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Three-dimensional thermal modelling of transformers in transformer room for spatial and temporal failure analysis

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Abstract: Temperature is a key factor for failure analysis of power transformers. Conventionally, transformer failure rate is calculated with hot spot temperature induced from IEEE empirical equations. This article firstly introduces a spatial and temporal related failure model based on three-dimensional thermal simulations of transformer and the related environment. The proposed thermal model is established with computational fluid dynamics for ventilation calculation and heat generation equations for power device simulation. Cooling strategies and mutual heating effect of power equipment are considered for an accurate temperature distribution prediction. By incorporating the three-dimensional thermal model into the service life-dependent and temperature-dependent model, the failure rate of each spatial point in power transformer could be calculated according to Arrhenius theory and Weibull distribution. The simulation results show that the proposed model clearly improves the accuracy of failure analysis and can be used for thermal and ventilation design of transformer room.

1 Introduction

Population growth followed by an increasing demand for power supply and space requirement gives rise to the development of underground and indoor substations. The lifetime and failure probability of the power devices strongly depend on their operation conditions. Thermal conditions are the key factors in underground/indoor substation that affect electrical device failure probability, especially for transformers. Excessive temperature rise of transformer accelerates insulation ageing and insulation breakdown, reduces service life, and may cause blackout accident as well as huge economic losses [1]. Therefore, thermal monitoring and failure analysis are essential issues to guarantee safe operation, power availability, and long service life.

There are mainly three methods in substation thermal studies: mathematical calculation model, equivalent thermal circuit model, and finite element method (FEM)/computational fluid dynamics (CFD) model. Mathematical calculation is based on the heat transfer mechanisms. It is the foundation of all type thermal studies and is usually applied in hot spot temperature (HST) prediction. In the past years, equivalent circuit models have been studied in depth. Transformers with/without ambient environment considerations are represented by different thermal-electrical circuit topologies. This method is usually applied in the thermal analysing of oil-immersed transformers/transformer stations. In recent years, more and more attention has been paid on an FEM thermal model to calculate transformer temperature distribution field. Two-dimensional and three-dimensional models for both oil-type and dry-type power transformers have been developed in many papers. For example, Smolka *et al.* [2] built a numerical thermal model of an encapsulated electrical transformer based on thermodynamics and fluid mechanics. Also, Smolka [3] introduced an effective design of cooling ducts for dry-type transformer based on a three-dimensional CFD model. A three-dimensional FEM transformer model for the coupled solution of CFD heat flow equations is proposed by Tsili *et al.* [4]. Lee *et al.* [5] presented the air temperature effect on dry-type transformer. Two-dimensional transient heat diffusion equation was solved by FEM. Also, Eslamian *et al.* [6] modelled temperature distribution of cast-resin transformers and verified the simulation with experimental data. Though a multi-dimensional transformer thermal model has been

studied for years, there are few attempts to take ambient environment and transformer operational status into account. Moreover, a multi-dimensional thermal model has never been applied in transformer failure analysis even though its accuracy is much higher than ANSI/IEEE standards in calculating the HST.

In this paper, a spatial transformer failure analysis model is introduced based on three-dimensional thermal simulations. The proposed thermal simulation method is derived from field measured data combined with ventilation, cooling strategies, mutual heating effect and operational status of power devices. Three-dimensional model is more accurate and comprehensive in describing thermal behaviour of objective substation. Temperature distribution of power devices under different operational conditions and environment is achieved, and the spatial failure analysis model rooted in it could be established. This spatial thermal and failure combined algorithm is applicable in any indoor/underground substations. It could help a lot in underground/indoor substation condition monitoring, such as power equipment ageing evaluation, operation status estimation, and cooling strategy design.

2 Spatial failure model coupled with thermal simulations

2.1 Three-dimensional FEM thermal model of transformer room

The temperature distribution of transformer room could be determined by the energy conservation equation:

$$\rho c_p \left(\frac{\partial E}{\partial t} + v_x \frac{\partial E}{\partial x} + v_y \frac{\partial E}{\partial y} + v_z \frac{\partial E}{\partial z} \right) = k_T \left(\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} \right) \quad (1)$$

where ρ is the density, c_p is the specific heat, E is the energy, t is the time, v_x , v_y , v_z represent the velocity in x , y , z directions, and k_T is the thermal conductivity. Continuity equation:

$$\nabla \cdot \mathbf{v} = 0 \quad (2)$$

where $\mathbf{v}$ is the velocity vector. Also, then Momentum conservation equation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{\nabla p}{\rho} + \frac{\mu}{\rho} \nabla^2 \mathbf{v} \quad (3)$$

where p is the pressure and μ is the dynamic viscosity. Owing to the unacceptable amount of calculation time, reasonable simplification is necessary [7]. In this model, we assume that both transformer winding and core are homogenous material with anisotropic thermal conductivity properties.

