Precise multi-dimensional temperature-rise characterisation of switchgear based on multi-conditional experiments and LPTN model for high-capacity application

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Abstract
As the power load increases, the capacity of switchgear becomes larger so the problem of overheating of switchgears becomes more significant. Whether the switchgears operate safely and reliably affects the reliability and economy of the entire power system. Different methods have been tried to study the thermal problems of switchgears. However, there are few experimental studies on the switchgear entity. In this study, a series of temperature rise tests were carried out on medium-voltage high-capacity switchgear to explore laws of temperature rise. First, five groups of multi-conditional experiments were carried out including changes of the load current, ventilation conditions and loop resistance. Then, multi-dimensional temperature-rise characterisation was analysed based on the experimental results and the relating theory. Finally, a circuit-based lumped-parameter thermal network (LPTN) model was developed by analysing the heat dissipation in switchgear and used to determine the steady-state temperature distribution of the switchgear. The model is verified by comparing the simulation results with the experimental results.

1 | INTRODUCTION

Switchgears are widely used in the power system to open, control and protect electrical equipment in the process of power generation, transmission, distribution and conversion. The development of the switchgear went through various development phases. In current distribution substations, the most frequently used switchgears are withdrawable metal-clad switchgears with vacuum circuit breakers. With the development of the power system, the capacity of the switchgears expands enormously but with smaller size which brings great challenges to the temperature rise of switchgears. Excessive temperature rise for a long time can weaken the mechanical strength of the conducting materials, bolted connections and dielectric insulation materials. What is more, overheating of the switchgears may shorten the lifespan of the switchgear or lead to catastrophic system failure. So it is necessary to explore the law of the temperature rise of switchgears and thoroughly analyse the temperature rise mechanism [1-4].

There are two approaches for the thermal analysis of electrical devices, modelling approaches and experimental approaches. The modelling approaches are mainly numerical method and the lumped-parameter thermal network (LPTN) method [5]. Numerical methods, known as computational fluid dynamics and finite element method are used to solve and analyse the coupling problems [6-10]. The main strength of numerical analysis method is that any complex geometry can be modelled in simulation software after some simplification. However, this method has a high demand for software and hardware capacity of the computer and is time-consuming.

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especially for switchgears in large capacity. Even sometimes, the finite element equations do not have convergent solutions. Therefore, researchers always focused on some important compartments or hot spots rather than the entity. In [11], the author studied the temperature rise of the bus-bar compartment by tests and simulations. In [12], an experimental study was conducted to establish a practical thermal design technique for the bolted connections between copper bus-bars in switchgears to determine the parameters that affect the contact resistance.

LPTN method, based on the analogy between Ohm's law of electrical conduction and Fourier's law of heat conduction, allows to lump a group of components of the same temperature to a single node and then forms a thermal circuit to represent the whole heat dissipation process in electrical devices. The parameters of the thermal circuit in LPTN model are obtained from the structural parameters of the equipment by simple calculation [13,14]. So this modelling method is easier to build and faster to calculate. LPTN model is widely used in the temperature prediction of GIS [15,16], transformers [17,18], motors [19-21] and other symmetrical power equipment. As the switchgear is big in volume and the thermal dissipation process is complex, there are only few LPTN models on the bus-bars other than the switchgear entity.

Moreover, the temperature distribution of electrical devices can be obtained by applying temperature sensors. However, when the large-size switchgear is in its normal working condition, it is difficult to measure the temperature inside the enclosure, even with small-size sensors like thermocouples. Temperature rise experiments can simulate the working state of switchgear and measure the temperature rise by using existing sensing techniques. However, there are few experimental studies on the whole switchgear entity. Therefore, more temperature rise tests should be done to have a more detailed and comprehensive understanding of switchgears.

In this paper, a medium-voltage, high-capacity switchgear-KYN28A-12Z was used to carry out temperature rise experiments by setting different experimental conditions to simulate the problems encountered in the operation of switchgears. Temperature rise variation rules are obtained by analysing the experimental data. In the meantime, LPTN model was developed by calculating thermal resistance of the switchgear to determine the temperature distribution of switchgear. The accuracy of this method is analysed through comparison with the experimental result.

