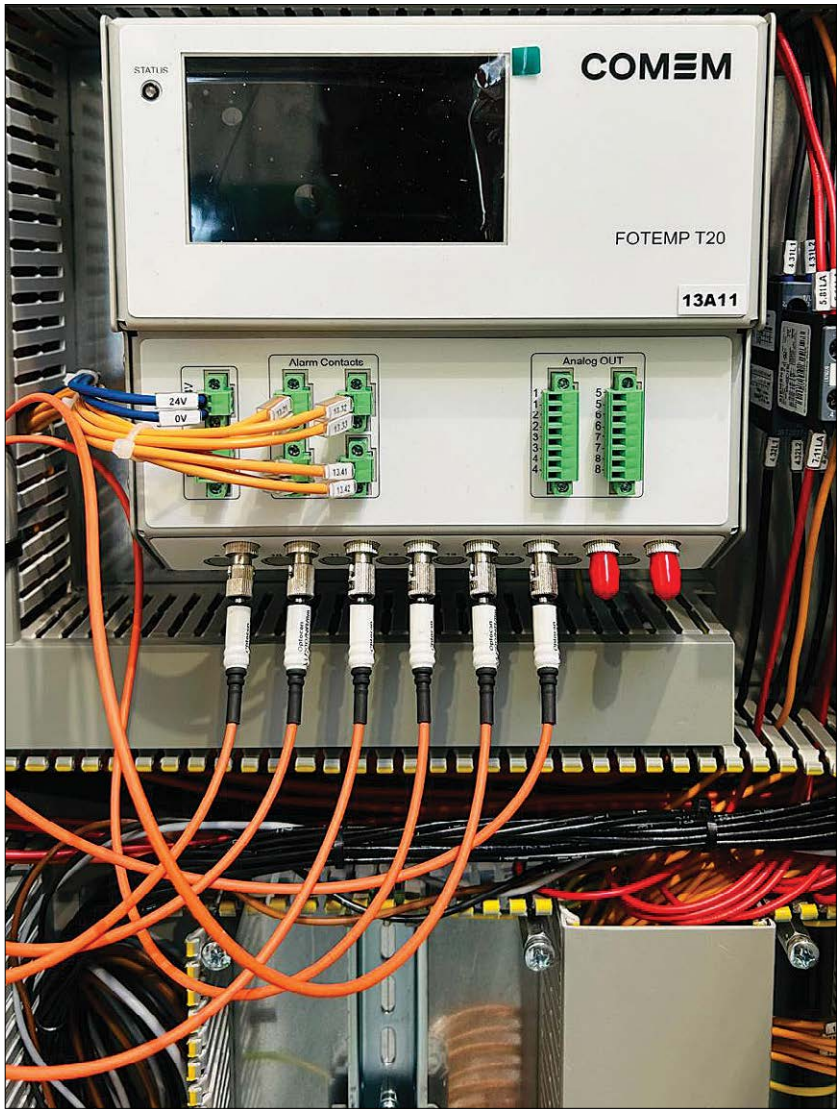

Figure 10. Fiber-optic temperature monitoring device

While transformer thermal design can ensure compliance with the average winding temperature rise limits, the local hot-spot temperature may exceed these limits by well above the commonly referenced 13 °C margin, thereby compromising winding insulation reliability. Direct hot-spot measurement eliminates this problem.

Exceeding the applicable temperature limits may legitimately entitle the customer, subject to contractual agreements, to request a price reduction or, in severe cases, to reject the transformer.

As a reference operating condition, continuous operation at rated load may be considered (see Section 6). Under this condition, a winding hot-spot temperature equal to the standard reference value of 98 °C would correspond to an average insulation service life of approximately 17 years. As discussed in Section 6, any increase in hot-spot temperature above this reference value results in a reduction of the average service life, which should be accounted for in the overall investment and lifecycle cost evaluation.

Within this framework, the manufacturer and the user may agree on a penalty criterion to be included in the supply contract, based on measured hot-spot temperature during acceptance testing or operation.

