Analysis of the Suspected Discharge Trace of Outer Insulating Porcelain of AC Filter Arrester in Convertor Station

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Abstract. The porcelain of the arrester is a defensive line to protect arrester from the influence of the external environment, so keeping the insulation performance of the porcelain well is a great significance for the safe operation of the arrester. The three dimensional model of the arrester is established by the finite element method, the influence of the top bolt of the arrester on the electric field under the clear and rainy days, and the power frequency voltage and the operating overvoltage are studied. Besides, the causes of suspected discharge trace of field arresters are analyzed. The results show that the average electric field strength of the air gap increases with the longer bolt, and the breakdown is likely to occur when the overvoltage is subjected. In the rain state, the bolt and the air gap of the shed profile are likely to break through when the water column is formed, and the air gap between the shed profile is likely to break after the shed profile forms the water column, forming a discharge trace. Therefore, the top bolts of the arrester should be avoided too long, or taken the opposite arrangement measures.

1. Introduction
In the electric power system, arrester is a kind of electrical equipment used to limit lightning overvoltage and internal overvoltage caused by the operation. Zinc oxide arrester is composed of outer insulating porcelain (shed profile), resistor disc, flange and aluminum gasket and the uniform potential distribution in each part of zinc oxide arrester is the precondition of stable operation of arrester[1-2].

The AC filter bank in the convertor station not only undertakes system filtering, but provides a certain reactive capacity, which is one of the important equipment in the convertor station. According to the requirements for the range of reactive power exchange, voltage and optimal filtering performance of the convertor station, it is necessary to frequently switch the filter in operation. If the circuit breaker does not close near the zero crossing point of voltage, it will produce a surge impact and cause the action of the arrester. In extreme adverse conditions such as excessive switching phase angle or extremely severe weather conditions, the residual voltage on the arrester is likely to exceed the level of external insulation of the arrester, forming a local or penetrating electric arc on the surface of the porcelain of the arrester. The porcelain of the zinc oxide arrester functions as a line of defense to protect the internal devices of the arrester from the external environment. If the porcelain is damaged or cracked due to local burning, it will accelerate the internal aging of the arrester, reduce the service life of the arrester and severely affect the stability and safety of grid operation once moisture enters the internal part.

At present, the research on the electric field of the arrester is mainly concentrated on the potential distribution of sheet metal inside the arrester. HAN She-jiao, SUN Hao and ZHANG Ai-wu have
studied the improvement effect of the equalizing ring on the electric field distribution inside the arrester and optimized the equalizing ring [3-7]. WANG Shi-shan and XU An have studied the potential internal distribution of the line arrester and optimized the structure [8-9]. ZHANG Pi-pei has discussed the changes in potential distribution when the arrester is affected with damp [10]. The above researches aim at arresters, but few types of research are conducted specifically on the electric field of the porcelain of the arrester. The researches on the electric field on the surface of electrical equipment mainly concentrate on the electric field of insulator shed profile [11-13]. In addition, there are researches on the electric field on the surface of electric reactor [14], but the researches on the electric field on the surface of other electrical equipment are rarely reported.

The AC filter arrester in the convertor station of certain DC power transmission project is found to have suspected discharge trace of the outer insulating porcelain due to frequent actions of the arrester caused by the poor effect of phase selection and switching on. To ensure the safe operation of the project, this paper carries out finite element simulation calculation on the potential distribution of the porcelain of the arrester, analyzes the electric field distribution under extreme conditions and analyzes the causes for suspected discharge trace.

2. Introduction of Abnormalities

Since the certain DC power transmission project was formally put into operation in 2014, it has been found to have the problem of frequent actions of C-type (parallel capacitor) AC filter arrester, and the main parameters of the arrester are shown in Table 1. Preventive test results show that the DC reference voltage of the arrester generally decreases by 2-5%. When inspecting the appearance of the arrester, some suspected discharge traces are found on the porcelain of C-type filter arrester, as shown in Figure 1. Previous researches show that the problem of frequent actions is caused by the switching impact generated by the deviation between the input time of the filter and the zero crossing point of voltage, that is, the effect of phase selection and switching on is not ideal. In the worst case, the overvoltage may exceed the level of external insulation of the arrester [15].

Figure 1. The suspected discharge trace of porcelain of arrester

| Model | Y141W1-56/151W |
|-------|----------------|
| Rated voltage | 56 kV |
| Continuous-running voltage | 46 kV |
| Operation shock protection level | 111 kV |
| | 15.7 kA |
| Operation insulation level | 150 kV |
| The reference voltage of DC 4mA | 81 kV |
3. Theoretical Basis for the Analysis of Electric Field

3.1 Analysis of electric field based on the finite element method

At present, the most widely used methods include the finite element method and other methods among the numerical calculation methods for the electric field of electrical equipment. The core idea of the finite element method is “numerical approximation” and “discretization.” It divides the solution region into several sub-regions through the grid, which is usually called “unit” or “finite element”. Then, it applies the solution boundary to each sub-region for a solution, and sums up the results of each sub-region to obtain the solution of the whole solution region.

