Overloading of power transformers

ABSTRACT

With the increase of the integration of Distributed Energy Resources, network operators must address the challenges posed by the intermittent nature of renewable energy. This article highlights the crucial role of Dynamic Transformer Thermal Modeling in assessing transformer ageing and overload capabilities. The article provides insights into optimizing transformer performance and ensuring grid reliability by utilizing advanced monitoring technologies like Direct Temperature Monitoring.

KEYWORDS:

thermal modelling, overload capacity, peak loading, Dynamic Transformer Thermal Modeling (DTTM), temperature monitoring, Direct Temperature Monitoring (DTM)

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The lifetime performance of a power transformer strongly depends on the temperatures its materials have been exposed to

Although transformers are designed for emergency overheating, they are not capable of handling recurring or constant overheating

1. Introduction

To face climate change, millions of electrified Distributed Energy Resources (DERs) are planned in the grid by 2050, triggering significant changes in the electricity system. The integration of renewable energy technologies into present power grids implicates significant challenges for network operators. Due to its unsteady character, the commonly provided output of a wind park often results in peak loading of the connected network components. Furthermore, the ongoing extension of established wind farms and the assembly of new wind parks amplify emerging peak loads for the existing network infrastructure. This development might induce network operators to tolerate temporary loading levels beyond nameplate rating. Nevertheless, long-term consequences concerning the ageing of the equipment have to be considered.

The lifetime performance of a power transformer strongly depends on the temperatures its materials have been exposed to. Because of their significant effect, a profound knowledge about these temperatures is of great interest. While a current state may also be derived from measurements, prospective developments can only be obtained by modelling. Due to transient load conditions, changing ambient conditions, adjustable cooling systems and their design and operation principles, transformers represent a rather complex thermal system. In addition, the particular design of a certain transformer, with its applied materials and installed components, complicates precise simulations tremendously. However, knowledge about the exact temperature distribution inside a transformer may not be necessary within the scope of every desired application. For instance, the determination of a constant, non-critical level of overload might already be achieved by means of a simplified thermal model. Since the overload capability of a transformer is mainly limited by oil and hot-spot temperature, accurate modelling is of great importance. In order to assess the overload capability of power transformers, a thermal model should be integrated into a monitoring system. This model should be a simple and empirical-based thermal model that can predict changes in oil and winding temperature accurately.

The IEC 60076-7 model uses a differential equation to calculate the top-oil temperature and the hotspot temperature

Figure 1. Overheated discs at the top of a winding (ONAF, 66 MVA transformer)

2. Dynamic Transformer Thermal Modelling (DTTM)

The life/ageing of power transformers is directly related to the degradation of the insulation, which is governed by three mechanisms [1]:

- Pyrolysis, promoted by heat;
- Hydrolysis, by reactions with water, is considered the enemy number one of solid insulation; and
- Oxidation by reactions with oxygen.

The ageing process is also catalyzed by primary transformer metal components (copper, aluminium, iron, etc.) and can be accelerated by ageing by-products, dirt, vibrations, electrical stress, etc.

Although transformers are designed for emergency overheating, they are not capable of handling recurring or constant overheating. Winding insulation is sensitive to temperature, as can be seen in Figure 1. The ageing in terms of loss of life dramatically increases with higher temperatures and the presence of catalysts (water, acids, copper, sludge, etc.). Monitoring the winding hottest temperature together with the top oil temperature is, therefore, a must [2], [3].

As dynamic thermal models are used in several online monitoring system applications, their empirical validation, statistical evaluation, and fundamental development are of key importance.

2.1 Thermal models

The IEC 60076-7 [4] model uses a differential equation to calculate the top-oil temperature and the hotspot temperature. The heat transfer differential equation can be solved by using the backward Euler method. As a result of the thermal-electrical analogy, the losses (generating heat) lead to a change in the top-oil temperature and can be calculated as follows:

$$P_{\mathrm{tot}}(k) = P_0 + P_{\mathrm{K}} \cdot K^2(k) \quad (1)$$

P_{tot} depends on the no-load loss P_0, the short-circuit loss P_{K} and the load factor K for the respective time step k.