2 | TEMPERATURE-RISE EXPERIMENT SETUP

The switchgear used in this paper is KYN28A-12(Z). The parameter characteristics are shown in Table 1 and the physical diagram is shown in Figure 1.

The switching cabinet is divided into four compartments, which are bus-bar compartment (A), instrument compartment (B), circuit breaker compartment (C) and cable compartment (D). The switchgear is equipped with three fans on the top of the bus-bar compartment, two fans on the top of the circuit breaker compartment, and two wind turbines at the front end of the overhead line room (below the circuit breaker compartment). The rated power of the fan is 60 W. The equivalent experimental circuit diagram is shown in Figure 2.

K-type thermocouples (omega 5TC-TT-K-40-36) are used for temperature monitoring because of its convenient installation and high accuracy. In the bus-bar compartment, the temperature sensors are placed at the static contact box outlet of A, B, C phases, the branch bus-bar and the overlap of the branch bus-bar and the bus-bar overlap as shown in Figure 3a. In the circuit breaker compartment, the sensors are placed at the up, down, left and right side of the upper and lower plum blossom contacts as shown Figure 3b; inside of the rear end of the circuit breaker contact arm as shown in Figure 3c; the up and left side of the outside of the contact arm rear end, the outside of the front of the circuit breaker contact arm as shown in Figure 3d; the static contact and the overlap of with bus-bar branch as shown in Figure 3e.

The settings of the standard temperature rise experiment is shown in Table 2 [22]. To obtain a more comprehensive understanding of the overheating of switchgears, a series of experiments are carried out based on the multi-conditions of the switchgear operation. In this paper, three main conditions are taken into account including the effect of bus-bar current, loop resistance and heat dissipation. The tests are divided into five groups (G1-G5), and the settings are shown in Tables 3-7 (to illustrate different issues, the same experiment will appear in different groups).

3 | TEMPERATURE-RISE CHARACTERISATION ANALYSIS COMBINED WITH THEORY AND TIME-VARYING AND LOCATION-VARYING EXPERIMENTAL RESULT

There are many factors affecting the thermal state of switchgears. From heat generation and heat dissipation, the bus-bar current, contact resistance and thermal convection of the switchgear matter the temperature distribution most.

The heat transmitted per second, also known as the thermal power, is Φ. The relationships between the current source and temperature rise are as follows:

| Parameter of the switchgear | Value |
|----------------------------|-------|
| rated voltage              | 12 kV |
| rated current              | 4000 A|
| rated short-time withstand current | 40 kA |
| rated peak withstand current | 100 kA |
| power frequency withstand voltage | 42 kV |
| lightning impulse withstand voltage | 75 kV |
| protection level           | IP4X  |
3.1 Influence of bus-bar current on temperature-rise

3.1.1 Effect of different three-phase balanced bus-bar current

Temperature-rise data of the plum blossom contact of phase-C in G1 with three-phase balanced current is shown in Figure 4.

These curve clusters show certain regularity in Figure 4. Curve fitting is used in Matlab to explore the relationship between current source and temperature rise and the result is shown in Table 8, where $\tau$ is the steady-state temperature rise value.

From the above fitting result, steady-state temperature rise increases dramatically with the increase of the load current. According to formulas (1) and (2), $\tau_s$ is proportional to the thermal resistance and square of the load current. However, the convection resistance and radiation resistance, which will be discussed later, are both related with temperature. Therefore, considering conduction, convection and radiation heat transfer together, the temperature rise is proportional to $I^\xi$, where $1 < \xi < 2$.

