Research on Static Potential Distribution Characteristics of Thyristor Valve of UHV Controllable Arrester

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Abstract. The ultra-high voltage(UHV) AC thyristor valve-type controllable arrester can realize the access and exit of the controllable unit through the action characteristics of the thyristor, dynamically change the volt-ampere characteristics of the arrester connected to the system, to reliably and deeply suppress the operating overvoltage. Under continuous operating voltage, stray capacitance will cause the uneven distribution of axial potential at the high-voltage end of the thyristor valve. In severe cases, the thyristor with higher voltage may be triggered by mistake, which endangers the system security. Due to the more changeable potential distribution of thyristor valve under different ambient temperatures and charge rates, higher requirements are put forward for the design and application of the thyristor valve. Therefore, based on the test data, this paper simulates and analyzes the influence of the voltage and temperature changes of the thyristor and resistor on the potential distribution of the thyristor valve under the continuous operating voltage, analyzes and compares the configuration modes of various voltage equalizing capacitors, and obtains the voltage equalizing measures with better optimization effect, which provides a reference for the voltage equalizing optimization of the thyristor valve.

1. Introduction
With the large-scale construction of UHV AC system, the operating overvoltage level has gradually become a key factor in determining insulation coordination, equipment selection and manufacturing difficulty. As a deep flexible suppression method of operating overvoltage, the controllable arrester can realize the access and exit of the controllable unit under the action of transient high-amplitude operating overvoltage. The partial body of the arrester is instantaneously shorted, and the volt-ampere characteristics of the arrester connected to the system are dynamically changed, which has high reliability and economy[1].

According to the different types of control units, AC UHV controllable arresters can be divided into mechanical switch-type controllable arresters and thyristor valve-type controllable arresters. Among them, the thyristor valve-type controllable arrester has the advantages of short action time, fast response and passive autonomous triggering, which gradually becomes the development trend of overvoltage depth suppression technology in UHV AC system[2].
The thyristor valve of controllable arrester is mainly composed of anti-parallel thyristor pairs in series, and is equipped with resistors to realize internal voltage equalization. The inherent junction capacitance of thyristors varies with voltage and junction temperature, thus the potential distribution of thyristor valve may be quite different under different ambient temperatures and charge rates. Under the continuous operating voltage, due to the dispersion of the capacitance characteristics of the thyristor valve voltage-equalizing resistors and the thyristor, as well as the influence of the stray capacitance, the series thyristor may be mistriggered due to the uneven voltage distribution, which will seriously affect the normal operating state of the controllable arrester.

This paper focuses on the static potential distribution of thyristor valve of UHV controllable arrester, and simulates the potential distribution of thyristor valve under the continuous operating voltage through three-dimensional finite element numerical analysis method[3]. The influence of thyristor voltage, junction temperature and parallel capacitors on the overall potential distribution of thyristor valve is comprehensively analyzed, and the accuracy of simulation results is verified by comparing with the measured results of optical fiber-current method, which provides a reference for the structural optimization of thyristor valve of controllable arrester.

2. Structural characteristics of thyristor valve-type controllable arrester

2.1. Structure of thyristor valve-type controllable arrester
The overall structure of thyristor valve-type controllable arrester is shown in Figure 1, which is composed of arrester body and thyristor valve. The arrester body is composed of uncontrollable unit MOA1 and controllable unit MOA2 in series. The thyristor valve, as the control unit, is paralleled with the main body controllable unit MOA2, adopting two antiparallel thyristor pairs (T1-T2) in series structure, equipped with a voltage equalizing resistance column MOR and L as current limiting inductance. The UHV thyristor valve-type controllable arrester studied in this paper has a controllable ratio of 15%, that is, the continuous operating voltage of the control unit thyristor valve is 15% of that of the arrester body.

![Figure 1. Structure of thyristor valve-type controllable arrester.](image)

2.2. Capacitance characteristics of thyristor valve components
Under continuous operating voltage, the thyristor valve-type controllable arrester works in the small current area, and both the resistor and the thyristor show capacitance characteristics. In order to explore the variation law of the equivalent capacitance of the resistor and the junction capacitance of the thyristor under different voltage and temperatures, the capacitance-voltage characteristics of the resistor and the thyristor at -40°C~60°C were tested by dielectric loss instrument on a specific experimental platform. $C_{MOV}$ is the resistor equivalent capacitance, $C_T$ is the thyristor junction capacitance. The test results are shown in Figure 2 and Figure 3.
Figure 2. Capacitance-voltage Characteristics of resistors at different temperatures.