According to the IEC 60076-7 standard, the top-oil temperature θ_{to} for the next time step k+1 can be estimated by the following equation considering the ambient temperature θ_{α} and the top-oil temperature rise $\Delta\theta_{to}$.

$$\theta_{\mathrm{to}}(k+1) = \theta_{\mathrm{a}}(k+1) + \Delta\theta_{\mathrm{to}}(k+1) \quad (2)$$

Equation (2) can be solved with the following discrete equation (4):

$$\theta_{\mathrm{to}}(k+1) = \theta_{\mathrm{to}}(k) + \frac{\Delta t}{K_{11}\tau_{\mathrm{to,r}}} \left[\Delta\theta_{\mathrm{to,u}} - \theta_{\mathrm{to}}(k) + \theta_{\mathrm{a}}(k+1)\right] \quad (3)$$

A variation in the load results in a delayed rise of the oil temperature, which is taken into account by the oil time constant $\tau_{\mathrm{to,r}}$ at rated load. The factor K_{11} should correct the calculated oil time constant $\tau_{\mathrm{to,r}}$ depending on the cooling mode. The ultimate top-oil temperature gradient and initial top-oil temperature gradient are considered by $\Delta\theta_{\mathrm{to,u}}$ and $\Delta\theta_{\mathrm{to,i}}$. The initial top-oil temperature gradient represents the temperature gradient at the previous time step. The ultimate top-oil temperature gradient is the resulting temperature gradient in steady-state conditions at applied load. $\Delta\theta_{\mathrm{to,i}}$ and $\Delta\theta_{\mathrm{to,u}}$ are calculated as follows:

$$\Delta\theta_{\mathrm{to,i}} = \Delta\theta_{\mathrm{to,r}}\left(\frac{K_{\mathrm{i}}^2 \cdot P_{\mathrm{K}} + P_0}{P_{\mathrm{K}} + P_0}\right)^x = \Delta\theta_{\mathrm{to,r}}\left(\frac{K_{\mathrm{i}}^2 \cdot R + 1}{R + 1}\right)^x \quad (4)$$

$$\Delta\theta_{\mathrm{to,u}} = \Delta\theta_{\mathrm{to,r}}\left(\frac{K_{\mathrm{u}}^2 \cdot P_{\mathrm{K}} + P_0}{P_{\mathrm{K}} + P_0}\right)^x = \Delta\theta_{\mathrm{to,r}}\left(\frac{K_{\mathrm{u}}^2 \cdot R + 1}{R + 1}\right)^x \quad (5)$$

with K_{i} and K_{u} considering the ratio of the specified load to the full load at the previous and current time steps. R describes the ratio of the short-circuit loss to the no-load loss. The parameter x is called the oil exponent, which considers the nonlinear temperature rise under different cooling modes. The rated top-oil temperature gradient $\Delta\theta_{\mathrm{to,r}}$ defines the temperature gradient at rated load and steady-state conditions.

According to the IEC 60076-7 standard [4], the hotspot temperature θ_h for the next time step, k+1 can be estimated by the following equation considering the top-oil temperature θ_{to} and the hotspot temperature rise $\Delta\theta_h$ [4].

$$\theta_h(k+1) = \theta_{to}(k+1) + \left(\Delta\theta_{h,1}(k+1) - \Delta\theta_{h,2}(k+1)\right) \quad (6)$$

Equation *(6)* can be solved with the following discrete equation:

$$\Delta\theta_{h,1}(k+1) = \left(K_{21} H g_r K(k+1)^y - \Delta\theta_{h,i1}\right) \cdot \frac{\Delta t}{K_{22}\tau_W} + \Delta\theta_{h,i1} \quad (7)$$

$$\Delta\theta_{h,2}(k+1) = \left((K_{21}-1) H g_r K(k+1)^y - \Delta\theta_{h,i2}\right) \cdot \frac{\Delta t}{\tau_O / K_{22}} + \Delta\theta_{h,i2} \quad (8)$$

$\Delta\theta_{h,1i}$ and $\Delta\theta_{h,2i}$ are the calculated excess temperatures from the previous time step which are used as input parameters in the calculation of the next time step. The winding to oil temperature gradient at the rated current g_r, the winding time constant τ_W, the winding exponent y, the hotspot factor H, and the correction factors K_{22} and K_{21} are further parameters of the thermal model. Here, the correction factor K_{21} represents the respective share of the superimposed temperature change of the hotspot and the significantly slower change of the oil temperature. K_{22} is a correction factor for the calculation of the winding time constant.

A parametric study was carried out to better understand the effect of parameters on the possible overload capacities of transformers during short-term and long-term emergencies

2.2 Influence of parameterization on overload calculation

Different models are used in the literature to estimate both the top oil temperature and the hot spot temperature. A parametric study was carried out to better understand the effect of parameters on the possible overload capacities of transformers during short-term and long-term emergencies [5]. For short-term emergency study, the ambient temperature is varied from -30°C to 40°C with 10°C intervals (8 values), and for each ambient temperature, the loading prior to the event is calculated to obtain a hot-spot temperature of 110°C. Then, a simulation is performed to determine the maximum loading that can be applied on the transformer until the hot spot reaches 140°C after 30 minutes. For long-term emergency loading, the maximum loading is calculated as if the transformer were operated in a steady state at a maximum hot-spot temperature of 140°C. 140°C is chosen as this is the temperature specified in the IEC standard, which could, as a potential risk, lead to bubble formation from insulating paper.