As an illustrative example, a criterion may be defined whereby hot-spot temperatures exceeding the standard reference value up to 2 °C are considered acceptable, while the supply is rejected if the excess exceeds 6 °C. For intermediate cases, a proportional penalty may be evaluated by assuming operation at rated load for 6 hours per day, corresponding to one quarter of the service duty cycle. By applying the insulation aging relationship described in the loading guides [2], [3], the resulting impact on insulation life can be quantified as in Tab.4.

It is therefore evident that the cost of hot-spot monitoring can be effectively recovered already during this phase.

In addition, direct measurement enables calibration of the thermal model,

Table 4

Hot spot temperature (°C)	Aging acceleration factor	Relative aging over the period considered	Additional relative aging	Penalty (% of transformer cost)
≤100	---	-----	------	zero
100÷101	1,33	0,33	0,08	8,0
101÷102	1,50	0,375	0.125	12,5
102÷103	1,68	0,42	0,17	17
≥104	-----	----	----	waste

improving the accuracy of hot-spot temperature assessment during operation.

Overloading with quantified risk

Transformers, particularly those operating in transmission or distribution networks, are typically commissioned with load levels well below their rated capacity, a condition that may persist for several years. As network requirements evolve, critical operating conditions may arise and require operation at significant overload levels. This need can be addressed by limiting the risk to the insulation system, including the ability to predict the formation of bubbles, through accurate measurement of the winding hot-spot temperature. In this way, the network can be operated with increased flexibility while maintaining a quantified and controlled risk level.

An estimate of the potential economic benefit associated with managing overload operation and the corresponding reduction in insulation service life is presented in the following example.

Consider a 100 MVA grid transformer that operates at 10 % overload for an average of 5 % of the year. The operational benefit is achieved at the expense of a reduction in effective service life, which can be evaluated using the insulation aging relationships discussed previously.

The following parameters are considered:

1. Rated power of the transformer (MVA): 100
2. Allowable overload with monitoring (%): 10
3. Total duration of overload (h/year): 440
4. Economic value of energy during overload (€/MWh): 77
5. Transformer cost, including replacement charges (€): 1,700,000
6. Reference insulation life with hot-spot temperature constantly at 98 °C (h) 150,000
7. Reference ambient temperature (°C): 30
8. Estimated hot-spot temperature during overload (°C): 112
9. Aging acceleration factor: 5

For power generation transformers, overloading is generally not expected, as the transformer is typically rated for the generator's maximum output

From the parameters above, the following results can be derived:

- Annual benefit from overload
  - (1 x 2 x 3 x 4): €338,800
- Annual cost of TR lifespan loss
  - (5 x 3 x 9) /6: €25,500
- Net annual benefit €313,300

For power generation transformers, overloading is generally not expected, as the transformer is typically rated for the generator's maximum output. However, winding hot-spot overheating may still occur when the ambient temperature exceeds the reference value, commonly assumed to be 30 °C. Under fullload operation during high ambient temperatures—such as in summer, elevated hot-spot temperatures may therefore be reached. These operating conditions should be treated equivalently to overload operation, and the considerations discussed above remain applicable. In this case, the economic value of the associated energy production is typically significantly higher than that of energy transport under overload conditions.

The proposed calculation is intended for illustrative purposes only and does not account for additional benefits related to operational safety or the implications for predictive maintenance, which would otherwise be more difficult to achieve.

Nevertheless, the example clearly demonstrates that the economic benefits of monitored overload operation can significantly exceed the cost of the hot-spot monitoring system.

Insurance premium reductions

Direct monitoring of the winding hot-spot temperature allows the operator to demonstrate to insurers that the transformer is operated within controlled and verified thermal limits, as one of the most critical operating parameters is continuously monitored. This increased transparency and risk control may support the negotiation of more favorable insurance conditions, including the reduced premiums or improved coverage terms.

The electric power sector is undergoing a technological transformation comparable to that already experienced in other industries

Impact on maintenance strategy

When a transformer is equipped with continuous thermal monitoring, a detailed record of its thermal operating history becomes available. This information can be integrated with other diagnostic data to enhance interpretation, including results from dissolved gas analysis (DGA). Consequently, a more accurate assessment of the transformer's condition and reliability can be achieved, enabling targeted and conditionbased maintenance actions that may result in significant cost reductions.