According to Lussier *et al.* [8], the effective thermal conductivity along the wires $k_{a,eff}$ is shown below [2]:

$$k_{a,eff} = L_a \cdot \sum_{i=1}^n \frac{k_{ai}}{L_{ai}} \quad (4)$$

where L_a stands for the length of winding along the wire, k_{ai} is the thermal conductivity of the i th material, L_{ai} is the length of the i th material layer in the direction long coil, and n is the total number of material layer. The thermal conductivity of wires in cross-section direction is mainly determined by that of insulating layer because of its low heat conductivity.

The effective thermal conductivity of transformer core in parallel directions to the flat steel laminates is achieved with (4). Also, the effective thermal conductivity in perpendicular direction $k_{p,eff}$ to the laminates is calculated by

$$k_{p,eff} = \frac{L_p}{\sum_{i=1}^n L_{pi}/k_{pi}} \quad (5)$$

where L_p is the thickness of laminates, L_{pi} is the thickness of the i th material layer, k_{pi} is the thermal conductivity of the i th material, and n is the total number of material layer.

Most of the heat generation in transformer room comes from transformers and switchgears, which includes core loss, winding loss, and dielectric loss. The core loss is composed of the hysteresis loss in the core and the stray losses in structural components, such as tank, frame, and so on. The value of hysteresis loss is related to hysteresis coefficient, frequency, maximum magnetic flux density, and the structure of laminates. The stray loss depends on the eddy current on the surface and the superficial area [9]. The core loss including hysteresis and stray losses under different operation conditions remains the same for specific transformers, and rated core loss could be achieved from manufacturer instructions. The hysteresis and stray losses are adopted as 0.014 and 0.028% of the rated capacity [10], respectively, in the thermal analysis of transformer.

The determination of heat losses in the windings P_w is:

$$P_w = P_s \beta^2 = P_s \left(\frac{I_m}{I_r} \right)^2 \quad (6)$$

where P_s is the transformer short circuit power loss, β stands for the load factor, I_m is the measured current of transformer while I_r represents the rated current. There exist additional eddy current losses, in addition to Joule losses in transformer windings. The origin of additional eddy current loss is in leakage magnetic fields to which the windings are exposed to [9]. For cast-resin dry-type transformers, these losses take 10% proportion of the total winding losses, which could not be ignored [11]. However, the additional losses of windings are included in the short circuit loss provided by the manufacturer. Equation (6) could be directly applied in winding loss calculation.

Apart from core loss and winding loss, dielectric loss takes place in the insulating materials of transformer due to the electric stress. However, it is negligible in small- or medium-size dry-type transformer because of the low-voltage difference between insulating materials.

The full load heat generation data of switchgear could be easily obtained from the manufacturer test report. Considering the loading of switchgear, the amount of heat generated by switchgear (P_{sg}) could be calculated as follows:

$$P_{sg} = P_r \times \left(\frac{I_m}{I_r} \right)^2 \quad (7)$$

where P_r is the heat generation under rated current, I_m is the measured current, and I_r represents the rated current of switchgear.

The heat transfer mechanism in transformer and switchgear includes convection, radiation, and conduction. Convection could be calculated with experimental equations given by Pierce [12] and is listed below:

$$q_{co} = h_{co}(T_s - T_{air}) \quad (8)$$

where q_{co} is the convection heat flux, h_{co} is the heat transfer coefficient for convection, T_s is the surface temperature, and T_{air} is the ambient temperature.

Radiation occurs at the outer surface of power equipment. The general equation of radiation is expressed as:

$$q_{ra} = \varepsilon \sigma (T_s^4 - T_{air}^4) \quad (9)$$

where q_{ra} is the radiation heat flux, ε presents the emissivity coefficient of surface, and σ stands for the Stefan–Boltzmann's constant ($5.78 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$).