A reference ONAF transformer is created using the following parameters: rated top-oil rise over ambient $\Delta\theta_{\mathrm{tor}} = 45$ K; rated hot-spot to top-oil gradient $\Delta\theta_{\mathrm{tor}} = 35$ K; losses ratio $R = 8$; oil exponent $x = 0.9$; winding exponent y=1.6; k_{11}=0.5; k_{21}=2.0; k_{22}=2.0; oil time constant τ_o=150 min and winding time constant τ_w=7 min. Then the parameters $\Delta\theta_{\mathrm{tor}}$, $\Delta\theta_{\mathrm{hr}}$, R, x, y, τ_o and τ_w are individually modified over a range of values, and the new applicable loads are calculated for the eight ambient temperatures. Averages of the percentage differences between the modified transformer and the reference transformer are calculated and are reported in Table 1. The reference transformer is built with a combination of parameters recommended in the IEC and IEEE loading guides. For example, the x and y exponents correspond to the oil and winding exponents from IEEE C57.91-2011, and most of the other parameters are in Table 4 of the IEC 60076-7 standard.

Table 1. Variation of transformer loadability vs. reference transformer

Parameter	Range	Short-term emergency loading vs. reference transformer	Long-term emergency loading vs. reference transformer
y	1.0 to 2.0	+10.83% to -4.72%	+2.89% to -2.31%
x	0.7 to 1.0	+2.91% to -1.29%	+2.44% to -1.29%
$\Delta\theta_{tor}$ / $\Delta\theta_{hr}$	40/40 to 65/15	-1.25% to +7.81%	+0.04% to -0.15%
τ_w (min)	5 to 9	-1.11% to + 1.34%	No effect
R	6 to 10	+0.34% to -0.20%	+0.31% to -0.19%
τ_O (min)	100 to 200	-0.36% to +0.23%	No effect

The parameters having the most impact on transformer loadability are the oil and winding exponents and gradients

One somewhat surprising result is the influence of T_w on short-term loadability since the observed data is after 30 minutes and T_w in the range of 5 to 9 minutes. This is explained by the mathematical representation of the thermal overshoot using T_w in *(7)*, which has a peak value at about 40 minutes, thus having an effect at 30 minutes of observation time. The parameters having the most impact on transformer loadability are the oil and winding exponents and gradients. Figure 2 illustrates the parametric study results for these parameters. For instance, a change of the winding exponents from the IEEE (1.6) to the IEC (1.3) recommended value generates an additional loading capacity of 4.8% and 2.6% for short-term and long-term emergencies, respectively.

Figure 3 illustrates the oil and winding gradients extracted from 53 extended temperature-rise tests on ONAN/ONAF/OFAF transformers from three manufacturers, ranging from 47 MVA to 550 MVA and 120 kV to 735 kV [5]. The values from another study on this topic [6] are also included in the graphs.

The statistics indicate an average top-oil exponent of 0.75 (based on 53 values) and an average winding exponent of 1.20 (based on 89 values). This analysis confirms that the oil and winding exponents provided in the IEEE loading guide (0.9 and 1.6) are conservative, and the ones proposed in the IEC loading guide (0.8 and 1.3) represent the average behaviour of the tested transformers more accurately.

2.3 Overloading capability of a wind farm transformer

The application of DTTM with the calculation of the overload capability is presented for a 110 kV wind farm transformer. All the measured data to train and validate the thermal model according to IEC 60076-7 [4] are collected during normal operation of the wind farm transformer. The measurement data consists of the ambient temperature, the top-oil temperature, the load factor, and the fan state of the transformer. The wind farm transformer was initially designed with a rated power of 63 MVA and no active fans. However, because of the high load of the wind farm and an installed power of 95 MW, the cooling system of the transformer was extended with 16 fans to raise the rated power up to 80 MVA. The activation temperature of the 16 fans is defined by the operator to be at an oil temperature of 55°C and the deactivation temperature to be at 50°C.