Comparison of system costs and resulting economic benefits

The cost of hot-spot monitoring system depends on several factors. Its configuration should be defined by mutual agreement between the operator and the supplier, based on the customer's requirements, which may vary depending not only on transformer rating but also on specific operational criticalities that may take precedence.

In general terms, the cost associated with installing the fiberoptic sensing system is comparable to that of the electronic data acquisition, processing, and communication components.

An alternative implementation approach may consist of installing the fiberoptic probes while omitting continuous online monitoring, using the sensors primarily during factory acceptance testing and for periodic or targeted onsite measurements. In this case, the benefits described in Section 7a are retained, together with the ability to use a portable interrogator (Fig. 11) that can be transferred between different units when a focused assessment is required.

Figure 11. Portable interrogator

Nevertheless, factory test data can also be used to calibrate the transformer thermal model, thereby enabling continuous hot temperature estimation during operation with significantly higher accuracy than would be achievable without the use of fiberoptic measurement support.

These considerations also highlight an important aspect of network and fleet planning: by optimizing the number, rating, and criticality of transformers within a network, operators can maximize the overall return on investment associated with hot-spot monitoring systems.

10. Conclusion

The implementation of direct hot-spot monitoring using fiber optic sensors is now technically feasible through systems that provide the required guarantees of reliability—both in terms of minimal invasiveness to the transformer active part and in terms of measurement accuracy and long-term performance.

The main benefits that can be highlighted are summarized below.

Direct verification of winding hot-spot temperature as a design guarantee.

Even during factory type and acceptance testing, the winding hot-spot temperature—one of the key parameter governing insulation aging and service life—can be measured directly rather than inferred.

It would therefore be desirable for applicable standards and regulations to explicitly allow, or even require, direct hot-spot measurement, at least for large-rate transformers or for series production involving multiple identical units.

Superior accuracy compared to thermalmodelbased estimation.

Direct measurement also offers clear advantages over thermal modeling and hot-spot temperature extrapolation.

Operational experience has shown that calculated values may deviate by 6–7 °C, thereby reducing the reliability of the thermal assessment.

The influence of temperature on the aging of solid insulation has been well established since the early 1980s

At the same time, fiberoptic measurements can be effectively combined with thermal models through model calibration, significantly improving the accuracy of hot-spot temperature evaluation during transformer operation.

Consequently, the main advantages are:

Load optimization

Enables operation under controlled overload conditions without compromising transformer integrity, thereby avoiding unnecessary oversizing in network design.

Extended transformer service life

Excessive thermal stress and the associated risk of vapor bubble formation—both potential causes of malfunction—are avoided or significantly mitigated.

Reduced maintenance costs

Supports the implementation of predictive and condition-based maintenance strategies, while continuously maintaining awareness of the transformer's reliability level.

Reduction in insurance premiums

Facilitate greater involvement of insurance providers and may lead to reduced premiums, supported by improved guarantees regarding operating conditions and effective risk mitigation.

Increased grid service reliability

Failure frequency is reduced and operational flexibility is enhanced, as increasingly required by the growing penetration of renewable and alternative energy sources.

Economic benefits

Although the implementation of a monitoring system entails initial costs, the return on investment (ROI) can be substantial. This is achieved through extended transformer service life, improved performance under overload conditions, reduced maintenance requirements, enhanced durability, potential reductions in insurance premiums, and increased overall reliability of the electrical system.

The adoption of equipment monitoring can no longer be deferred. The electric power sector is undergoing a technological transformation comparable to that already experienced in other industries, such as the automotive sector, where condition monitoring and diagnostics have long been supported by computer-based tools.

The Smart Grid is no longer a conceptual vision; consequently, winding hot-spot monitoring should be regarded as a fundamental element of modern power-transformer systems.

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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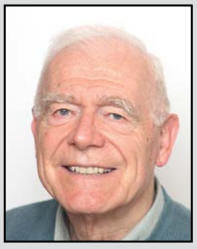

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