As AC electrical equipment mainly works at the PF voltage of 50 Hz, the electromagnetic wave wavelength is 3,000 km, the insulation distance between electrodes is far less than the electromagnetic wave wavelength and the voltage between electrodes changes slowly with time. When the high-voltage electrical equipment is subjected to lightning impulse voltage and switching impulse voltage, the shock wave moves for several hundred meters only as the voltage rises from zero to amplitude, but it is still much greater than the dimensions of the electrical equipment. Therefore, the electric field of general AC electrical equipment at any instant can be approximately equivalent to being stable, and can be studied and analyzed according to the electrostatic field.

When it comes to the calculation of the potential distribution of electrical equipment, Poisson equation and Laplace equation are usually used to describe the quasi-static field. The poisson equation is suitable for low-frequency time-varying field. The time-varying term in general equations can be neglected. The static electric field caused by charge excitation is described by the Poisson equation. As shown in Equation (1), the Laplace equation can be used to describe when the space free charge is 0, as shown in Equation (2):

\[ \nabla^2 \varphi = -\frac{\rho}{\varepsilon} \quad (1) \]

\[ \nabla^2 \varphi = 0 \quad (2) \]

Where, \( \varphi \) refers to potential value, \( \rho \) refers to free charge density and \( \varepsilon \) refers to relative dielectric constant.

Based on the Equations (1-2) mentioned above, the finite element simulation software COMSOL Multiphysics is used to calculate the electric field. COMSOL is a kind of software based on finite element method to simulate physical phenomena by solving partial differential equations or systems of partial differential equations in physical fields and to solve physical phenomena by mathematical methods.

Since this paper researches the impact of the bolt at the top of the arrester on the electric field and the bolt is not symmetrical, it is necessary to establish a three-dimensional model of the arrester, as shown in Figure 2.

Figure 2. The three dimensional model of the arrester

In software simulation calculation, the boundary conditions of the electric field of the model are set as Equations (3-5) below:
\[ \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0 \]  

\begin{align*}  
\varphi &= U \\
\varphi &= 0 
\end{align*} 

(3) 

Where, Equation (3) sets all regions including the arrester and air field; Equation (4) sets the terminal at the top of the arrester; \( U \) is 43kV under PF voltage, and \( U \) is 150kV under operating voltage; Equation (5) sets the metal field at the bottom of the arrester and air at infinity, which is equivalent to ground processing.

3.2 Breakdown field strength of air gap in the porcelain of the arrester

The discharge phenomenon of air gap under atmospheric pressure is generally explained by streamer theory. The uniformity of the electric field can be expressed by the non-uniformity coefficient \( k_e \), which is the ratio of the maximum field intensity to the average field intensity, as shown in Equation (6):

\[ k_e = \frac{E_{\text{max}}}{E_{\text{av}}} \]  

(6)

The uniformity of the electric field can be determined according to the equation, which may directly affect the breakdown voltage of the air gap. When \( k_e < 2 \), the electric field is less nonuniform; when \( k_e > 4 \), the electric field is extremely nonuniform.

The air gap between the bolt and shed profile and between the water column and shed profile is extremely ununiform electric field, which can be represented by the rod-plate model. Relevant researches have shown \(^{16}\) that the average breakdown field intensity of rod-plate gap is approximately proportional to the distance, which is about 4.8 kV/cm when the gap distance is more than 20 cm. When the gap is less than 20cm, the breakdown field intensity is slightly larger than the value. In addition, the operating impulse discharge voltage can be obtained by multiplying the impulse coefficient 1.1 by the PF discharge voltage with regard to the air gaps below 220kV in the power system.

To judge the insulation intensity of the air gap of the shed profile of the arrester, 4.8kV/cm and 5.28kV/cm are used as the reference values of the air breakdown electric field intensity under PF voltage and operating voltage by referring to the above research results.

4. Simulation Calculation and Analysis of the Electric Field of the Porcelain of the Arrester

4.1 Research on electric field distribution of the porcelain in the sunny state

4.1.1 Research on electric field distribution of the porcelain under PF voltage

A long-term working phase voltage of 43 kV is applied to the top terminal of the arrester, and the bottom of the arrester and the air field are grounded at infinity. The potential distribution of the arrester is shown in Figure 3.
Figure 3. The potential distribution of porcelain under the power frequency voltage

As shown in Figure 3, the axial potential distribution of the arrester is uniform. For the porcelain of the arrester, the potential distribution from the top metal to the first shed profile is more concentrated, so the electric field intensity at this place shall be larger. Through simulation calculation, the air gap between the outer tip of the bolt and the first shed profile (hereinafter referred to as the “bolt-shed profile air gap”) is shown in Table 2 Electric Field Intensity.