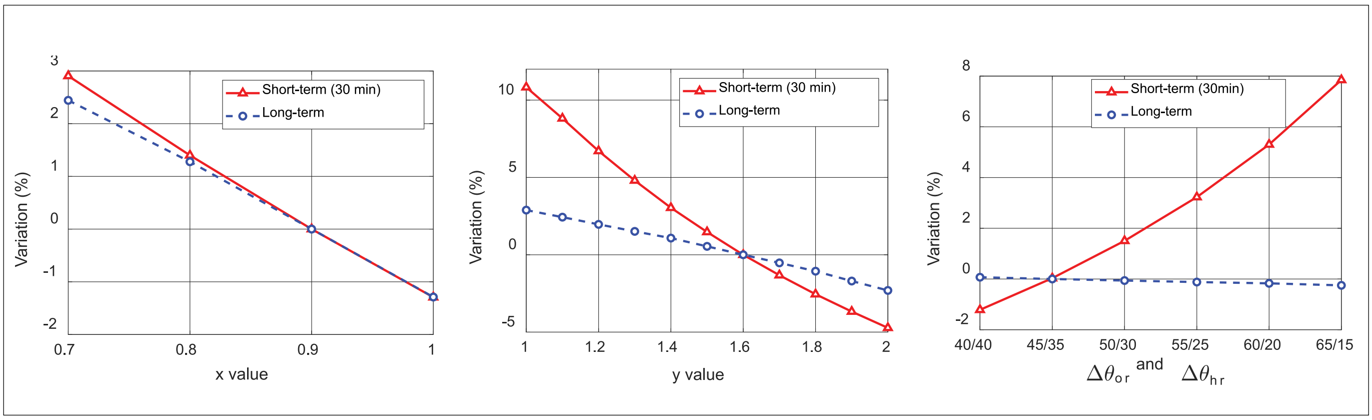

Figure 2. Parametric effect of (a) oil and (b) winding exponents and (c) gradients on the variation of short-term overloading capacity vs. reference transformer

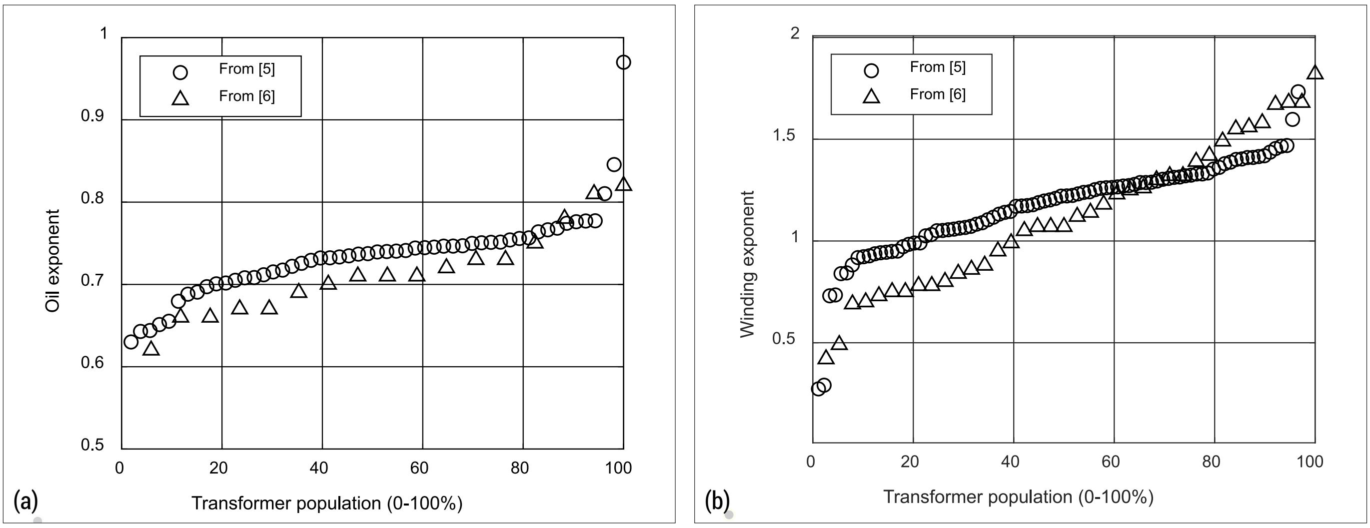

Figure 3. Exponents extracted from extended temperature rise tests (a) oil (b) winding exponent

To use the thermal model to predict the top-oil temperature and the hotspot temperature, the widely used IEC-60076-7 model [4] was used. Every thermal model has its own empiric parameters to fit the thermal behaviour of the transformer. These empiric factors can be determined during a heat run test or with online measurements during normal operation of the wind farm transformer. For this transformer, the hotspot factor, the winding exponent according to IEC 610076-7 and the winding temperature gradient according to the test protocols of the manufacturer are used. The other parameters were determined by using a training dataset based on the measured data and the cooling mode of the transformer. By using training data for each cooling state (ONAN or ONAF) individually, the thermal model was also parameterized for both cooling states. After a successful parameterization, the measured top-oil temperature is compared with the calculated top-oil temperature to check the performance of the model. Finally, the hot-spot temperature and, thus, the overload capability are calculated using the parameters from Table 2.