The relationship between $\tau_s$ and $I$ states as follows:

$$\frac{\tau_1}{\tau_2} = \left(\frac{I_1}{I_2}\right)^\xi$$

(3)

$$\xi = \log_{I_1/I_2}\left(\frac{\tau_1}{\tau_2}\right)$$

(4)

where $I_1$ and $I_2$ are different load currents, $\tau_1$ and $\tau_2$ are the steady-state values of temperature rise corresponding to $I_1$ and $I_2$, respectively. $\xi$ can be calculated by values of $\tau$ and $I$. Taking the data of upper plum blossom of phase-B into account, when $I_1 = 4400A$, $\tau_1 = 96.43A$, and $I_2 = 3150A$, $\tau_2 = 56.48A$, $\lambda = 1.653$. Taking all conditions into account, the average value of $\xi$, $\bar{\xi} = 1.618$. So formula (3) can be expressed as:

$$\frac{\tau_1}{\tau_2} = \left(\frac{I_1}{I_2}\right)^{1.618}$$

(5)

The calculation result is consistent with the relevant provisions in [23]. Suppose $I = 4400A$, then temperature rise of the switchgear at any current can be obtained, which provides a method for temperature monitoring and prediction [24].

3.1.2 Effect of three-phase unbalanced bus-bar current

The result of the data in G3 which has an unbalanced current is shown in Figure 5. It is obvious that when there is an
absence of one phase current, the stable values are all lower than the state of balanced current due to the decrease of the power losses. Therefore, when other factors are not limited (such as insulation conditions), the temperature rise during phase-absence operation will not limit the short-term operation of switchgear in case of failure. However, there are also conditions that the current is several times of the rated current, the steady-state temperature value would be greatly larger than that of the rated current according to formula (5), which will pose a great threat to the safety and reliability of the switchgear and should be avoided.

### TABLE 2 Conditions of the standard temperature-rise test

| Number | Condition |
|--------|-----------|
| 1 | $I = 1.1\times I_r = 4400$ A |
| 2 | $v = 0.5$ m/s |
| 3 | $f = 50$ Hz |
| 4 | $t_{\text{test}} = 8$ h or $\Delta T_{\text{h}} \leq 1$ K |
| 5 | ventilation on $T_{\text{max}} \geq 60$ K |

(1) $I_r$ is the rated current of the switchgear, $I_r = 4000$A, $I$ is the 3-phase balanced load current; (2) $v_{\text{air}}$ is the speed of the air flow at the experimental site; (3) $f$ is the frequency of the input current; (4) $t_{\text{test}}$ is the time of the temperature-rise test; $\Delta T_{\text{h}}$ is the temperature difference within 1 h; (5) $T_{\text{max}}$ is the highest temperature of the switchgear.

### TABLE 3 G1: The effects of load current

| Aim | Test No. | Experimental setting |
|-----|---------|---------------------|
| effects of load current | 1 | $I = 4400$ A, no ventilation |
| | 2 | $I = 3150$ A, no ventilation |
| | 3 | $I = 2500$ A, no ventilation |
| | 4 | $I = 1600$ A, no ventilation |

### TABLE 4 G2: The effects of convection heat dissipation

| Aim | Test No. | Experimental setting |
|-----|---------|---------------------|
| effects of heat convection | 1 | $I = 4400$ A, no ventilation |
| | 2 | $I = 3150$ A, no ventilation |
| | 3 | $I = 3150$ A, with ventilation |
| | 4 | $I = 4400$ A, with ventilation |

### TABLE 5 G3: The effects of unbalanced current

| Aim | Test No. | Experimental setting |
|-----|---------|---------------------|
| effects of unbalanced current | 6 | $I_A = I_B = I_C = 4400$ A |
| | 8 | $I_A = I_C = 3150$, $I_B = 0$ |
| | 9 | $I_B = I_C = 3150$, $I_A = 0$ |