The heat conduction equation in three-dimensional Cartesian coordinates is illustrated as follows:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) + Q = \rho c_p \frac{\partial T}{\partial t} \quad (10)$$

where k represent the thermal conductivities in x, y, z directions, Q is the heat source term, ρ is density, c_p means specific heat, T is temperature, and t is time.

By substituting energy and thermal conductivity equations and values to (1)–(3), the governing equations could be solved numerically by commercial software that provides CFD for thermal management such as Ansys, Cosmo etc.

2.2 Spatial and temporal failure field of transformer room

Failure rate is a basic function to describe the frequency of material failures or thermal runaway. The spatial risk model we proposed is capable of obtaining the failure rate of each spatial point in the model with its temperature value and physical property as is shown in Fig. 1, it is dominantly induced from transformer room temperature distribution, which is generated by the combined effect of electric and environmental stresses described above. The failure rate defined in (11) has spatial diversity and time dependence characteristic due to the layout of different equipment in the room and the time varying loading, cooling, and ambient conditions.

$$\lambda(t, x, y, z) = \frac{f(t, x, y, z)}{1 - Q(t, x, y, z)} = \frac{dQ(t, x, y, z)/dt}{1 - Q(t, x, y, z)} \quad (11)$$

where (x, y, z) are three-dimensional coordinates of a given point, and $f(t, x, y, z)$ and $Q(t, x, y, z)$ are the probability density function and the failure function of the reliability cumulative distribution [13] at a given point.

In this paper, we choose the most representative line $y_0 = 0.1$ in XY -plane ($z_0 = 0.9 \text{ m}$) for spatial failure rate discussion: the failure rate switches among λ_{td} , λ_{tc} , λ_{tw} of dielectric, core, and winding in transformer, and λ_s of switchgear. The failure rates in different regions have different temperature-dependent shapes and condition-dependent factors. Thus, the failure rate at different points in the figure can be extended to four partitions corresponding to four materials, and these failure rates can be obtained as follows:

$$\lambda(t, x, y, z) = \begin{cases} \lambda_{td}(t), (x, y, z) \in S_{td} \\ \lambda_{tc}(t), (x, y, z) \in S_{tc} \\ \lambda_{tw}(t), (x, y, z) \in S_{tw} \\ \lambda_s(t), (x, y, z) \in S_s \end{cases} \quad (12)$$

where S_{td} , S_{tc} , S_{tw} are the point sets of the dielectric, core, and winding partitions in transformer, and S_s is the point set of the switchgear partition.

The electric stresses from transformer loading, switchgear, and the environmental stresses from ambient temperature and air conditioner will lead to uneven temperature distribution in the transformer room. High temperature area occurs in transformer coils and cores. According to Arrhenius theory [14], high temperature accelerates the degradation of insulation paper. Therefore, uneven temperature distribution amplifies the spatial diversity of failure rate. For each given point in transformer and switchgear, the failure rate is a function of time and temperature.

Weibull distribution has been widely used in failure probability calculation of transformer, switchgear, and other power equipment [13, 15]. According to the definition of Weibull distribution, the instantaneous failure rate is

$$\lambda(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} \quad (13)$$

where β is the shape parameter and η is the scale parameter. When $\beta = 1$, the instantaneous failure rate remains constant over time; $\beta > 1$ and $\beta < 1$ indicate rising and falling failure rates with time. The scale parameter η has no effect on the shape of the failure rate function. It is a life measurement of equipment and can be assumed inversely proportional to the reaction rate based on Arrhenius theory [14]. The relationship between scale parameter η and temperature T can be written as follows:

$$\eta(T) = \frac{\eta_{ref} L(T)}{L(T_{ref})} = \frac{\eta_{ref} e^{B/(T+273)}}{e^{B/(T_{ref}+273)}} = A e^{B/(T+273)} \quad (14)$$

where T is the temperature in celsius, $L(T)$ is the nominal life measure, T_{ref} is the rated temperature, and η_{ref} is the scale parameter reference to a given equipment with rated service life. A , B are the empirical constants defined in IEEE C57.91-1995. The temperature distribution has an obvious dispersion and diversity in three-dimensional space, and the spatial failure rate in the equipment can be calculated by substituting (14) into (13) and (12). The spatial failure rate in three-dimensional space can be achieved as follows:

$$\lambda(t, x, y, z) = \begin{cases} \frac{\mu_{td}\beta_t}{A_t} \left(\frac{t}{A_t} \right)^{\beta_t-1} e^{-(\beta_t B_t/(T(t, x, y, z)+273))}, (x, y, z) \in S_{td} \\ \frac{\mu_{tc}\beta_t}{A_t} \left(\frac{t}{A_t} \right)^{\beta_t-1} e^{-(\beta_t B_t/(T(t, x, y, z)+273))}, (x, y, z) \in S_{tc} \\ \frac{\mu_{tw}\beta_t}{A_t} \left(\frac{t}{A_t} \right)^{\beta_t-1} e^{-(\beta_t B_t/(T(t, x, y, z)+273))}, (x, y, z) \in S_{tw} \\ \frac{\beta_s}{A_s} \left(\frac{t}{A_s} \right)^{\beta_s-1} e^{-(\beta_s B_s/(T(t, x, y, z)+273))}, (x, y, z) \in S_s \end{cases} \quad (15)$$

where λ_s and λ_{ti} represent the spatial failure of switchgear and transformer, the subscript $i = d, c, w$ represent the dielectric, core, and winding of transformer, respectively, and μ_{ti} is the failure proportion related to different materials of transformer, $\mu_{td} + \mu_{tc} + \mu_{tw} = 1$. Incorporating terminal and tap-changer failures into winding failures, the typical failure proportion value could be assigned to $\mu_{td} = 0.129$, $\mu_{tc} = 0.142$, and $\mu_{tw} = 0.729$ from the failure survey of transformer [16]. It is noted that the failure proportions are the expected values of failure proportion of different materials in transformer and cannot reflect the temperature and time-related effects. The combination of Weibull distribution and Arrhenius

Fig. 1 Spatial distribution of failure rate in transformer room

theory can both represent the temperature- and time-related relationship of failure rate.

During the calculation of spatial failure rate in Fig. 1, the model parameters of failure rate can be firstly achieved according to the partition of point (x, y, z) , and then the temperature of the point can be obtained using the thermal simulation of transformer room. Finally, the temperature and the material age of the point (x, y, z) can be substituted into the corresponding failure rate model in (15) to compute the spatial failure rate. According to the temperature distribution in the line shown in Fig. 2a, the failure rate of switchgear and transformer at their ages of $t = 30$ years are calculated by the proposed method. Fig. 2b shows the spatial failure rates of the transformer considered as a whole or partitioned into three materials, where $\beta_s = 3.5$, $A_s = 25$, $B_s = 320$ and $\beta_t = 5$, $A_t = 25$, $B_t = 250$. In Fig. 2b, the failure rate fluctuates with temperature and the values are different in different equipment and materials. The computing results of transformer which is partitioned as three materials are smaller and more refined than that of the non-partitioned case. The failure risks of dielectric and core materials in transformer are less than that of the transformer winding. Thus, the reliability analysis of the whole transformer is more conservative. The failure rate of switchgear in Fig. 2b is larger than that of the dielectric and core materials and less than the failure rate of winding in the transformer.

The cumulative failure probability of electrical equipment can be calculated with spatial failure rate and shape parameter as is shown below:

$$F_j(t, x, y, z) = 1 - e^{(-\lambda'_j(t, x, y, z)t)/\beta_j} \quad (16)$$

where $j = s$, t_i represent the switchgear and the materials of transformer, $\beta_{ti} = \beta_t$. Fig. 2c shows the surface of failure probability versus time and temperature according to the typical parameters of a transformer in Fig. 2b. The transformer stays at a normal operation status when the temperature is 30°C , and the corresponding failure probability is 60% at the end of the 40 years designed life. Since the failure rate increases with time and temperature, the rise of corresponding failure probability is accelerating.

3 Case study

The design scheme of our objective transformer room is shown in Figs. 3a and b. Three ABB cast-resin dry-type transformers with protection cabinet, three SIEMENS low-voltage switchgears of the transformers, and three air conditioners are installed in the room. Air ventilation and cooling is undertaken by air conditioners. The red dots represent the humidity/temperature sensor position. All the size parameter units are millimetre. Heat transfer coefficient is considered to be constant (10 W/Km^2) under free air convection condition. Different intake air temperature and airflow speed of air conditioner are set in the simulations for thermal analysis, and the pressure in transformer room is considered to be standard atmosphere pressure. According to the Reynolds number, turbulent flow is chosen. Radiation is taken into account and free outlet

Fig. 2 Spatial temperature and failure rate in a transformer room
(a) Spatial temperature in transformer room, (b) Spatial failure rate of transformer room at the line of $y=y_0$ and $z=z_0$, (c) Failure probability surface of a transformer

boundary condition for grills on transformer cabinets is assumed in the simulation.

