Numerical simulation of the condensation process in high voltage switchgear based on the temperature and humidity distribution

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Abstract: The condensation on solid materials surface inside switchgear is an important reason threatening its safety and reliability. The formation of condensation is closely related to the temperature and humidity distribution inside the switchgear. A 3-D simplified finite element calculation model for the switchgear is established, including the bus bar, the wall bushing, the circuit breaker, the cables and other key components. Based on the electromagnetic-temperature-humidity multi-physical field coupling method, the temperature distribution inside the switchgear are calculated when the operating current flows through the bus-bar. Furthermore, the humidity diffusion process is also calculated when the relative humidity of the external environment was 0.8, and the relative humidity inside the switchgear is obtained. The calculation results show that the surface humidity of the contact box of the circuit breaker is the highest whereas the temperature is the lowest, which is the location where the condensation is easy to occur.

1. Introduction
With the rapid development of the power system, high voltage switchgear is widely used due to its compact structure and occupying small area. At present, the high voltage switchgear gradually tends to be miniaturized, the distance between metal conductors and ground electrode is reduced. At this time, it is necessary to strictly control the humidity inside and outside the switchgear. Once the moisture diffuses into the switch cabinet, it is difficult to eliminate the moisture via natural convection due to the compact structure of switchgear [1]. The remained moisture is conducive to forming condensation on the surface of metal conductors and insulating materials, especially at low temperature. The occurrence of condensation seriously affects the insulation performance and service life of insulating materials as well as the function of metal conductor in the switchgear, which poses a serious threat to the safe and stable operation of the switchgear [2, 3].

The condensation phenomenon has been extensively investigated by lots of scholars. K. N. Rhee et al analyzed the formation conditions of condensation of water vapor [4]. Some others proposed useful measures to improve the temperature and humidity distribution inside the switchgear such as the heating plate, semiconductor dehumidification and air conditioning. In terms of theoretical research, simple models are mostly used to study the temperature and humidity distribution inside the switchgear [5]. However, at present, the mechanism of condensation phenomenon in the switchgear still lacks deep understanding. It is urgent to establish the accurate simulation model to study the
condensation process inside the switchgear. In this study, a simulation calculation model is established to investigate the temperature and humidity distribution inside the switchgear. It is hoped that the research results can provide theoretical guidance for the anti-condensation design of switchgear.

2. Description of the simulation model

2.1. The computation of electro-magnetic, temperature and humidity coupling field

When a large current flows through the high voltage conductor in the switchgear, Joule heat is generated due to the eddy current loss. The heat inside the switchgear mainly radiates towards the surrounding environment through natural convection, heat exchange and heat radiation, resulting in the increase of gas temperature in the switchgear [6]. The relationship between the temperature and the heat inside the switchgear satisfies the following equation (1). The heat transfer process mainly includes the heat conduction between high voltage conductor and insulating materials, the heat convection and radiation between high voltage conductor/grounded enclosure and surrounded gas, as presented by equation (2).

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \lambda \frac{\partial T_1}{\partial x})}{\partial x} + \frac{\partial (\rho \lambda \frac{\partial T_1}{\partial y})}{\partial y} + \frac{\partial (\rho \lambda \frac{\partial T_1}{\partial z})}{\partial z} + Q
\]

\[
q = k_c(T_1 - T_{ab}) + \varepsilon \sigma(T_1^4 - T_{ab}^4)
\]

Here, \(c\) is the Specific heat capacity of involved materials. \(\rho\) is the density of involved materials. \(T_1\) is the temperature inside the switchgear. \(t\) is the time. \(x, y, z\) is the direction of the coordinate axis. \(\lambda\) is the thermal conductivity. \(Q\) is the generation rate of the volumetric heat. \(q\) is the heat. \(k_c\) is the coefficient of heat convection. \(T_2\) is the surface temperature of conductor and insulating material. \(T_{ab}\) is the temperature of environment. \(\varepsilon\) is the thermal emissivity of solid surface. \(\sigma\) is the Boltzmann constant, \(1.38 \times 10^{-23}\) J/K.

The moisture transfer process inside the switchgear satisfies the Fick diffusion law, as displayed by equation (3).

\[
\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} = \frac{1}{D} \frac{\partial C}{\partial t}
\]

Here, \(C\) is the content of the moisture. \(D\) is the diffusion coefficient of moisture.

The moisture content is often discontinuous at the interface of different materials, while the relative humidity is continuous [6]. The relative humidity distribution \(W\) inside the switchgear can be calculated by equation (4).

\[
W = \frac{C}{C_{sat}}
\]

\[
\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} + \frac{\partial^2 W}{\partial z^2} = \frac{1}{D} \frac{\partial W}{\partial t}
\]

Here, \(W\) is the relative humidity. \(C_{sat}\) is the saturated moisture content.