Every thermal model has its own empiric parameters to fit the thermal behaviour of the transformer, which can be determined during a heat run test

The wind farm transformer was initially designed with a rated power of 63 MVA and no active fans, however, with the installation of 16 fans, the power was increased to 80 MVA

IEC 610076-7 recommends a winding temperature gradient of 26 K for ONAN and ONAF, whereas the manufacturer specifies a winding temperature gradient of 17 K for ONAN and 26 K for ONAF. In addition, the empiric factors determined during operation are used to calculate the top-oil temperature and to represent the thermal behaviour on the air side and oil side.

Table 2. Characteristics of the wind farm transformer

Rated Power	63 MVA / 80 MVA
Short Circuit Loss	202 kW / 326 kW
No Load Loss	21 kW
Mass of Oil	15.1 t
Mass of Active Parts	52.1 t
Mass of Tank	14 t
Number of Fans	16
Cooling System	ONAN / ONAF
Hotspot Factor	1.3
Winding Exponent	1.3
Winding Gradient gr	17 K / 26 K
Max. Hotspot Temp.	120°C

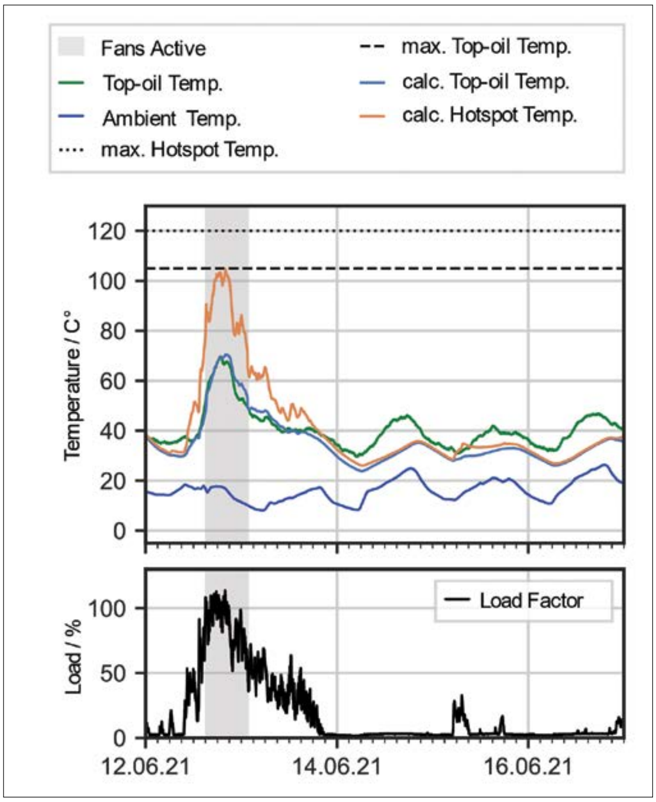

Figure 4. Calculation of top-oil temperature and hotspot temperature during summer

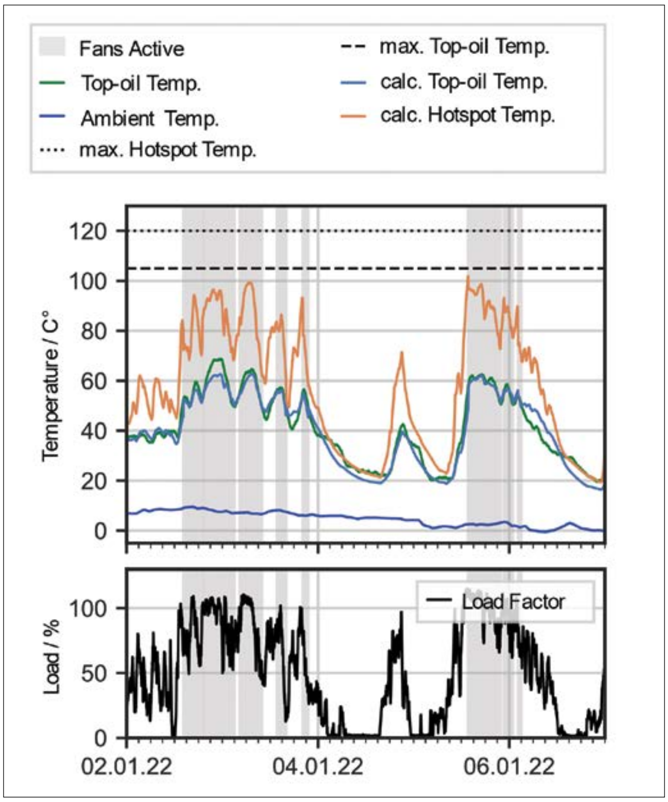

Figure 5. Calculation of top-oil temperature and hotspot temperature during winter

With the thermal modelling of this wind farm transformer, the estimation of the overload capability can be part of a digital twin

