Analysis of Condensation Problem in High Voltage Switchgear and Design of Anti-condensation System

Hu Jinlei¹, Li Yangyang¹, Lai Junju¹, Wang Wei¹, Yang Fan², Liu Yuhang², Zhao Yao²

¹Guangdong Power Grid Co., Ltd. Qingyuan Power Supply Bureau, Qingyuan, Guangdong, 511500, China.
²College of Electrical Power Engineering, Shanghai University of Electric Power, Shanghai, 200090, China

*Corresponding author’s e-mail: zhaoyao@shiep.edu.cn

Abstract. The southern region is hot, rainy and humid, and the switchgear is prone to moisture and condensation during long-term operation in this environment, causing partial discharge and other failures. To solve the problem that the switchgear is prone to condensation, this paper studies the conditions for the condensation phenomenon and analyses the condensation temperature calculation curve based on the air temperature and relative humidity in the cabinet. Then a three-dimensional model of the switchgear was established, and the thermal-electric coupling finite element simulation was performed to obtain the spatial temperature distribution of the switchgear under long-term operation and different humidity states. The simulation results are combined with the condensation temperature calculation curve to study the condensation situation of the switchgear under different conditions and the parts prone to condensation. Finally, according to the analysis results, a moisture-proof and anti-condensation control and early-warning system based on optical fiber temperature and humidity sensor is provided to detect the data in the cabinet and conduct comprehensive research and judgment, which provides theoretical basis for anti-condensation and intelligent operation and maintenance of switch cabinet.

1. Introduction
The switchgear plays a role in controlling and protecting electrical equipment in the power system [1]-[3]. When the switchgear is operated in a high temperature and high humidity environment for a long time, it is easy to produce condensation, and may cause insulation breakdown, cause partial discharge, cause a short circuit, power failure, and other problems, and cause great damage to power system equipment [4]-[5].

Given the problem of switchgear condensation, In paper [6], related factors of switchgear condensation were studied, and related measures and improvement methods of anti-condensation were studied, and the anti-condensation plan of dry air source dehumidification system was proposed. In [7], starting with the air humidity and structure of the switchgear, the influence of relative air humidity on the operation of the switchgear is discussed. From the perspective of operation and maintenance, a strategy to prevent condensation based on the humidity threshold is proposed. Paper [8] aimed at the problem of easy condensation on the surface of insulators, a condensation simulation experiment platform was established to study the influence of temperature difference, relative humidity, pollution, and other factors on the condensation state of the composite insulation surface, and summarized the
occurrence and Distribution form. In the paper [9], by constructing a simulation experiment of the condensation problem, the influence of different roughness on the condensation degree under different environmental conditions was analysed, and the relationship between the roughness of the cabinet wall, the temperature difference, the moisture content and the condensation phenomenon was obtained. In paper [10] analysed the advantages and disadvantages of the three main anti-condensation methods of switchgear based on the mechanism of switchgear condensation, and based on the principle of dry air dehumidification, gave the dry air source and the airflow in the cabinet Combined anti-condensation measures. The above studies are mostly based on basic theories and simple experiments to analyse the relationship between temperature, humidity, and condensation.

This paper studies the occurrence of condensation in switchgear, based on the conditions of condensation, the relationship between air temperature and relative humidity in the cabinet and condensation is analysed, and the condensation temperature calculation curve is obtained. Then through the finite element simulation analysis, the spatial temperature distribution of the switchgear under long-term operation and different humidity states is obtained. Combined with the condensation temperature calculation curve, the condensation situation of the switchgear under different conditions and the parts prone to condensation are analysed. Finally, based on the simulation results, a reasonable anti-condensation strategy is proposed, and a control system based on the optical fiber temperature and humidity sensor is designed to lay the foundation for the safe and stable operation of the switchgear.