### 3.2 Influence of contact resistance on temperature-rise

Heat in the switchgear is generally produced because of the resistance in the conductive loop. Ignoring the change of copper resistivity caused by temperature variation, the resistance of copper bus-bars is obtained by formula (6) and the contact resistance especially at the plumb blossom contact is calculated by formula (7) [10]

$$R_c = \rho \frac{L}{S}$$  \hspace{1cm} (6)

$$R_j = \frac{k_j}{(0.102F)^{m}}\mu \Omega$$  \hspace{1cm} (7)

where $\rho$ is the copper resistivity (\Omega\cdot m), $L$ is the length of the copper bus-bar (m), $S$ is the cross-sectional area of copper bus-
TABLE 6  G4: The effects of contact condition of the plum blossom

| Aim                                      | Test No. | Experimental setting                      |
|------------------------------------------|----------|-------------------------------------------|
| effects of contact condition of the plum blossom | 6        | $S_b, n = 84, R_A = 23 \ \mu\Omega, R_B = 23 \ \mu\Omega, R_C = 22 \ \mu\Omega$ |
|                                          | 10       | $S_b, n = 64, R_A = 27 \ \mu\Omega, R_B = 27 \ \mu\Omega, R_C = 28 \ \mu\Omega$ |
|                                          | 11       | $S_b, n = 84, R_A = 45 \ \mu\Omega, R_B = 33 \ \mu\Omega, R_C = 44 \ \mu\Omega$ |
|                                          | 12       | $S_b, n = 64, R_A = 29 \ \mu\Omega, R_B = 27 \ \mu\Omega, R_C = 28 \ \mu\Omega$ |

(1) $S_b$ indicates the breaker of the switchgear works in a normal position; $S_1$ indicates the breaker of the switchgear works in a under position; $S_2$ indicates the breaker of the switchgear works in the over position; (2) $n$ is the number of the fingers of the spring contact; (3) $R_A$ is the circuit resistance of phase-$A$; so with $R_B$ and $R_C$.

TABLE 7  G5: The effects of the bolt torque on the bus-bar overlap

| Aim                                      | Test No. | Experimental setting                      |
|------------------------------------------|----------|-------------------------------------------|
| effects of the bolt torque on the bus-bar overlap | NO.6     | $T = 160 \ \text{Nm}, R_A = 23 \ \mu\Omega, R_B = 23 \ \mu\Omega, R_C = 22 \ \mu\Omega$ |
|                                          | NO.13    | $T = 80 \ \text{Nm}, R_A = 23 \ \mu\Omega, R_B = 23 \ \mu\Omega, R_C = 22 \ \mu\Omega$ |
|                                          | NO.14    | $T = 50 \ \text{Nm}, R_A = 24 \ \mu\Omega, R_B = 24 \ \mu\Omega, R_C = 22 \ \mu\Omega$ |
|                                          | NO.15    | $T = 0 \ \text{Nm}, R_A = 29 \ \mu\Omega, R_B = 30 \ \mu\Omega, R_C = 23 \ \mu\Omega$ |

(1) $T$ is the torque applied to the bolt of the bus-bar overlap.

To explore the influence of the resistance change on the temperature-rise, equivalent experiments are given in this paper. The possible bad contact conditions in actual operation are simulated by changing the number of contact fingers of plum blossom contacts. At the same time, over-position and under-position which may happen in actual working conditions are discussed. Contact resistance of the bus-bar overlap is simulated by changing the torque at the bus-bar connection. The detailed analyses are discussed as follows.

3.2.1 Effect of contact resistance of the plum blossom

For the plum blossom contact, $k_1 = 100$, $F = 40$ N and $m = 0.7$ in formula (7). As the plum blossom contact consists of spring-tightened fingers, the change of temperature can lead to the shrinkage of the spring, which will finally cause the increase of the contact resistance. Aging of conductive glue, oxidation, dust accumulation and peeling off of the tin plating layer can also increase the contact resistance. Data of G4 by changing the number of the contact fingers from $n = 84$ to $n = 64$ is shown in Figure 6a. For $n = 64$, circuit resistance increases by 4 $\mu\Omega$, bringing about 4 K temperature-rise. For more serious cases, there will be a higher temperature-rise, bringing greater harm to the normal operation of switchgear.

