Simulation of Potential Distribution and Leakage Current of 800kV DC Arrester under Different Degrees of Degradation

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Abstract. 800kV DC arrester is widely used in UHV converter stations. If long-term damp or breakdown short-circuit of the resistor is degraded during operation, the potential distribution of the arrester is unreasonable and the leakage current increases, resulting in arrester heating or even explosion, so it’s necessary to analyze and calculate the potential distribution and leakage current under different degrees of degradation. In this article, the ANSYS simulation model of 800kV DC arrester was built, which was used to calculate the potential distribution and leakage current of the arrester when long-term damp and breakdown short-circuit, and the correctness of simulation results are verified by field test of leakage current.

1. Introduction
The ±800kV DC arrester (hereafter referred to as ‘arrester’) is mounted on the DC bus side for lighting and protection of the DC switchyard. Due to the high withstand voltage and high energy absorption during operation, arrester must use multi-column parallel connection and multi-section series structure to meet the requirements [1-5]. If long-term damp or breakdown short-circuit of the resistor is degraded in the long-term operation, the potential distribution of the arrester is unreasonable and the leakage current increases, causing arrester heating or even explosion, so it’s need to analyze and calculate the potential distribution and leakage current under different degrees of degradation.

The calculation models for the potential distribution of 220kV, 330kV, 500kV and 1000kV AC arresters were established in [6-9], in which the potential distribution under continuous AC operating voltage was regarded as an electrostatic field problem, that is, the voltage is inversely distributed according to the dielectric constant of each medium, but the electric field under the DC operating voltage doesn’t satisfy this law. In [10,11], it is considered that the electric field distribution of the arrester satisfies the condition of constant field under the continuous running voltage of DC, in which the resistivity of the medium determines the potential distribution, and the 3D model of arrester is established to simulate the potential distribution during normal operation, but there is no consideration of the change in potential distribution and leakage current after the deterioration of the arrester.

In this paper, ANSYS finite element analysis software is used to establish a complete 3D electric field analysis model according to the actual size of ±800kV DC arrester. The potential distribution and leakage current of arrester under different degrees of degradation are simulated and the correctness of simulation results are verified by field test of leakage current.

2. 3D model and calculation method
±800kV DC arrester consists of 5 arrester sections connected in series (numbered Ⅰ, Ⅱ,Ⅲ,Ⅳ,Ⅴ from top to bottom). The height of each section is 2852mm, and there are 3 column resistors in parallel in each section, which is divided into upper, middle and lower three resistor package units. Resistors are shape of rings, with outer diameter 115mm, inner diameter 38mm, thickness 20mm, and each of the two resistors is separated by aluminum gaskets of the same size. The total height of the arrester is about 14m, and the base 0.3m high at the bottom in the test.

According to the actual structural size of the arrester, the ANSYS 3D simulation model is established. The overall and internal structure diagram is shown in figure 1. At the same time, a rectangular outer air domain of 20 000×20 000×40 000(unit: mm) was established to simulate the air area of the external space of the test site, as shown in figure 2.

![Figure 1. ANSYS model of arrester.](image1)

![Figure 2. Air domain of arrester.](image2)

Under the action of DC continuous running voltage, the internal current is mainly conducted current. At this time, arrester can be regarded as a network composed of equivalent resistance, and the distribution of potential between the media is proportional to the resistivity, so the potential distribution problem of arrester is transformed into a constant electric field problem to solve. [12]

SOLID232 in ASYS is selected as the analysis unit to assign the resistivity of each component of the arrester, and the tetrahedral mesh is divided into the arrester and the air region. Since the electric field inside the metal conductor is 0 in a constant electric field, and the surface potential of the metal conductor is equal, the metal conductor does not participate in the meshing, and the node potential is coupled with degrees of freedom in the surface of the component such as a flange, a grading ring, an aluminum gasket, etc. The resistivity of each component of arrester is shown in table 1.

| Component | Resistivity/(Ω·m) |
|-----------|------------------|
| Air       | $10^{14}$        |
| Flange, gasket, etc. | No meshing |
| Porcelain sleeve | $2.5\times10^{12}$ |
| Insulation pole | $10^{13}$ |
| ZnO resistor | 1012 |

Table 1. Resistivity of each component.
Finally, the boundary condition is applied to the 3D model, and the test voltage $U_T$ of the arrester is applied to the uppermost flange and the grading ring, and 0V is applied to the outermost surface of the air area, the base and the bottom flange. Then a constant electric field can be solved for $\pm 800\text{ kV DC}$ arrester.

3. Potential distribution of arrester during normal operation

According to the grid divided in Section 1 and the applied boundary conditions, and applying a test voltage of 925kV to the arrester, the potential contour on the axisymmetric section of the arrester is obtained as shown in figure 3.