Table 2. The electric field intensity value of air gap between the bolt and shed profile under the power frequency voltage

| Electric field strength /(kV/cm) | Max.  | Min.  | Average |
|---------------------------------|-------|-------|---------|
|                                 | 8.22  | 0.75  | 1.61    |

From Table 2, it can be seen that $k_e > 4$ through calculation based on Equation (6), and the electric field of the air gap between the bolt and shed profile is the extremely nonuniform electric field. Under the PF voltage, the average electric field strength of the air gap between the bolt and shed profile is far less than the reference value (4.8kV/cm) of the breakdown field strength of air gap under PF voltage. The possibility of air gap breakdown is small and safe.

4.1.2 Switching overvoltage

When the switching overvoltage intrudes into the arrester, the top terminal of the arrester applies the switching overvoltage of 150 kV, and the other boundary conditions are set in consistence with the previous. After simulation calculation, the potential distribution is similar to that under PF voltage, and only the potential value is different. In addition, the electric field strength of the air gap between the bolt and shed profile is shown in Table 3:

Table 3. The electric field intensity value of air gap between the bolt and shed profile under the switching overvoltage

| Electric field strength /(kV/cm) | Max.  | Min.  | Average |
|---------------------------------|-------|-------|---------|
|                                 | 23.51 | 2.57  | 5.40    |

Compared with the PF voltage, the electric field strength of the air gap in the porcelain of the arrester has increased. Meanwhile, the local maximum electric field strength of external air has increased from 9.41kV/cm to 32.1kV/cm.

It can be found from Table 3 that the average electric field strength of air gap between the bolt and shed profile under switching overvoltage is higher than the reference value (5.28kV/cm) of the
breakdown electric field strength of the air gap under switching overvoltage, so that the air gap may be broken down.

4.2 Research on electric field distribution of the porcelain in the rain state

Arrester is usually installed outdoors, so that the bolt and shed profile may get rainwater in the rain state, and the rainwater may change the surface and surrounding potential distribution of the porcelain of the arrester.

Given the difference in rainfall duration and precipitation, there is a development process of rainwater distribution on the surface of porcelain shed profile, which can be divided into three processes, water drop, water film and water column [17]. Through analysis, the arrester will show the following states under the rainfall condition: At first, the rainwater will converge under the top bolt tip of the arrester to form water drops; then it will form water drops under the bolt and on the shed profile; finally it will form water film and water column under the bolt and on the shed profile.

Given the electric field distribution of the arrester under adverse conditions, the switching overvoltage of 150kV is loaded at the top terminal of the arrester, and other boundary conditions are set in consistence with the previous, and only water drop, water column and water film are added to the model. The water drop is equivalent to a cylinder with a radius of 5m and a length of 7mm, and the water column is equivalent to a cylinder with a radius of 5mm and a length of 20mm. In the rain state, the electric field strength around the porcelain and bolt of the arrester is shown in Figure 4.

(a) When water drop is formed on the bolt

(b) When water drop is formed on the bolt and shed profile

(c) When water film and water column are formed on the bolt and shed profile

Figure 4. The electric field intensity of porcelain under the switching overvoltage in the rain
When water drop is formed at the top of the bolt, the water drop is in direct contact with the bolt. Since water is a good electrical conductor, the water drop and the bolt are basically equipotential. Besides, the electric air field around the water drops is distorted seriously since the water drops are smaller. When a water curtain is formed between the bolt and the shed profile, the decrease in the distance of the air gap between the bolt and the shed profile will certainly lead to an increase in the average electric field strength. In addition, the electric field strength of the air gap between the bolt and shed profile and that between Group 1 shed profiles with varying length ("air gap between shed profiles") in different rain states is shown in Table 4.

Table 4. The electric field intensity value of air gap under the switching overvoltage in the rain

| Electric field strength/(kV/cm) | Air gap               | Max. | Min. | Average |
|--------------------------------|-----------------------|------|------|---------|
| When water drop is formed on the bolt | Bolt-shed profile     | 36.05| 2.40 | 5.66    |
| When water drop is formed on the bolt and shed profile | Bolt-shed profile     | 48.61| 2.18 | 5.77    |
|                                 | Shed profile-shed profile | 8.31| 0.48 | 3.28    |
| When water film and water column are formed on the bolt and shed profile | Bolt-shed profile     | 40.63| 2.00 | 6.22    |
|                                 | Shed profile-shed profile | 13.43| 1.40 | 8.19    |

By comparing Table 3 and Table 4, it can be seen that the average and maximum values of the electric field strength of the air gap between the bolt and shed profile has increased due to the electric field distortion of a water drop, water film and water column to the surrounding air in the rain state.