2. Analysis of Condensation Problem in Switchgear

2.1. Condensation

The water vapor in the air has exceeded its maximum containment capacity, making the water vapor liquefy on the surface of the low-temperature object immediately after reaching the condensation temperature and become a liquid. This phenomenon is called condensation [11]. Among them, the condensation temperature refers to the temperature at which water vapor saturated in the air is converted into liquid droplets on the surface of a low-temperature object under a certain atmospheric pressure. The condensation phenomenon of the switch cabinet is because the condensation temperature of the air in the cabinet is higher than the surface temperature of the object, forming a temperature difference, causing the water vapor to condense into liquid droplets on the surface of the object. Aiming at the problem of condensation, it is mainly considered from the two factors of air temperature and relative humidity in the cabinet.

2.2. Condensation temperature

The relative humidity $\phi$ (unit %RH) is the percentage of the ratio of the vapor pressure $p_v$ in the humid air to the saturated vapor pressure $p_s$ of water at the same temperature, and its expression is:

$$\phi = \frac{p_v}{p_s} \times 100\%$$ (1)

According to Magnus formula [12], when the air temperature is $t$ °C ($t>0$), the saturated steam pressure $p_s$ of water is

$$p_s = p_0 \times 10^{\frac{a(t)}{b+t}}$$ (2)

In the equation (2): $p_s$ is the saturated water vapor pressure when the temperature is $t$ °C, hPa; $p_0 = 6.11hpa$, is the saturated water vapor pressure when the temperature is 0 °C; $a$ and $b$ are the correction coefficient coefficients, when $t>0$ °C, take the water surface value $a=7.5$, $b=237.3$, corrected according to the Goff-Grattch formula, take $p_0=6.10695hpa$, $a=7.59271$, $b=240.72709$, then the equation is

$$p_s = p_0 \times 10^{\frac{a(t)}{b+t}} = 6.10695 \times 10^{\frac{7.59271t}{240.72709+t}}$$ (3)

According to the saturated vapor pressure formula and the correction coefficient of Magnus shunt, the equation for calculating the condensation temperature is obtained:
Where \( T_d \) is the condensation temperature, °C; \( a \) and \( b \) are correction coefficients; \( p_0 \) is the saturated water vapor pressure at a temperature of 0 °C, and the value is 6.11 hPa; \( p_v \) is the water vapor pressure in humid air; \( p_s \) is the same. The saturated vapor pressure of water at temperature.

According to equation (4), the condensation temperature calculation curve based on relative humidity and air temperature is obtained, as shown in Figure 1. Combined with the condensation problem of the switchgear, it can be seen that two main factors are affecting the condensation temperature: the air temperature in the cabinet \( t \) °C, and the relative humidity of the air in the cabinet \( \phi \% \text{RH} \).

2.3. Temperature field and condensation phenomenon in switch cabinet

As shown in Figure 2 for the structure of the switchgear cabinet, due to the different heating conditions of electrical components in different rooms during the operation of the switchgear, the gas temperature distribution in each room is different [13], which leads to the air temperature near the heating components and the inner wall of the cabinet. The temperature difference is large, causing condensation. In response to this problem, this paper considers the gas temperature of each part of the switchgear during operation and studies the specific parts of the condensation phenomenon.
The heat transfer process inside the switchgear mainly includes heat conduction between high-voltage conductors and insulating materials, convective heat transfer and heat radiation between high-voltage conductors and air, and convective heat transfer and heat radiation between the switchgear enclosure and the surrounding air[14]. The heat transfer process can be expressed by:

\[ q = k(T_s - T) + \varepsilon \sigma (T_s^4 - T^4) \tag{5} \]

Where \( q \) is the amount of heat transfer; \( k \) is the convective heat transfer coefficient; \( T_s \) is the surface temperature; \( T \) is the air temperature; \( \varepsilon \) is the heat generation rate; \( \sigma \) is the Boltzmann constant, \( \sigma = 1.38 \times 10^{-23} \text{J/K} \).