Figure 6b shows the result of the circuit breaker in under-position ($S_1$) and over-position ($S_2$). Temperature rise of conditions $S_1$ and $S_2$ is larger than that of normal condition ($S_0$). Temperature rise is 8 K higher when the circuit breaker is not in the proper position and the contact fingers are in poor contact conditions.
3.2.2 Effect of contact resistance of the overlap of bus-bar

Bus-bar is connected by bolt at the turning point in switchgear. In normal condition, the torque at the overlap equals to 160 Nm. When $T = 80$ Nm, the temperature rise is unchanged; when $T = 50$ Nm, the temperature-rise rises slightly, which is about 6 K higher than that of $T = 160$ Nm; when $T = 0$ Nm, the temperature-rise changes by 20 K shown in Figure 7.

Although the case of $T = 0$ Nm rarely occurs but we need to note that the electric force under long-term operation of the switchgear will loosen the bolt and resulting in greater contact resistance. What is more, the thermal expansion of metals caused by high temperature will change surface contact between metals into point contact, which will further increase the contact resistance here.

3.3 Influence of heat dissipation on temperature-rise

3.3.1 Ways of heat dissipation in switchgear

There are three basic ways of heat transfer in switchgear: heat conduction, heat convection and heat radiation [25,26].

i. Heat conduction: As the temperature of the conductor increases with the current flowing through, so does the temperature of other parts in contact with it. This kind of contact between objects, or the heat transfer between parts of an object, is heat conduction. The mechanism is the transfer of molecular kinetic energy between objects with
different temperatures. That is, molecules with higher kinetic energy (higher temperature) transfer energy to molecules with smaller kinetic energy (lower temperature) adjacent to them. According to Fourier’s law, thermal resistance of conduction for plate heat conduction is analysed

$$\frac{\Theta}{T} = \frac{\tau}{l/\lambda A} = \frac{\tau}{R_t} (W)$$

where $\lambda$ is heat conductivity (W/m$^\circ$K), $A$ is the area of the plate (m$^2$), $l$ is the thickness (m), $\tau$ is the temperature difference between two sides of the plate (K), $\Theta$ is the heat transmitted per second or the heat power or flow rate (W), $R_t$ is the equivalent thermal conduction resistance (K/W).

ii. Heat convection: The heat transfer process of fluid flowing through an object surface is called convective heat transfer. Convection heat transfer can be divided into natural convection and forced convection. Natural convection is caused by the different densities of the cold and hot parts of the fluid. If the flow of fluid is caused by other pressure differences such as fans, it is called forced convection. The basic calculation formula of convective heat transfer is Newton’s formula

$$\frac{\Theta}{T} = \frac{\alpha A (\theta_1 - \theta_2)}{R_t} = \frac{(\theta_1 - \theta_2)}{R_t} (W)$$

where $A$ is the area in contact with the fluid (m$^2$), $\alpha$ is the coefficient of heat convection [W/(m$^2$·°K)], $\theta_1$ is the temperature of the object surface (K), $\theta_2$ is the average temperature of the fluid (K), $R_t$ is the equivalent thermal convection resistance (K/W). However, convection is a very complex phenomenon. It is affected by the physical properties of the fluid such as density, viscosity, and thermal conductivity etc. Moreover, coefficient $\alpha$ is affected by the state of fluid flow, such as natural convection or forced convection, laminar or turbulence flow.

In switchgear, the forced convection is mainly laminar flow. There are two kinds of convective heat transfer modes: convection sweeping the surface of an object and convection across the surface of an object. The convective heat transfer coefficient can be got from formulas (10) and (11), respectively

$$Nu = \frac{\alpha l}{\lambda} = 0.664Re^{1/2}Pr^{1/3}$$

(10)

$$Nu = \frac{\alpha l}{\lambda} = C_{Re}^n Pr^{1/3}$$

(11)

$$Re = \frac{ul}{v}$$

(12)

where $u$ is the air velocity (m/s), $l$ is the length for the object or the diameter for a cylinder (m), $v$ is the Kinematic viscosity (m$^2$/s), $Re$ is the Reynolds number, $Pr$ is one of the physical parameter $C$ is determined by $Re$.