Three-dimensional model of objective transformer room in underground substation is set up in Ansys Icepak 14.5 according to the design scheme. The three cast-resin dry-type transformer parameters are the same and are tabulated in Table 1. The physical properties of transformer materials are summarised in Table 2.

Since core loss (iron loss) of transformer remains the same under normal working conditions, the variation of transformer heat loss and temperature mainly depends on its winding loss. The full load heat generation of switchgear is 888 W referring to technical brochure. To reduce calculation complexity while taking switchgear cabinet thermal effect into consideration, three switchgears in transformer room are regarded as uniform heat source. Combining power facilities specifications with the algorithm introduced in Section 2, all simulation parameters could be calculated. In addition, the fire-proof doors of transformer room are supposed to be closed during operation.

Fig. 3 Design scheme of a transformer room
(a) Top view in design scheme of transformer room, (b) Side view in design scheme of transformer room

Table 1 Transformer parameters

Parameters	Values
insulation class (HV/LV)	F
frequency	50 Hz
rated power	1250 kVA
rated high voltage	22,000 V
rated low voltage	415 V
rated HV current	32 A
rated LV current	1739 A
rated copper loss	11,500 W
rated iron loss	2700 W
protection cabinet size	1.8 m × 2.3 m × 2.4 m radius: 277.3 mm, 187.3 mm (internal radius)
winding size	height: 1323 mm; insulation thickness: 2 mm wire radius: HV: 2.5 mm, LV: 5 mm
core size	lamine thickness: 20 mm lamine numbers 11 lamine height: 1794 mm

Table 2 Physical properties of transformer materials

	Density ρ , kg/m ³	Specific heat c_p , J/kg/K	Conductivity k , W/m/K
core (iron)	7650	478.39	72.39
windings (copper)	8933	390.84	412.68
insulations (class F)	1100	550	0.2
protection cabinet (steel)	7860	490	54

3.1 Thermal analysis of transformer room

Five indices are employed in describing the thermal performance of transformer room under different simulation scenarios. $T_{\max}$ stands for the HST of transformer, ΔT represents the temperature rise of transformer, T_{initial} is the initial ambient temperature of transformer room as well as that of transformer, T_{air} means the cooling airflow temperature, and $\bar{T}$ stands for the average temperature of transformer cores and windings. We define the

Fig. 4 Thermal behaviour of transformer room under full load operation conditions

(a) Cross-section at 0.9 m height (XY-plane with $z = 0.9$ m), (b) Vertical-section through the centre of TR-002 (YZ-plane, $x = 5.8$ m) with no air conditioner cooling, (c) Cross-section at 0.9 m height (XY-plane with $z = 0.9$ m), (d) Vertical-section through the centre of TR-002 (YZ-plane, $x = 5.8$ m) with $2 \text{ m}^3/\text{min}$, 20°C air conditioner cooling

Fig. 5 Thermal behaviour of transformer room

(a) Cross-section at 0.9 m height (XY-plane with $z = 0.9$ m), (b) Vertical-section through the centre of TR-002 (YZ-plane, $x = 5.8$ m) under 50% load operation condition with $2 \text{ m}^3/\text{min}$, 20°C air conditioner cooling, (c) Cross-section at 0.9 m height (XY-plane with $z = 0.9$ m), (d) Vertical-section through the centre of TR-002 (YZ-plane, $x = 5.8$ m) under 10% load operation condition with $2 \text{ m}^3/\text{min}$, 20°C air conditioner cooling

Table 3 Transformer room thermal behaviour characteristics

Simulation no.	$T_{\text{initial}}, ^\circ\text{C}$	$T_{\text{air}}, ^\circ\text{C}$	$T_{\text{max}}, ^\circ\text{C}$	$T, ^\circ\text{C}$	$\Delta T, ^\circ\text{C}$	Operation load, %	Cooling air speed, m^3/min	Highest temperature area
1	20	20	147.134	123.182	127.134	100	0	middle of windings
2	20	20	146.994	123.174	126.994	100	2	middle of windings
3	20	20	80.648	66.989	60.648	50	2	middle of cores
4	20	20	77.484	59.492	57.484	10	2	middle of cores

average temperature as the average value of the highest and lowest temperature of cores and windings.