![Figure 3. Potential contour during normal operation.](image)

The degree of voltage commitment is usually measured by the voltage bearing rate on the resistor, which is defined as

$$v_i = \frac{U_i}{U_0/n}$$  \hspace{1cm} (1)

Where: $U_0$ is the test voltage of the arrester; $n$ is the number of resistors in each group; $i$ and $U_i$ are the voltage bearing ratio of the $i$-th resistor and the actual withstand voltage.

800kV DC arrester five sections have 220 resistors in total, numbered from 1 to 220 from top to bottom, then the voltage bearing ratio of each resistor according to formula(1) is calculated as shown in figure 4. The potential distribution of the three-column resistor is completely the same, so the simulation result of the voltage bearing ratio is given by taking one of the columns as an example. It can be seen that since the resistivity of the ZnO resistor is different from the magnitude of the dielectric resistivity of the surrounding medium, there is almost no leakage current in the surrounding medium under the DC test voltage, and the voltage bearing ratio of the arrester resistors is 1.

4. Potential distribution and leakage current when damp in single section

Considering that the glaze layer and the plating layer on the surface of the resistor and aluminum gasket have a certain water repellency, the water will condense on the surface in the form of water droplets. When the damp is long-term, a large number of water droplets will be connected to the band. At the same time, in order to easily divide the grid and solve the process, a semi-cylindrical water band with a radius of 3mm(resistivity of 1000 $\Omega \cdot m$) is attached to the surface of the damp resistor as a simulation model for the damp of the UHV DC arrester, as shown in figure 5.
Taking the damp of section V as an example, and the test voltage is applied to the arrester at 925kV. The simulation results of the potential distribution and the leakage current density are shown in figure 6 and figure 7.

It can be seen from figure 6 that the potential distribution of the damp is in the same pattern: the voltage bearing ratio of the damp part is reduce to about 0.523, and the potential of the normal resistor remains evenly distributed in other sections, of which the voltage bearing ratio rise to 1.128. This is because the damp band is equivalent to being connected in parallel around the resistor, so that the overall equivalent resistivity of the damp portion is reduced. Since the potential is proportional to the resistivity in a constant electric field, the voltage bearing ratio of the damp portion is lowered, and the normal resistor voltage bearing ratio increases.

It can be seen from figure 7 that the leakage current flows only inside the column composed of resistor and aluminum gasket, and the current density is $J \approx 0.657 \text{A/m}^2$, and the leakage in the insulating pole, the porcelain sleeve and the air domain is substantially zero. The current density is integrated into the area to obtain the current flowing through the area, as follows

$$I = \int \vec{J} d\vec{S} = 3 \cdot J \cdot \pi r^2$$  \hspace{1cm} (2)

In the formula, $J$ is the current density flowing through the column of the resistor, and the $r$ is the radius of the resistor. The total leakage current of the three-column resistor is $3 \times 0.657 \times \pi \times 532 \times 10^{-6} \approx 17.39 \text{mA}$.

5. Potential distribution and leakage current when 2/3 short-circuit in single section
When the resistor is short-circuited, its role in the constant electric field is the same as that of the conductor. Therefore, it is necessary to couple the degrees of freedom of the node potential on surface, so that the potential simulation of 800kV DC arrester when 2/3 short-circuit in single section can be solved(where the 2/3 short-circuit means all the three-column resistors in the upper and lower unit short-circuit).
Taking the 2/3 short-circuit of section $V$ as an example, and apply a short-circuit test voltage of 407.5kV to the arrester. The simulation results of the potential distribution and the leakage current density are shown in figure 8 and figure 9.

![Figure 8. Potential distribution when 2/3 short-circuit in section V.](image)

![Figure 9. Leakage current when 2/3 short-circuit in section V.](image)

It can be seen from figure 8 that the potential distribution of the 2/3 short-circuit is in the same pattern: the voltage bearing ratio of the short-circuit part becomes 0, and the potential distribution of remaining normal resistor keeps even, while the voltage bearing ratio rises to 1.146, because the normal resistors share the voltage that the short-circuit resistor should bear.

It can be seen from figure 9 that the leakage current flows only inside the column composed of resistor and aluminum gasket, and the current density is $J \approx 0.387 \text{A/m}^2$, and the leakage in the insulating pole, the porcelain sleeve and the air domain is substantially zero. Similarly, the total leakage current of the three-column resistor can be obtained from equation(2) to be $3 \times 0.387 \times \pi \times 532 \times 10^{-6} \approx 10.22 \text{mA}$.