When a large current flows through the bus bar in the switch cabinet, Joule heat is generated on the metal conductor, which spreads in the space through heat convection and thermal radiation, causing the temperature of the gas in the switch cabinet to rise. The relationship between the internal temperature distribution of the switch cabinet and the heat is:

\[ \nabla \cdot \left( \rho \frac{\partial T}{\partial t} - \lambda \nabla T \right) + \frac{\partial}{\partial x} \left( \rho c_p \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho c_p \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \rho c_p \frac{\partial T}{\partial z} \right) = Q \tag{6} \]

Where: \( c \) is the specific heat capacity, \( \rho \) is the density, \( T \) is the gas temperature in the switchgear, \( \lambda \) is the thermal conductivity, \( Q \) is the Joule heat generated by the conductor, and \( x, y, \) and \( z \) are the three-dimensional directions.

Since the series of processes of heat generation, conduction, convection, and radiation involves the interaction of multiple physical fields and are closely related, the partial differential equations that characterize the above processes have strong nonlinearity. For this kind of coupled field problem, the finite element analysis method can be used to solve it.

3. Simulation analysis

Figure 3 shows the three-dimensional model of the KYN armored handcart cabinet. This model retains the components of the busbar compartment and cable compartment and simplifies the instrument room and circuit breaker room. The material of the bus bar, contact, and contact arm is copper, and the insulating sleeve and contact box are made of epoxy resin. Table 1 shows the materials of each part of the switch cabinet.

| material               | density /kg/m³ | Specific heat /J·K⁻¹·K⁻¹ | Resistivity /Ω·m | Thermal conductivity /W·m⁻¹·K⁻¹ |
|------------------------|----------------|---------------------------|------------------|-------------------------------|
| Copper conductor       | 8930           | 386                       | 1.862×10⁻⁸       | 397                           |
| Epoxy resin            | 1120           | 1400                      | -                | 0.2                           |
| Handcart               | 1896           | 375                       | -                | 0.139                         |
| Stainless steel plate  | 7980           | 442                       | 0.73×10⁻⁶        | 45                            |
| air                    | 1.4128         | 1.4                       | 100              | 0.028                         |
The thermal-electric coupling module in the finite element analysis is used to analyze the contact temperature rise of the conductor models of the busbar compartment and the cable compartment. First of all, give material properties and divide the grid, apply current to the finite element model of the busbar compartment and cable compartment conductor, and observe the influence of Joule heat generated by the conductor carrying capacity on the temperature distribution of the cabinet. Then apply thermal convection and thermal radiation boundary conditions to observe the overall temperature distribution of the switchgear under different conditions.

3.1. The relationship between the operating time of the switch cabinet and the temperature

According to the actual operation of a power supply company in a certain place, the maximum three-phase current of the conductor of the switchgear is set to 1250 A, the ambient temperature is 25℃, and the relative humidity is 50%RH. Figure 4 shows the overall temperature distribution of the switchgear during long-term operation.

Through simulation, the temperature changes of the main components during long-term operation are obtained, as shown in Figure 5.
It can be seen from Figure 5 that the temperature of each element of the switchgear is positively related to the running time of the switchgear, and the temperature of the contact and the branch busbar is relatively high. When the switchgear is running for a long time, the overall temperature of the cabinet rises, but the temperature of the bottom and top inner walls of the busbar room and the cable room is relatively low, and the temperature difference between the electrical components of the switchgear and other parts of the cabinet is large, combined with the condensation temperature curve to judge, condensation is more likely to occur on the busbar room and the inner wall of the cable.

3.2. Condensation under different humidity conditions

According to the actual operation of a power supply company, the maximum three-phase current of the switch cabinet is set to 1250A, and the ambient temperature is 25°C. The simulated humidity conditions are constantly changed to obtain the overall temperature distribution of the switch cabinet under different humidity conditions. When the relative humidity is 60%RH, the temperature distribution of each element of the switchgear is shown in Figure 6.