Figure 3. Capacitance-voltage Characteristics of thyristors at different temperatures.

The measurement results show that at the same temperature, the equivalent capacitance of the resistor basically shows a decreasing trend with the increase of the voltage, and the decreasing trend is more obvious in the high temperature region. At 60°C, with the voltage of the resistor changes from 0kV to 3.5 kV, its equivalent capacitance decreases the most, which is 9.19%. Moreover, the equivalent capacitance of the resistor under the same voltage basically shows a rising trend with the rise of temperature. When the temperature rises from -20°C to 60°C, the maximum increase of the equivalent capacitance of the resistor under different voltage reaches 44.63%. Therefore, in the design and use of the thyristor valve resistors, it is necessary to focus on the influence of temperature on the capacitance under the continuous operating voltage.

Compared with the capacitance characteristics of the resistor, the PN junction capacitance characteristics of the thyristor are quite different. At the same temperature, the junction capacitance of the thyristor approximately decays exponentially with the increase of the voltage. At 20°C, as the voltage of the thyristor changes from 0 kV to 5 kV, the decrease of the junction capacitance reaches the maximum, which is 59.87%. Unlike resistors, the thyristor junction capacitance under the same voltage has no obvious difference at -40°C~40°C, and the maximum difference is only 7.46%. During the temperature rising from 40°C to 60°C, the increasing trend of the thyristor junction capacitance under the same voltage is more significant, and the maximum increase is 22.80%. Therefore, the exponential decay characteristics of thyristor junction capacitance under different voltage should be mainly considered in its design and use.

3. Static potential distribution characteristics of thyristor valve of controllable arrester

3.1. Potential distribution calculation model

According to the structure of thyristor valve and the calculation method of arrester potential distribution recommended in the IEC standard, a three-dimensional calculation model of thyristor valve is established. Since the electrical size of thyristor valve is much smaller than the wavelength of electromagnetic wave under the continuous operating voltage of power frequency AC, the electric field at any instant can be regarded as stable and can be analyzed according to the electrostatic field[4]. Moreover, under the continuous operating voltage of power frequency, the thyristor valve does not conduct and is in a cut-off state. It works in the small current area. The axial potential distribution is mainly determined by the equivalent capacitance.

3.2. Accuracy verification of the potential distribution calculation model

The simulation model restores the electromagnetic environment and layout scene of the thyristor valve potential distribution measurement in the laboratory. Considering the dispersion of the test resistors
and the influence of high voltage wire, the accuracy of the thyristor valve potential distribution model is verified by comparing the measured data with the simulation results. Since the experiment is carried out at room temperature, the junction capacitance-voltage equation (1) of the thyristor fitted at 20°C is used as the numerical iteration basis to accurately consider the influence of the change of the thyristor junction capacitance on the potential distribution under actual voltage.

\[
C = 1706.3 \times e^{- \frac{U_m}{\sqrt{2 \times 1224.6}}} - 0.719 \times e^{- \frac{U_m}{\sqrt{2 \times 1048.07}}} + 838.5
\]  

(1)

The electric potential distribution result of the thyristor valve obtained by simulation is shown in Figure 4. The calculated results of the nonuniform coefficient of potential distribution of each layer of the thyristor valve and the actual measured result of the "fiber-current method" are shown in Figure 5. 

![Electric potential distribution of thyristor valve](image1)

Figure 4. Electric potential distribution of thyristor valve.

![Nonuniform coefficient of thyristor valve potential distribution](image2)

Figure 5. Nonuniform coefficient of thyristor valve potential distribution.

It can be seen from Figure 5 that the distribution trend of nonuniform coefficient of the thyristor valve in simulation results and the measured results is basically the same, and the overall trend is decreasing. The maximum error of nonuniform coefficient of each point in the simulation and measured results is 4.61%, which can verify that the thyristor valve simulation model has high accuracy.