6. **Leakage current result in field test**

The same as the degree of degradation in Section 4 and 6, the leakage current tests when damp and 2/3 short-circuit were performed in the site. The test results are shown in table 2 and table 3.

| Time  | Voltage(kV) | Leakage current(mA) |
|-------|-------------|---------------------|
| 10:25 | 834         | 3.80                |
| 10:30 | 881         | 7.40                |
| 10:48 | 925         | 15.50               |
| 11:08 | 925         | 17.40               |
| 11:23 | 925         | 17.40               |
| 11:28 | 925         | 17.40               |

| Time  | Voltage(kV) | Leakage current(mA) |
|-------|-------------|---------------------|
| 14:33 | 289         | 0.01                |
| 15:06 | 400         | 3.10                |
| 15:11 | 406         | 7.00                |
| 15:35 | 406         | 10.06               |
| 15:50 | 407         | 10.20               |
| 15:52 | 407         | 10.20               |

It can be seen from the test results that when the voltage rises to the test voltage, the leakage currents measured by the damp test and the short-circuit test are 17.40mA and 10.20mA respectively, where the simulation results in Section 4 and 5 is 17.39mA and 10.22mA, which verifies the
consistency between the simulation results and the field test data. It also shows that the ANSYS 3D model established in Section 2-5 and the processing of boundary conditions for damp and short-circuit can simulate the scene situation more realistically.

7. Conclusion
In this paper, ANSYS is used to establish a complete 3D simulation model of ±800 kV DC arrester. The constant electric field analysis method is used to simulate the potential distribution of arrester under different degrees of degradation after assigning the resistivity of each component and applying boundary conditions. Results prove that:

1) The potential distribution of arrester is even under the DC test voltage, and the voltage bearing ratio of the arrester resistors is 1;
2) When damp in single section, the voltage bearing ratio of the damp part is reduced to about 0.523, and the potential of the normal resistor remains evenly distributed in other sections, of which the voltage bearing ratio rise to 1.128, and the simulation result of leakage current in the bottom is 17.39mA;
3) When 2/3 short-circuit in single section, the voltage bearing ratio of the short-circuit part becomes 0, and the potential distribution of remaining normal resistor keeps even, while the voltage bearing ratio rises to 1.146, and the simulation result of leakage current in the bottom is 10.22mA;
4) The leakage currents measured by the damp test and the short-circuit test in section V are 17.40mA and 10.20mA respectively. It is basically consistent with the simulation results, which verifies the validity and correctness of the model and simulation results.

References
[1] ZHANG W L, YU Y Q and LI G F 2007 Researches on UHVDC Technology Proceedings of the CSEE 27(22) 1-7
[2] ZHOU P H, ZHAO J and LV J Z 2009 Arrester Protection Scheme and Arrester Parameters Selection for ±800kV YunGuang UHV DC Converter Station High Voltage Engineering 35(11) 2603-11
[3] ZHANG X X, LI Z and ZHAO D C 2010 Key Technologies Applied in Research and Development of HVDC Surge Arresters Power System Technology 34(8) 150-154
[4] WANG B S, LIU Y and TANG L 2012 Research on characteristics of voltage distribution of the metal oxide arrester without gap used for AC system Insulators and Surge Arresters 1 38-49
[5] ZHANG H T, HE J M and ZHANG H J 2011 The optimization research of 500kV MOA without gap Insulators and Surge Arresters 6 103-107
[6] MA Y, GUO J and JIAO L X 2015 Study on the influence of the grading ring structure on potential distribution of MOA for 750kV AC system Insulators and Surge Arresters 1 139-143
[7] HAN S J, LI P Z and LU Y F 2001 3D potential distribution calculation and design of grading rings for post-type ZnO surge arrester for 1000kV substations Proceedings of the CSEE 21(12) 105-114
[8] Han S J, Zou J and He J L 2005 Calculation of the potential distribution of high voltage metal oxide arrester by using an improved semi-analytic finite element method IEEE Trans on MAG 41(5) 1392-95
[9] SUN H and LI X W 2010 Finite element calculation and experiment of potential distribution for a 500kV porcelain zinc oxide arrester High Voltage Apparatus 46(3) 23-27
[10] HU S H 2016 Research on Pole Bus Metal Oxide Surge Arrester for ±800kV UHVDC Converter Station High Voltage Apparatus 34(8) 34-45
[11] AN C C, LIU H and WANG Q 2009 Calculation of Electric Potential and Field Distribution of UHVDC Bus Bar MOA High Voltage Apparatus 45(5) 9-15
[12] TIAN J H, SHA Y C, ZHOU Y X 2011 Simulation of AC and DC Electric Field for 800kV Grade High Voltage Disconnector High Voltage Engineering 37(5) 1216-23