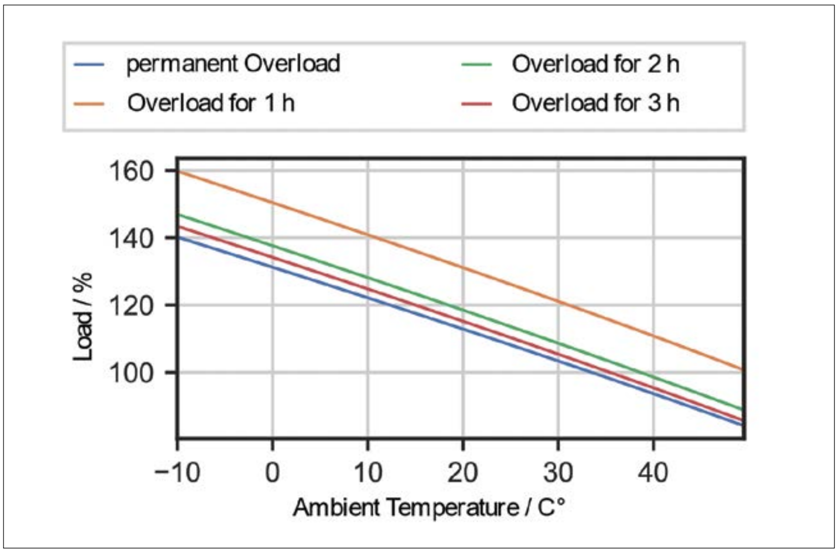

Figure 6. Calculated ambient temperature-dependent overload capability curve for ONAF cooling for different overload durations for a normal cyclic loading

A high temperature insulation system offers an opportunity to improve the overloading capability of distribution transformers facing seasonal load variation

After successful training by minimizing the least square error, the model can predict the change in the top oil temperature depending on the load factor, ambient temperature, and fan state. In Figure 4 and Figure 5, the validation of the IEC 60076-7 model is displayed by comparing the measured and calculated top oil temperatures for summer and winter. The model shows good agreement for assessing the top oil temperature. To obtain a more accurate prediction of the hotspot temperature and, thus, the overload capability, the winding temperature should be measured using fibre-optic temperature sensors. For the wind farm transformer under test, only the calculated hotspot temperature is available. Therefore, the hotspot temperature is calculated according to Equation *(6)* with the winding exponent y and the hotspot factor H according to the IEC 60076-7 [2] and the rated winding gradient g_r given by the datasheet of the manufacturer.

To calculate the current overload capability, the maximum hotspot temperature of

120°C during normal cyclic load with an ageing rate > 1 must be considered.

With the thermal modelling of this wind farm transformer, the estimation of the overload capability can be part of a digital twin. This allows the operator to calculate the operating limits depending on the thermal behaviour of the transformer.

Tools and measures to support DTTM

2.4 High temperature insulation system

A high temperature insulation system offers an opportunity to improve the overloading capability of distribution transformers facing seasonal load variation. A high temperature insulation system was chosen due to thermal calculation based on a typical loading curve on the China Southern Power Grid [7]. In order to evaluate candidate high temperature insulation systems, Nomex® T910 (Aramid-Enhanced Cellulose, AEC) immersed in FR3 (natural ester) was investigated by a dual-temperature thermal ageing test compared with a conventional insulation system, Kraft paper impregnated with mineral oil. Throughout the thermal ageing test, mechanical, chemical, and dielectric parameters of both paper and insulating oil were investigated in each ageing cycle.

The thermal ageing results determined that the thermal class of the FR3-T910 insulation system meets the request of overloading a transformer needs. For solid insulation materials, even under higher thermal ageing temperatures, the tensile strength of T910 dropped more slowly compared with Kraft paper; that means the thermal index of T910 is higher than that of Kraft paper. In addition, the variance of dielectric strength for paper is smaller, and T910, in particular, showed better performance during the whole thermal ageing process.

For fluids, the viscosity of mineral oil and FR3 have relatively similar values, showing that the oxygen reaction between solid insulation and fluids is not evident under nitrogen protection. The acidity of FR3 is higher compared with mineral oil based on chemical composition. Fatty acid was generated by glycerol fatty acid ester after hydrolysis during the thermal ageing process. However, the esterification of fatty acid and cellulose postpones the degradation of cellulose, which is opposite to other acids. After thermal ageing, the breakdown voltage of FR3 maintained a high level, except after 1000 hours at 180°C, but was still higher than the threshold specified by the standard IEC 62975:2021. In summary, compared with a conventional insulation system consisting of mineral oil and Kraft paper, the FR3 impregnated T910 insulation system meets the overloading demand of distribution transformers.