The temperature distribution of the conductor and the cabinet in the busbar compartment is shown in Figure 7(a). It can be seen that the temperature at the contact point of the moving and static contacts in the branch small busbar in the busbar compartment is the highest, about 84.14°C, of which the B-phase main bus has the highest temperature, with a temperature rise of 62°C, and the A phase is the next, the highest is about 80°C, with uniform temperature distribution, Phase C is in good condition, about 77°C. The temperature of the air at the contact between the branch bus and the static and dynamic contacts of the busbar indoors is the highest. The temperature between the top and the inner wall of the left cabinet
is lower, and the temperature difference is large. The condensation temperature of the high-temperature air is higher than the temperature of the top of the busbar room and the inner wall of the left cabinet.

Figure 9 (a) shows the temperature distribution of the conductors and various components in the cable compartment. The A and B phase cables have the highest temperature, about 83°C, with a temperature rise of about 58°C; followed by the current transformer, with a temperature of about 73°C. The gas temperature of the cables and transformer components in the cable room is slightly higher, and the temperature of the inner wall and the bottom cabinet is lower, and the temperature difference is larger.

![Temperature Distribution in Cable Room](image)

Figure 7. Temperature distribution of busbar room and cable room when relative humidity is 60%RH.

There is a partial temperature rise in the inner walls of the busbar room and the circuit breaker room, especially in the inner wall of the cabinet near the wall bushing, the highest temperature is about 64°C. The temperature of the inner wall of the cable room and the handcart room also increased, the highest was about 32°C, and the lowest was 22°C.

When the ambient temperature remains unchanged and the relative humidity increases to 89%RH, the cabinet temperature distribution is shown in Figures 8 and 9. When the relative humidity of the air increases, the maximum temperature of the cabinet will only slightly change, but the relative dielectric coefficient of the air and the cabinet will increase, and the overall temperature of the cabinet will rise. In particular, the temperature of the cabinet in the handcart room rises to a maximum of about 58°C. The temperature difference between the inner wall of the cabinet at the junction of the cable room and the handcart room is relatively large, with the lowest being about 29°C and the highest being about 50°C.

![Temperature Distribution in Switchgear](image)

Figure 8. Temperature distribution of the switchgear at a relative humidity of 89% RH.
Figure 9. Temperature distribution diagram of the handcart room at a relative humidity of 89% RH.

To compare the temperature of each part of the switchgear with the condensation temperature of the gas in the switchgear, the switchgear is divided into four parts: busbar room, cable room, handcart room, and instrument room. The average temperature of the gas in each room was measured under humidity conditions, and the results are shown in Table 2.

Table 2. The average air temperature of each room under different relative humidity conditions.

| Relative Humidity | Busbar Room | Cable Room | Handcart Room | Instrument Room |
|------------------|-------------|------------|---------------|-----------------|
| 45%RH            | 29.2°C      | 28.9°C     | 27.1°C        | 25.6°C          |
| 60%RH            | 30.7°C      | 30.6°C     | 29.1°C        | 26.2°C          |
| 78%RH            | 34.4°C      | 34.5°C     | 30.2°C        | 28.2°C          |
| 89%RH            | 36.2°C      | 35.9°C     | 31.7°C        | 30.1°C          |

Combined with the gas condensation temperature curve, when the condensation temperature of the air is higher than the temperature of the object in the switch cabinet, condensation will occur. Combined with the previous simulation analysis, it can be seen that condensation is prone to occur in the position shown in Figure 10.