Fig. 4 shows the simulation results of transformer room thermal behaviour with three transformers operating under full load condition without and with air conditioner cooling. The temperature of air conditioner intake air is set to be 20°C , the speed of inlet cooling air is $2 \text{ m}^3/\text{min}$, the direction of airflow is -30° , and the initial temperature of transformer room is supposed to be 20°C .

Fig. 4 shows the surface temperature of transformer cores and windings. During the full load operation process, the highest temperature area appears in the middle coil due to the mutual thermal effect radiation and convection among coils. Fig. 4a shows the cross-section temperature distribution of transformer room at 0.9 m height and Fig. 4b provides vertical-section temperature distribution through the centre of middle core in TR-002. The highest temperature area appears on windings due to their large amount of heat generation. In addition, the highest temperature area of core is in the middle part as we assume that airflow in this transformer room is only driven by air conditioners.

Compare Figs. 4a and b with Figs. 4c and d, the air conditioners have obvious cooling effect on transformer room temperature but limited effect on transformer windings and cores because of the transformer protection cabinet. Though grills are designed on protection cabinet, it impedes cooling air from flowing through transformer windings and cores, which makes a great discount on the cooling ability of air conditioners on transformers. Moreover, the transformer cabinets block the airflow that lead to the non-uniform temperature distribution of the room.

The heat generation of transformer winding changes with working loads. When transformer output load decreases to 50% of rated power, the highest winding temperature drops to 65°C as shown in Figs. 5a and b. Comparing Figs. 4c and d to 5c and d, the airflow patterns remain almost the same, but the temperature of ambient air decreases with loading. Besides, the highest temperature area transfers to transformer core from windings when load decreases. When transformer output load drops to 10% of rated power, this phenomenon is very obvious as is shown in Figs. 5c and d. The output load of transformer is the main factor that decides transformer winding temperature.

Based on the simulation results explained above, transformer room thermal characteristics under different operation conditions are tabulated in Table 3. According to simulation results and these data, factors that affect transformer room thermal behaviour could be summarised:

- (1) Cooling air speed and temperature controls the room temperature, but have little effect on transformer internal temperature because of the protection cabinet.
- (2) Operation load is the key factor that affects transformer operating temperature, especially winding temperature. When operation loads decrease, the highest temperature area transfers from windings to cores.
- (3) Temperature distribution of transformer room largely depends on the air conditioner locations as well as the arrangement of transformers. In a general situation, the temperature map of transformer room depends on the cooling source and heat source location.

Fig. 6 Temperature and spatial failure rate of the line $y = 2.1$ m at XY -plane ($z = 0.9$ m)

(a) Temperature, (b) Spatial failure rate under full load condition with no air conditioner cooling and $2 \text{ m}^3/\text{min}$, 20°C air conditioner cooling, (c) Spatial failure rate full load and 10% load condition with $2 \text{ m}^3/\text{min}$, 20°C air conditioner cooling

3.2 Spatial failure analysis of transformer room

Fig. 6a shows the temperature distribution of the line $y = 2.1$ m at XY -plane ($z = 0.9$ m) as is in Fig. 1 in the transformer room for full load condition with no air cooling which is shown in Figs. 4a and b, full load condition with $2 \text{ m}^3/\text{min}$, 20°C air conditioner cooling which is shown in Fig. 4c and d, and 10% load condition with $2 \text{ m}^3/\text{min}$, 20°C air conditioner cooling which is shown in Figs. 5c and d. Using the simulated temperature, the spatial failure rate can be obtained by (14) and (15) for different load and cooling conditions and is shown in Figs. 6b and c, where the ages of transformer and switchgear $t = 30$ years, the parameters $\beta_s = 3.5$, $A_s = 25$, $B_s = 320$, and $\beta_t = 5$, $A_t = 25$, $B_t = 250$. In Fig. 6b, the failure rate of no cooling condition, especially for the winding of transformer, is significantly larger than that of $2 \text{ m}^3/\text{min}$ cooling condition. The failure rate of 10% load is less than that of the full load case in Fig. 6c. The failure rates of switchgear are similar for the three conditions, which indicate that the potential risk of switchgear mainly depends on ambient temperature instead of load level. This finding also implies that the load and cooling conditions both have significant effect on transformer failure risk.