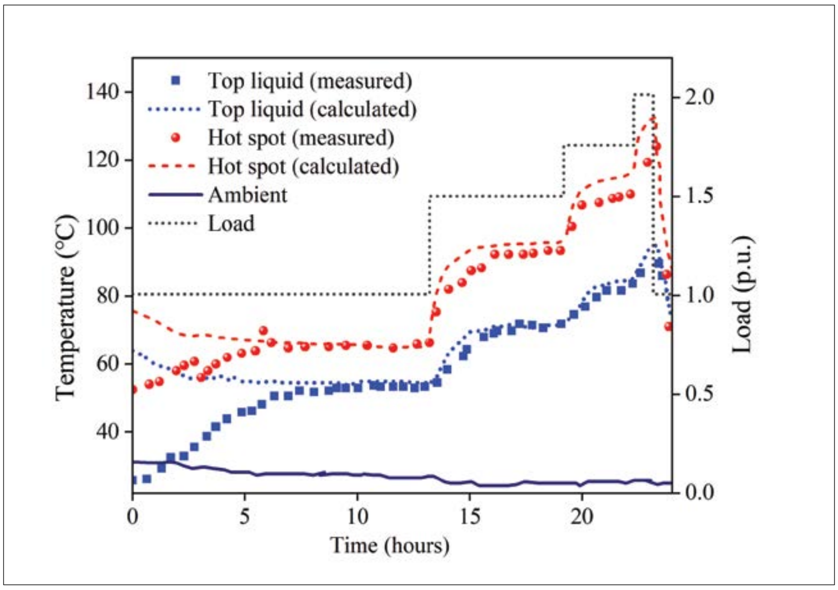

Figure 7. The top liquid and hot spot temperatures under the varying load [8]

> **At the maximum loading condition of 200%, the hot spot temperature peaked at 134°C, while the top oil temperature reached 98°C**

A prototype transformer of 10 kV/0.4 kV, 400 kVA has been developed utilizing T910, aramid enhanced cellulose (AEC), immersed in natural ester and integrated with Fiber Bragg Gratings (FBG) [8]. The purpose of this prototype is to monitor real-time temperature variations. To validate its performance under extreme conditions, a rigorous loading regime recommended by the China Southern Power Grid for industrial applications was employed. This regime entails sustained overloading, with loading levels set at 150% for 6 hours, 175% for 3 hours, and 200% for 1 hour within a single day. Both the hot spot temperature and the top oil temperature were monitored using FBGs and calculated through a refined thermal model, the results of which are depicted in Fig. 7. The calculated temperatures closely match the measured values, demonstrating a consistent trend. Notably, the hot spot temperature was found to be concentrated at the top of Phase B. Under normal operating conditions (100% loading), the top oil temperature stabilized at approximately 55°C, while the hot spot temperature remained at 68°C. As the load increased to 150%, both temperatures rose, with the top oil temperature reaching 72°C and the hot spot temperature escalating to 96°C. Further escalation of the load to 175% resulted in a top oil temperature of 84°C and a hot spot temperature of 114°C. At the maximum loading condition of 200%, the hot spot temperature peaked at 134°C, while the top oil temperature reached 98°C. The insulation degradation results indicate that the overall equivalent ageing factor for AEC was just 0.79, which refers to an accumulated ageing factor for 24 hours. However, the equivalent ageing factor for the applied overload regime was 10.5 for the Kraft insulation, provided that the 400 kVA transformer was overloaded to the same degree.

A suitable temperature monitoring system can use this data and a suitably parameterized thermal model to calculate the current overload capacity and provide a temperature forecast as required

2.5 Extended temperature rise test

For a more precise parameterization of the thermal model with an adapted oil exponent and the winding exponent, an extended temperature rise test (type test) is recommended in accordance with IEC 60076-7 and IEEE C57.119 with 70%, 100% and 125% of the nominal current [4], [9]. The data recorded may be used to determine the thermal characteristics needed to solve the transformer loading guide equations. The three temperature rise tests should be performed with measurement of the hot spot temperature by fibre optics for Direct Temperature Monitoring (DTM). The extended temperature rise test provides additional information on the thermal behaviour in overload operation. During the overload test, care should be taken to ensure that all fans are in operation, and thus, the cooling behaviour at maximum cooling is mapped. [16] used measured extended temperature rise test data to improve the accuracy of the IEC thermal model described in section 2.2 by refining its thermal parameters. Verification of the refined model using a 6.6/0.415 kV, 1 MVA distribution transformer showed that the accuracy of predicting the hotspot temperature is improved by reducing the maximum error from 25.8 to 3.6 K under constant loads and 8.15 to 4.16 K under cyclic loads.