Figure 10. Condensation easily occurs in the switchgear when the relative humidity is 89% RH.
The ambient temperature of the switchgear is 25℃. As shown in Table 3, the condensation situation of the switchgear under different humidity conditions is obtained.

| Relative humidity | Condensation situation | Condensation rate | Condensation area               |
|-------------------|------------------------|------------------|---------------------------------|
| 45%RH             | Almost no condensation | Extremely slow   | Top of busbar room, bottom of   |
|                   |                        |                  | cable room                      |
| 60%RH             | Start to condense      | Slower           | Top of busbar room, left and    |
|                   |                        |                  | bottom of cable room            |
| 78%RH             | Condensation           | Fast             | Top of busbar room, left and    |
|                   |                        |                  | bottom of cable room            |
| 89%RH             | Serious condensation   | Faster           | Bus room, cable room and        |
|                   |                        |                  | interior wall of handcart       |

Obviously, the higher the temperature and humidity in the cabinet, the greater the temperature difference between the air in the cabinet and the cabinet body, and the easier it is to produce condensation. For the equipment in the busbar room and the cable room, since the conductors and electrical components generate high heat during operation, the surrounding air temperature is high, higher than the air condensation temperature, and the temperature difference between the equipment surface and the air is small, so condensation is not easy to occur. The high-temperature and high-humidity air form a large temperature difference with the inner wall of the cabinet, and the temperature of the inner wall of the cabinet is lower than the condensation temperature of the air, which is easy to produce condensation. As shown in Figure 10, it can be seen that the inner wall, top, and bottom of the busbar room and cable room are prone to condensation, and the inner wall where the handcart room meets the busbar room and cable room is also prone to condensation. As time changes, condensation generally spreads from the periphery to the middle from the edge of the cable room and the inner wall of the handcart. Without effective protective measures, a large area of condensation may form.

4. Design of anti-condensation system

Combined with theoretical derivation and simulation analysis, the occurrence of condensation mainly depends on the temperature and relative humidity in the cabinet. Anti-condensation should consider the strategy of mainly controlling humidity and controlling temperature as a supplement [15], and heating dehumidification controllers can be installed in areas prone to condensation.

According to the simulation results, the inner wall, top, and bottom of the busbar room and cable room are prone to condensation, and the inner wall where the handcart room meets the busbar room and cable room is also prone to condensation. To realize the intelligent anti-condensation of the switchgear, the optical fiber temperature, and humidity sensor can be installed at the controller at the same time, the temperature sensor is installed in the cable room and the busbar room to measure the temperature of the element, and the temperature and humidity sensor is installed on the wall of the instrument room to measure the temperature and humidity of the air in the cabinet. humidity. All sensor signals are transmitted to the control end of the system through optical fibers, and collected into the data management system for real-time monitoring, as shown in Figure 11. At the same time, it can combine the historical operating data of the switchgear, and use intelligent algorithms such as fuzzy clustering to extract the historical fault characteristics of its operating history, obtain a reasonable fault threshold, and build a historical fault early warning database. Then compare and analyze the real-time monitoring temperature and humidity data with historical fault warning data, and comprehensively analyze the operating status of the switchgear, as shown in Figure 12.
Combined with the simulation results, the temperature and humidity thresholds can be set for the anti-condensation controller. When the relative humidity of the air reaches 89%RH, it is easy to produce condensation. To prevent condensation, set the condensation controller to start at a relative humidity of 78%RH. Combining the cabinet temperature distribution under the long-term operation of the switchgear, heating should be started when the inner wall temperature is lower than 25°C, and the heating should be triggered at the point where the temperature is high and the relative humidity is high and the starting value is not reached so that the temperature in the cabinet is always higher than the condensation temperature. Destroy the formation of condensation conditions; at the same time, set the condensation controller to stop working when the relative humidity is 60%RH or the temperature of the cabinet inner wall is higher than 29 ℃, and condensation will hardly occur. Monitoring and analysis of the collected sensor data through the management system, combined with the threshold of the anti-condensation controller, can realize early warning and remote control of the switchgear condensation problem.

5. conclusion
(1) The condensation phenomenon of the switch cabinet mainly depends on the temperature (℃) and relative humidity (%RH) in the cabinet. Through these two factors, the condensation temperature and condensation judgment index can be obtained. Only when the surface temperature of the object in the cabinet is low, condensation will only occur at the condensation temperature of the air.