When the precipitation is larger, or the duration of the rainfall is longer, the distance of air gap shall be reduced after water column is formed on the bolt and Group 1 shed profile, as shown in Figure 4(c). At this time, the average electric field strength of the air around the bottom of the bolt increases significantly to 6.22 kV/cm, and the possibility of gas breakdown discharge is greatly improved. The average electric field strength of the air around the shed profile is 8.19 kV/cm, which is higher than that of the air gap between the bolt and shed profile. At this time, the air gap between shed profiles is also likely to have discharge breakdown.

5. Analysis of Suspected Discharge Trace of the Porcelain of the Arrester

During the preventive on the AC filter arrester in the project, the maintenance personnel finds that the porcelain shed profile under the bolt of the top metal flange of most C-type AC filter zinc oxide arresters has the suspected discharge trace, as shown in Figure 5.
By checking the design drawings of the arrester, it is found that the bolt length of the field arrester does not conform to the design drawings. The bolt length of the field arrester is much longer than the design drawings, and the length is about 1.5 times that of the design drawings. Through preliminary analysis, it is considered that the discharge trace is caused by the electric field distortion of the porcelain of the arrester due to longer bolt, coupled with the intrusion of switching overvoltage, the higher voltage between the bolt and shed profile and between shed profiles than the air breakdown voltage as well as discharge breakdown of air gap.

Suppose the arrester is in a rain state, water film and water column are formed on Groups 1-3 of shed profile, and the arrester is subject to the intrusion of the switching impulse of 150kV, the results of simulation calculation are shown in Figure 6 and Table 5.

|/(kV/cm) Electric field strength/(kV/cm) | Group 1 long-Group short | Group 1 short-Group 2 long | Group 2 long-Group 2 short | Group 2 short-Group 3 long |
|---|---|---|---|---|
| Group 3 long-Group 3 short | 14.42 | 9.43 | 12.33 | 8.07 |
| Group 3 short-Group 4 long | Bolt-shed profile | Electric field strength/(kV/cm) | 11.12 | 6.59 | 5.42 |
As shown in Figure 6 and Table 5, the electric field strength of air gap in Groups 1-4 increases obviously as long as the water film and water column are formed in group 1-3 shed profiles. Among them, the electric field strength of the air gap between long and short shed profiles in the group is higher because the air gap between long and short shed profiles is greatly reduced and the electric field distortion is increased after the water column is formed on the long shed profile, so that the electric field strength is increased.

In addition, the average electric field strength of the latter group is lower than that of the former group, that is, the air gap between latter shed profiles is likely to have a smaller possibility of breakdown than former shed profiles, and the shed profiles in Group 1 are the most likely to have a breakdown.

Based on the above simulation and analysis results, the air gap between shed profiles in Group 1-4 will be broken down after the water column is formed on the shed profiles in Groups 1-3. The results are in consistency with the results of the suspected discharge trace in the shed profile of the field arrester. Therefore, the electric field of the field arrester is seriously distorted after the water column is formed on the bolt and shed profile in the first three groups. Meanwhile, the switching overvoltage intrudes the arrester, and the air gap between the bolt and shed profile, between the shed profiles in Groups 1-3 and between long shed profiles in Group 4 is found to have breakdown discharge, cauterizing the shed profiles.

6. Conclusion

With regard to the suspected discharge trace of the porcelain of the AC filter zinc oxide arrester in the convertor station, the finite element method is used to research the electric field distribution of the arrester porcelain when the bolt is too long under extreme conditions and analyze the breakdown possibility of air gap, and the following conclusions are drawn:

1) The electric field at the tip of the porcelain bolt of the arrester is concentrated. The air gap between the bolt and shed profile is less likely to break down when the arrester is under PF voltage; the air gap between the bolt and shed profile is more likely to break down when the arrester is under switching overvoltage.

2) In the rain state, the air gap is more likely to break down than in the sunny state after water drop, water film or water column is formed on the bolt.

3) When the water column is formed on the bolt and shed profile, the electric field is most severely distorted. In addition to the air gap between the bolt and shed profile, that between shed profiles is also likely to break down.

4) After water column is formed on the bolt and shed profiles in the first three groups of the arrester, the air gap between the bolt and shed profile and between shed profiles is likely to have breakdown discharge and cauterize the shed profiles, and the simulation and analysis results of the electric field are consistent with the field operation.

5) To sum up, a too long bolt of the arrester shall be avoided in the project, and the design of reverse bolt may be directly adopted.

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