2.6 Temperature monitoring systems

A temperature monitoring system should be used to verify the calculated top oil and hotspot temperatures. This temperature monitoring system should measure the oil temperature with a top-oil temperature sensor (for instance, a PT100) together with the winding temperatures using temperature sensors inside the winding. In addition to measuring the temperatures inside the transformer, the ambient temperature and the current load are also needed. A suitable temperature monitoring system can use this data and a suitably parameterized thermal model to calculate the current overload capacity and provide a temperature forecast as required. This is often a separate system for the transformer but can also be integrated into a SCADA system. Integration into the substation control is particularly helpful in the event of a dynamic overload during operation.

Direct measurement of winding hotspots using fibre optic sensors for Direct Temperature Monitoring (DTM) during Factory Acceptance Testing (FAT) provides asset owners with several benefits, which can have immediate payback, e.g., closer check of thermal design and parametrization of the thermal model with higher accuracy. It also provides useful information to those concerned about the level of thermal stresses and the management of the lifecycle of the transformer. In a period of heavy overloading, online temperature monitoring is available. The log of all events during the lifetime of the transformer is available for analysis. The estimate of the remaining life of the transformer is more accurate. Immediate knowledge of the winding hotspot temperature provides the margin for bubble formation [10] [11]. Bubbling originates from the emission/generation of gas from wet insulation paper under thermal runaway. This phenomenon has two consequences: (i) formation of vapour-filled cavities (bubbles) on the surface of the solid insulation and in the bulk of the oil, and (ii) de-impregnation of the turn insulation due to gas voids. The operation of the transformers is impaired if the bubbles move into the area under high dielectric stresses with a concomitant increase in partial discharge activities or breakdown in critical cases. Bubbling is, therefore, another significant limiting factor for any loading strategy. Recent experimental research [17] on bubble formation temperature of high temperature insulation systems indicated that the Bubble Formation Temperature (BFT) is not dependent upon liquid types, but a BFT difference can be caused by paper types. A combination of either Kraft paper or Thermal Upgraded Paper (TUP) with mineral oil/GTL/ester liquid has been tested through a small-scale laboratory test setup. Nevertheless, the water content in the paper is still the dominating factor in determining the bubbling temperature, highlighting the importance of keeping a transformer dry in operation.

The existing thermal models and loading guides can be improved with respect to accuracy by parametrization with the help of DTM. It has been shown that the dynamic winding hotspot calculation methods proposed in the “old” loading guides [12] and [13], yield significantly lower hotspot temperature than actual values during transients, especially in the case of a short-term emergency loading [2]. This is a critical limitation in the open market environment, where network planners, operators and asset managers are trying to exploit the capacity of existing equipment fully. It has also been observed that the top-oil temperature time constant is shorter than the time constant suggested by the former loading guide [12], especially where the oil is guided through the windings in a zig-zag pattern for the ONAN and ONAF cooling modes [14]. Also, experimental data indicates that the hotspot-to-top-oil gradient at rated current, applied with the IEC 60076-7 (2005-12) equations, needs to be increased by at least 10°C in cold environments to compensate for the higher oil viscosity at very low ambient temperature [15].

3. Conclusion

The increasing integration of electrified Distributed Energy Resources (DERs) into the grid, driven by the imperative to combat climate change, poses substantial challenges for network operators, particularly in managing the variable output of renewable energy

Thermal modelling, particularly Dynamic Transformer Thermal Modeling, emerges as a crucial tool for assessing the ageing and overload capability of power transformers

sources, such as wind parks. The surge in peak loads due to the expansion of wind farms strains existing grid infrastructure, potentially leading operators to tolerate temporary loading levels beyond standard ratings despite long-term consequences for equipment ageing.

Thermal modelling, particularly Dynamic Transformer Thermal Modeling (DTTM), emerges as a crucial tool for assessing the ageing and overload capability of power transformers. Understanding the complex thermal dynamics of transformers, influenced by factors like load variations, ambient conditions, and cooling systems, is pivotal in ensuring their reliable operation and longevity. Parametric studies underscore the importance of accurately characterizing transformer parameters in thermal models. The influence of parameters such as oil and winding exponents on overload capacity highlights the necessity for precision in modelling efforts. Furthermore, extended temperature rise tests provide invaluable data for refining thermal models and optimizing transformer performance.

The incorporation of advanced monitoring systems such as temperature monitoring and Direct Temperature Monitoring (DTM) enhances the accuracy of thermal models and enables real-time assessment of transformer health and overload capacity. By leveraging these tools, operators can better manage the dynamic demands placed on transformers, ensuring their resilience in the face of evolving grid conditions and maximizing their operational lifespan.

Overall, the comprehensive integration of thermal modelling, advanced monitoring systems, and innovative insulation technologies presents a multifaceted approach to addressing the challenges posed by the increasing penetration of DERs in the grid. By continually refining and optimizing these strategies, grid operators can navigate the transition to a more sustainable and resilient energy landscape while ensuring the reliable operation of critical infrastructure.

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