(2) For the equipment in the busbar room and cable room, it is not easy to produce condensation due to the high conductor temperature during operation. Due to the high humidity and large temperature...
difference, the inner wall, top, bottom of the busbar room and the cable room, and the cabinet at the junction of the handcart room and the cable room are prone to condensation.

(3) Arrange a heating dehumidification controller in the part prone to condensation, and transmit the signal to the management system through the temperature and humidity sensor, and set a reasonable fault threshold through fuzzy clustering algorithm analysis to realize real-time monitoring and early warning of the switchgear control.

Acknowledgments
Authors acknowledge financial support from Guangdong Power Grid Co., Ltd. funded science and technology projects (031800KK52170056).

References
[1] Yu Z. Temperature Rise Test and Analysis of High Current Switchgear in Distribution System[J]. The Journal of Engineering, 2018.
[2] Gu F C. Identification of Partial Discharge Defects in Gas-Insulated Switchgears by Using a Deep Learning Method[J]. IEEE Access, 2020, PP(99):1-1.
[3] D'Antona, Gabriele, Perfetto, et al. Partial Discharge Localization in Insulated Switchgears by Eigenfunction Expansion Method[J]. IEEE Transactions on Instrumentation and Measurement, 2019.
[4] GU B C. Study on Measures to Prevent 35kV Switchgear Dewing[D]. Tianjin University, 2016.
[5] Nie Y X, Xu W D, Zhou W W, et al. Discharge Characteristics of Air-Gap Defects in Insulating Material of 12kV Solid Insulated Switchgear[J]. Transactions of China Electrotechnical Society, 2018, 33(12):2894-2902.
[6] Pan Q Z, Yang F, Yang Z. Discussion on mechanism of the dampness and dewing inside 12 kV high-voltage switchgear and its key control techniques[J]. Power System Protection and Control, 2019, 47(05):160-172.
[7] Liu J G. Influence of relative air humidity and condensation on center-mounted switchgear and countermeasures[J]. Electric Engineering, 2016(02):1-6.
[8] Liu X D, Hu Y X, Li Y W, et al. Experimental Research of the Influence of Condensation on Flashover Characteristics of Silicone Rubber Surface[J]. Power System Technology, 2019, 43(08):3047-3054.
[9] Liu Y P, Guo J Y, Guo Q, et al. Research on Condensation in Secondary Cabinet of Ring Main Unit Considering the Impact of Roughness[J]. Journal of North China Electric Power University, 2017, 44(02):1-6.
[10] Yang F. Pan Q Z. Key Technologies Investigation of Damp-proofing and Anti-dewing for 12kV High-voltage Switchgear[J]. High Voltage Apparatus, 2018, 54(08):40-47.
[11] Liu R X, Bai B J, Guo Q, et al. Analysis on Condensation Phenomenon Mechanism of Switchgear[J]. High Voltage Apparatus, 2018, 54(10):80-84.
[12] Xiao Z Y, Miao T, Chen B, et al. Influence of boattail shape on Magnus effects of a spinning rotating body[J]. Acta Aeronautica et Astronautica Sinica, 2018, 39(06):43-52.
[13] Wang L, Li X, Lin J, et al. Studies of Modeling and Simulation Method of Temperature Rise in Medium-Voltage Switchgear and Its Optimum Design[J]. IEEE Transactions on Components, Packaging, and Manufacturing Technology, 2017:1-8.
[14] Ren S Z, Xue J, Wu H, et al. Simulation Study on Three Dimensional Switchgear Temperature & Humidity Distribution Based on Electromagnetic-Temperature-Humidity Coupling Calculation[J]. Grid Analysis & Study, 2019, 47(09):81-85+126.
[15] Chen R, Yan X, Zhang C, et al. Numerical study of several anti-condensation methods for closed switch cabinet[J]. Energy Conservation, 2015, 34(09):26-31+2.