Heat radiation: Unlike conduction and convection, heat can transfer in vacuum without transfer medium. The radiation energy radiated by an object depends on its nature, surface condition (colour, roughness etc.), surface area and surface temperature and so on. The heat exchanged between two objects through radiation can be expressed as the following equation:

$$\frac{\Theta}{T} = \frac{\varepsilon \sigma_0 A (T_1^4 - T_2^4)}{R_t} = \frac{(T_1 - \theta T_2)}{R_t} (W)$$

(13)

where $A$ is the radiated surface area of an object (m$^2$), $T$ is the absolute temperature of the surface (K), $\sigma_0$ is the Boltzmann constant [W/(m$^2$·°K)], its value is $5.67 \times 10^{-8}$ [W/(m$^2$·°K)], $\varepsilon$ is the emissivity of the object, and it is less than 1, $R_t$ is the thermal radiation resistance (K/W).

Related factors affecting heat conduction are difficult to change in the experiment while factors affecting convective heat dissipation are easy to change. So only convective heat dissipation is discussed in this paper.

3.3.2 Effect of heat convection by changing ventilation conditions

According to formula (9), factors affecting convective heat dissipation are the contact area and coefficient of heat convection. Since the area is hard to change in switchgear, methods are taken to change the coefficient of heat convection by opening and closing the fans. Experiments are carried out at
\( I = 3150 \) and 4400 A with and without fans, respectively, in G2. Data of the plum blossom contact of phase-C is shown in Figure 8.

Figure 8a shows the difference when \( I = 3150 \) A and Figure 8b shows the difference when \( I = 4400 \) A. For the dot line, fans are on from time \( t_1 \); for the line, fans are off from the beginning but have to be turned on from time \( t_2 \) for the temperature exceeds the limit of the switchgear. The opening of the fan makes the convection change from natural convection to forced convection, the convective heat transfer coefficient larger and the time required to reach steady state shorter. In Figure 8a, the steady state temperature rise value when fans are off is more than twice of that when fans are on, which means the convection heat transfer takes nearly 60–70% of the heat in the switchgear. So fans play an important role in accelerating heat dissipation and reducing temperature of switchgear. In switchgear, fans are selected with proper power to dissipate enough heat to avoid excessive temperature. However, according to Schroeder and Gibson [27] fans for heat dissipation are one of the ten most vulnerable electronic products to failure. Its failure easily leads to the reduction of air flow and the reduction of convective heat transfer performance. So it is necessary to check the fan's health state in the annual inspection of switchgears.

The location-varying experimental result-part of the temperature distribution of the switchgear is shown in Figure 9. By analysing the temperature distribution of the whole switchgear, temperature of the circuit breaker is generally higher than that of other parts in switchgear basically because of the high resistance and difficult heat dissipation. Temperature of the plum blossom is even higher. To avoid the fault caused by overheating inside of the circuit breaker, effective measures should be taken to monitor or early warn the temperature here.

4 | LPTN MODEL OF SWITCHGEAR

4.1 | LPTN model based on analogy of thermal and electrical circuit

The temperature-rise experiment is the most accurate way to get the temperature distribution of switchgear. However, when the switchgear has to be modified and redesigned, it is necessary to rebuild the temperature-rise experimental platform for testing for times. This method is not appropriate to the structural modification and design of switchgear. In this paper, LPTN method is used to obtain the temperature
distribution of switchgear. LPTN method utilises the analogy between electric and thermal quantities. The comparison is shown in Figure 10 and Table 9.

4.2 Developed steady-state thermal model

When the heat produced equals to the dissipated, the temperature-rise of the switchgear reaches a steady state. As mentioned above, the time from the beginning of temperature change to a steady state is called the time constant. In switchgear, the temperature distribution at the maximum temperature rise is very important for the reliable operation of switchgear. Therefore, in this paper, the steady-state thermal model of the switchgear is established to explore the steady-state temperature distribution.