2.2. The simulation model of temperature and humidity distribution inside the switchgear

The switchgear cabinet contains many different devices distributed in different rooms such as bus room, cable room and circuit breaker room. In order to improve the efficiency of numerical computation, the simplified simulation model is established, as presented in figure 1.
In this model, the bus bar, circuit breaker, contact box, wall bushing, and cables are considered. The overall size of the switchgear is about 2.8m×1.4m×2.6m. The mainly involved materials contain copper, epoxy resin and surrounded air. The electrical and thermal parameters are displayed in table 1.

| Materials | Electric conductivity/(S·m⁻¹) | Thermal conductivity/(W·m⁻¹·K⁻¹) | Heat capacity/(J·kg⁻¹·K⁻¹) | Relative permittivity |
|-----------|-------------------------------|-----------------------------------|----------------------------|----------------------|
| Copper    | $5.9 \times 10^7$             | 400                               | 385                        | 1.0                  |
| Epoxy resin | $4.6 \times 10^{-16}$       | 0.5                               | 260                        | 3.2                  |
| Air       | $4.6 \times 10^{-10}$        | 5.2                               | 620                        | 1.0                  |

In the calculation of temperature distribution, the current flows through bus bar, and the magnitude is 1250A. The temperature of external environment is 293K. In the calculation of humidity distribution, the relative humidity of external environment is 80%. At the initial period, the interior of switchgear is in a dry state. The overall simulation lasts about 55hours. The equation (1) and (4) are highly similar, which indicates that the computation of humidity distribution can be determined by referring to the calculation of temperature distribution.

3. Simulation results

3.1. The temperature distribution inside switchgear

When the large current flows through bus bar, the Joule heat is generated. Since the difference in heat transfer rate between metal conductor and the insulating materials, the temperature inside the switchgear is non-uniformly distributed. The calculation result of temperature distribution is displayed in figure 2. The generated Joule heat is mainly due to conductive loss from the current flowing through the resistance, including the resistance of the metal conductor and the contact resistance between the bus bar and other components. In addition, it can be seen that the temperature distribution on the surface of three-phase conductors is non-uniform. The temperature on conductors of phase A and C is lower than that of phase B (located at the centre in figure 2). This is because that the heat transfer of the three-phase conductor is mainly through thermal radiation and heat convection with the surrounding air. The conductor of phase B is located between phase A and C, resulting in that its heat dissipation conditions are worse than those of phase A and C. Therefore, the temperature on conductor of phase B is higher than that of phase A and C. As for insulating materials, the temperature on the contact box of the circuit breaker is higher than that of the wall bushing, which is mainly because that the structure of the contact box is semi-hollow and the heat is difficult to diffuse. In addition, the
temperature distribution of the three-phase contact box is also uneven. On the one hand, it is closely related to the temperature on the contact terminal of the circuit breaker. On the other hand, the low heat dissipation rate of the contact box due to its semi-hollow structure is also an important reason for the uneven temperature distribution.

![Figure 2: The temperature distribution inside the switchgear](image)

3.2. The relative humidity distribution inside the switchgear

When the relative humidity of external environment is about 0.8, it is found from the simulation that when the moisture diffuses naturally over 30 hours, the steady state is realized. The calculated relative humidity distribution at steady state inside the switchgear is presented in figure 3. It can be seen that the distribution of relative humidity inside the switchgear is more uniform compared to the temperature distribution. The humidity distribution on different components of each phase is almost the same. The average relative humidity distribution of contact box is higher than that of three-phase metal conductor and wall bushing. The relative humidity at the locations contacting with the switchgear shell in the three-phase cable and wall bushing is higher than that in other locations. It is mainly because the initial relative humidity of the switchgear metal shell is the highest.

![Figure 3: The relative humidity distribution inside the switchgear](image)

3.3. Analysis on the formation of condensation

When the water vapour in the air gets oversaturated, the condensation would occur if wet air on the surface of low-temperature solid materials reaches the dew point temperature. Therefore, if the relative humidity inside the switchgear is very high, and the wet air contacts with low-temperature solid materials such as metal conductor and insulating materials, the wet air would condense to form droplets accumulating on insulating materials surface. The electrical insulation performance will be reduced greatly and the surface flashover may be incurred, thus bringing hidden dangers to the safe operation of the switchgear.
The condensation occurs more easily on insulating materials surface, such as contact box of circuit breaker, wall bushing and three-phase cables. The average temperature and humidity on the surface of these materials are shown in figure 4. It can be seen that the difference in the temperature of the contact box, the cable and the wall bushing is small. The steady temperature is about 325K. From figure 4(b), there is a great difference in relative humidity among the three. The relative humidity on the surface of the contact box is the largest, and there is little difference between the cable and the wall bushing. At steady state, the average relative humidity on the surface of the contact box is about 0.43, while that on the cable and wall bushing is close to 0.3. According to the formation conditions of the condensation, the wet air is easy to condense on the surface of the contact box due to the high humidity and low temperature on its surface. In the long-term operation, the wet air will diffuse to the surface of the dynamic and static contact terminals of the circuit breaker, leading to the corrosion of the contact terminals and ultimately damaging the breaking performance of the circuit breaker. Therefore, it is necessary to find protective measures to inhibit the formation of condensation on the surface of the contact box.

![Figure 4](image_url)

(a) The average temperature (b) The average relative humidity

4. Conclusions

This study investigates the formation of condensation inside the switchgear by numerical simulation method. The temperature and relative humidity distribution on metal conductors and insulating materials are obtained. The temperature of the bus bar inside the switchgear rises fastest, and the temperature distribution of the three-phase contact box of circuit breaker is uneven. The moisture absorption rate of insulating materials is higher than that of metal materials. Compared with wall bushing, it is difficult for the contact box to repel the moisture because of its semi-hollow structure. Above all, the contact box has the highest humidity and the lowest temperature, which is the most vulnerable component suffering the condensation.

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