The failure probability increases with the age of power equipment due to the natural ageing process and some contingency events. Higher temperature in transformer winding leads to accelerated rise of the corresponding failure probability. The failure

probability of a transformer in normal operation conditions with strict maintenances will come to 0.5 at the end of the designed service life [14].

Figs. 7a–c demonstrate the three-dimensional surface, side view, and top view of the spatial failure probability of transformer room along the x -axis varying from 0 to the designed service life of 40 years when there is no air conditioner cooling in the transformer room. As is shown in the figure, the failure probabilities of TR-001, TR-002 and TR-003 exceed $F(t, x, y, z) = 0.5$ at the different ages of transformer. Owing to the uneven temperature distribution in the room, the service life of TR-002 and TR-003 is 32 years, while the service life of TR-001 is 33.5 years. When there is no cooling, the available time of transformer will reduce 6–8 years from the designed service life. The heating effect of switchgear under full load condition is limited, so its failure probability is < 0.5 when thermal stress and ageing process are considered. It is noted that the failure of switchgear is mainly caused by the mechanical problem [15], which is not incorporated in the proposed spatial risk model.

The contour lines of $F(t, x, y, z) = 0.1, 0.3, 0.5$, and 0.7 for the three load and cooling conditions are shown in Fig. 8. The surrounding area of $F(t, x, y, z) \geq 0.5$ for the full load condition with $2 \text{ m}^3/\text{min}$ cooling is less than that of the full load condition with no cooling, which indicates that the appropriate cooling measures can extend the service life of transformer (from 32 to 35.5 years for TR-002 in the figure). In Fig. 8c, the surrounding area of $F(t, x, y, z) \geq 0.5$ is almost to 0, and the operating conditions are better than the other two cases. These results show that lower load level and active cooling can extend transformer service life. If the transformer load, in practice, is always less than full load, its expected service life will be in the range of 32 years to the designed service life.

3.3 Experiments

At current stage, all three transformers are operating at 10% average load in the target transformer room; therefore, we compared these 10% load simulation results with the temperature data we collected on site to verify the model. The onsite loads can only be adjusted in a small range and always has a slight fluctuation during a stable operating state, because the main loads of transformers are some pipeline transportation pumps, and the pumping flow is fluctuating in the onsite tests. Six temperature sensors are installed evenly spaced on the two long side walls of transformer room at the height of 0.9 m, as was shown in Fig. 3. Also, each of the transformers has a PT100 temperature sensor imbedded in the middle coil. The operating times of onsite transformers are all 4.3 years, and the duration for the transformer loading is 60 min in the experiment. The temperature data are stable after the duration time, and thus, this temperature is recorded in the experiment and simulation. The comparison of onsite data and simulation results is listed in Table 4.

The absolute error and the relative error (absolute value) of the temperatures are provided in the table to quantify the degree of similarity of the simulated and onsite measured results. The comparison reveals that the relative errors of S1–S6 are lower than 10% and acceptable for the thermal analysis. To further analyse the adaptability of the simulation, the relative errors of S1–S6 under different cooling air temperatures and cooling air speeds are shown in Fig. 9. The cooling air speed is maintained at $2 \text{ m}^3/\text{min}$ in Fig. 9a, and the cooling temperature is 20°C in Fig. 9b. The relative errors of S1–S4 and S6 are lower than 5% for different air conditioner cooling strategies, and the error of S5 is the largest one. Fig. 9 also shows that increasing the setting temperature of intake air and decreasing the speed of inlet cooling air are beneficial to reduce the error of S5. The comparison under different air conditioner cooling strategies confirms that though temperature deviation exists between simulation and real data, the simulation matches onsite data to a great extent. The reasons of temperature deviation between onsite air temperature and simulation results might come from following aspects:

Fig. 7 Spatial failure probability of the line $y = 2.1$ m at XY -plane ($z = 0.9$ m) under full load condition with no air conditioner cooling
(a) Three-dimensional surface, (b) Side view, (c) Top view

(1) Onsite data collection might not be that accurate. The initial temperature of transformer room and power devices could not be exactly 20°C as is in the simulations. Besides, the fluctuation of transformer load affects the heat generation, due to the oil pumping flow changes in the main load of transformer.

(2) Ideal simulation condition is set in the model while the real environment is not exactly the same as that in simulation: this sample transformer room is part of an underground project, and staffs visit this transformer room frequently since this project is under construction. While in our simulation, we suppose both of fire doors are closed during operation. Walking staffs in transformer room uniform the temperature distribution of surrounding air. Moreover, the ventilation rate of grills on transformer cabinet is lower than the ideal value defined in simulation, which leads to the phenomenon that the simulated ambient temperature on S1, S2, and S3 sides is higher while lower on the opposite side.