The switchgear is huge in volume. Power loss is distributed in all places where there is resistance. According to the structural characteristics, the switchgear is divided into three parts: the inlet bus-bar (I), the vacuum circuit breaker (II) and the outlet bus-bar (III). The steady-state lumped thermal model of single phase is shown in Figure 11.

Because of long length of the inlet bus-bar, it is divided into the upper part and the lower part, representing by node 1 and node 8. Nodes 9 and 10 represent the upper and lower arms of the vacuum circuit breaker, respectively. Node 9 represents the pole of the vacuum circuit breaker. Node 8 represents the outlet bus-bar. P1-P8 represent the losses at the corresponding locations. Tl is the temperature at the inlet bus-bar, Tb is the temperature of the air in room D in Figure 1, Te is the temperature of the air in circuit breaker, Td is the temperature of the air in room A and Tc is the temperature at outlet bus-bar. Heat can be transferred in both axial and longitudinal directions. Rm and Rm (i = 1–6) represent the conduction thermal resistance of the inlet bus-bar, circuit breaker and outlet bus-bar. Rm represents the conduction thermal resistance from copper to the coated epoxy resin, Rm-Rm represent the convection and radiation thermal resistance to the surrounding air. When calculating the whole switchgear, including phase A, phase B and phase C. We use Rmn (m represents phases A, B, C; n represents nodes 1-8) to express the heat transfer process between three-phases which is not shown in Figure 11.

The thermal model is established in Matlab/Simulink. In practice, the load current of switchgear is about 50% of the rated current. Therefore, the load current value is set to 2500 A in simulation. The simulation result is shown in Figure 12.

The bar chart in the figure above shows the temperature rise of experiment and simulation result, and the line shows the error between them. In Figure 12, there are six nodes of each phase and the maximum relative error is about 11% in node 4. Errors of other nodes are <3%. We can say that the developed thermal model can basically reflect the temperature distribution of switchgear.

5 DISCUSSION

As the switchgear is a closed entity, its on-line temperature monitoring has always been a difficult problem, especially the hot spot temperature. The temperature at the contacts of circuit breakers, for example, is difficult to measure with existing temperature sensors. To realise direct on-line temperature monitoring of switchgear, new types of sensors or new monitoring methods have to be developed. A wireless temperature sensor is developed in our lab shown in Figure 13, which can be tied to the contactor arm of circuit breaker and
obtain energy by electromagnetic induction, and the details will be discussed further. At the same time, the temperature-rise experiments or the LPTN model can provide the temperature difference between the monitoring point and the unknown point. Therefore, we can get the temperature of any point by the new sensor and easy calculation.

6 | CONCLUSION

In this paper, multi-conditional experiments including changes of bus-bar current, contact resistance and heat dissipation conditions were carried out for the purpose of exploring temperature-rise characterisation of switchgears. Conclusions can be drawn from the above analyses:

i. The multi-dimensional including time-varying and location-varying temperature-rise characterisation was discussed in detail. The curve of temperature-rise with time varying is similar to the first-order step response. The location-varying result shows temperature of the circuit breaker even the plum blossom contact is the most serious part in the switchgear. However, the temperature here is also the most difficult to monitor. The temperature-rise experiment is the first method to obtain the temperature-rise distribution of the high-capacity application.

ii. The temperature-rise value of steady state is exponential to the load current. Formula (5) also indicates that if the switchgear works under the condition of over-current, overheating of the switchgear will be very serious. This is the first method in this paper to determine the temperature of the hot spot at any load current.

iii. LPTN model, based on the analogy of thermal circuit and electrical circuit, is established. An average 5% error simulation result shows that this method has a certain accuracy. It provides another way to realise on-line temperature monitoring of switchgear.

iv. Combined with temperature-rise experiment, the use of a wireless sensor which can monitor the temperature near the measuring point will become a more direct way of temperature monitoring.

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