Owing to the capacity limitation of onsite load, the load level of transformer is hard to increase, so that the shutting down experiment of air conditioners is implemented to investigate the extreme thermal behaviour in the transformer room. Fig. 10 shows the measured and simulated temperature of S5 which is the maximum one among S1–S6, and the simulated HST when the three air conditioners are shutting down at $t_0 = 90$ min. Before the shutting down, the setting temperatures of air conditioners are 20°C and the speeds of inlet cooling air are $2\text{ m}^3/\text{min}$. These temperatures rise drastically after the shutting down, and the simulated temperature of S5 is consistent with that of the measured temperature.

The threshold values of HST and room temperatures are adopted as 110 and 40°C to determine the abnormal state for the

Fig. 8 Contour lines of spatial failure probability versus x and years of operation

(a) Full load condition with no air conditioner cooling, (b) Full load condition with $2\text{ m}^3/\text{min}$, 20°C air conditioner cooling, (c) 10% load condition with $2\text{ m}^3/\text{min}$, 20°C air conditioner cooling

Table 4 Comparison of onsite data and simulations

Position/temperature	S1	S2	S3	S4	S5	S6
onsite data, $^{\circ}\text{C}$	29.1	29.0	29.2	34.0	34.8	34.5
simulation, $^{\circ}\text{C}$	28.2	28.2	28.2	35.2	36.9	35.2
absolute error, $^{\circ}\text{C}$	0.9	0.8	1.0	-1.2	-2.1	-0.7
relative error, %	3.09	2.76	3.42	3.53	6.03	2.03

10% loading level of transformer [17, 18]. The measured temperature of S5 reaches 40°C at $t_3 = 127$ min. The simulated S5 and HSTs rise to the corresponding thresholds at the same time $t_2 = 114$ min. After the time at the temperature threshold, the alarm signal can be triggered. The maximum failure probability computed by the proposed method is also shown in Fig. 10. The failure probability also rises significantly with the increasing of temperature and beyond the threshold value of 0.6 at $t_1 = 106$ min. The early warning signal can be generated by using the failure probability due to $t_1 < t_2 < t_3$. The finding implies that it is possible to detect the potential abnormal state of transformer room by the proposed method for the prediction of failure probability.

4 Conclusion

A spatial and temporal risk model for indoor/underground substation is developed based on three-dimensional temperature field simulations. Cooling strategies and power device operational status are firstly considered for failure probability analysis. This

Fig. 9 Relative errors between onsite data and simulation under different air conditioner cooling strategies
(a) Different cooling air temperature, (b) Different cooling air speed

Fig. 10 Measured and simulated temperatures, maximum failure probability during the shutting down process of air conditioners

model is capable of predicting temperature behaviour and failure rate of substations as well as power facilities. It is applicable in triggering early warning and alarm for condition monitoring system. Moreover, optimal substation design scheme cooling strategy and operational conditions could be obtained with thermal behaviour prediction and failure analysis. According to simulation results, some general conclusions are drawn:

- (1) A passive cooling method for dry-type transformer with protection cabinet is not effective as that for oil-type transformers, and active cooling strategy is necessary for high power dry-type transformer cooling.
- (2) As one of the cooling sources for indoor/underground transformer room, air conditioner has the advantages of easily controlled temperature and airflow volume, and it has

dehumidification function, which reduces the occurrence probability of partial discharge. The large discharge will result in the high-energy electric arc which is an unexpected heating source in transformers. However, compared to nature airflow ventilation, it is electricity consuming; the risk of air conditioner breakdown is also a threatening to power facilities. Carefully considerations should be taken before choosing a proper cooling method for indoor/underground transformer room.

(3) The highest temperature limit for dry-type transformer is different according to the insulation type, and that is much lower than oil-immersed transformer. It is necessary to simulate its thermal behaviour under different operation conditions with onsite environment before put it into use. Our model is a good choice for both power facilities and ambient environment thermal behaviour and service life prediction.

(4) The service life of power equipment, especially power transformer, is greatly affected by its load and cooling strategy. When the load is unchangeable, proper cooling and maintenance is essential to ensure safe and long-term operation.

5 References

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