3.3. Potential distribution characteristics of thyristor valve

3.3.1. Influence of different parallel voltage equalizing capacitor configuration. The voltage equalization design of thyristor valve can follow the conventional voltage equalization measures of traditional arresters, namely, the installation of voltage equalizing ring and parallel capacitors[5]. The installation of voltage equalizing ring is relatively economical and easy to realize. However, due to the high requirement of external insulation strength under the operating impulse voltage and the influence of site layout, the diameter and depth of the voltage equalizing ring are greatly restricted, and the voltage equalizing effect is relatively limited[6]. The high voltage equalizing ring used in original design of the thyristor valve (double ring with a ring diameter of 1420mm and a pipe diameter of 60mm) can only reduce the nonuniform coefficient of the thyristor potential distribution from 1.157 to 1.141. In order to further reduce the non-uniformity of potential distribution, it is necessary to consider the measure of parallel voltage equalizing capacitors. Based on the actual structure and installation convenience of the thyristor valve, the three capacitor layered configuration methods shown in Table 1 are mainly analyzed here.
Table 1. Parallel voltage equalizing capacitor configuration methods.

| Configuration method | ① | ② | ③ |
|----------------------|---|---|---|
| Capacitance C/pF     | 200 | 400 | 700 |
| Distribution location| Layer 1-16th | Layer 1-16th | Layer 1-16th |
| Withstand voltage Ur.m.s./kV | 3.85 | 3.5 | 3.5 |

According to the simulation results, the voltage of each thyristor layer is extracted, and the curve of nonuniform coefficient of the thyristor valve potential distribution is obtained by calculation, as shown in Figure 6.

![Figure 6. Nonuniform coefficient of thyristor valve potential distribution under different capacitor configuration methods.](image1.png)

![Figure 7. Nonuniform coefficient of thyristor valve potential distribution under different operating ambient temperatures.](image2.png)

When the thyristor valve is not paralleled with the voltage equalizing capacitor, the potential distribution of the thyristor is relatively nonuniform. The maximum nonuniform coefficient in the first and second section are 1.141 and 0.952, with a difference of 19.85 %. In order to reduce the voltage of the first section (layer 1-16th) of the thyristor valve, it is necessary to compensate the capacitance. As the value of the equalizing capacitor increases, the compensation effect is gradually improved, and the pressure difference between the first and second sections is gradually reduced. Method ① can reduce the maximum nonuniform coefficient to 1.104, and reduce the maximum nonuniform coefficient difference between the first and second sections to 13.70%. Method ② can reduce the maximum nonuniform coefficient to 1.070. At this time, the voltage of the two sections is relatively uniform with a difference of only 5.00%. Method ③ is an over-compensation method, the voltage of the second section is obviously higher than that of the first section, and the maximum nonuniform coefficient appears on the 18th layer, which is 1.064. What’s more, the difference between the two sections is 4.00%. Under the three configuration methods, the withstand voltage of the voltage equalizing capacitor can all meet the requirements. Therefore, for economic consideration, the configuration method ② can be used to achieve better voltage equalizing effect.

3.3.2. Influence of different operating ambient temperatures. It can be seen from 3.3.1 that adding 400pF voltage equalizing capacitors in layer 1-16th of the original structure can make the voltage of each layer more uniform at room temperature. However, some extreme high and low temperatures may occur in the actual operating environment of the controllable arrester. Since the equivalent capacitance of the thyristor and the resistor varies with temperature, whether the voltage equalizing measure still has a good effect and whether the overall potential distribution of the thyristor is consistent with that at room temperature still need further exploration. Therefore, based on the equivalent capacitance of the thyristor and the resistor at -40°C, 20°C and 60°C obtained by experiments, the extreme ambient temperature is simulated. Similarly, the influence of the change of
the thyristor junction capacitance on the potential distribution under the actual voltage is accurately considered based on the numerical iteration equation (2) at 60°C and the equation (3) at -40°C.

\[
C = 1594.09 \cdot e^{\left(-\frac{U_r}{\sqrt{546.17}}\right)} + 719.835
\]

\[
C = 115.147 \cdot e^{\left(-\frac{U_r}{\sqrt{24837.41}}\right)} + 1678.481 \cdot e^{\left(-\frac{U_r}{\sqrt{2479179.31}}\right)} + 958.881
\]

As Figure 7 shows, as the temperature rises from -40°C to 60°C, the equivalent capacitance of the resistors changes by 31.51%, and the junction capacitance changes only 15.3% under the continuous operating voltage of the thyristor. Since the number of thyristors is twice as many as the number of resistors, the junction capacitance of thyristors is mainly determined by the change of junction capacitance of thyristors. Therefore, under the two extreme temperatures, the difference of thyristor potential distribution is small, and the maximum nonuniform coefficient decreases from 1.073 to 1.057, only changing by 1.49%. The overall thyristor valve tends to be more uniformly distributed, which can verify that the voltage equalizing measures adopted at room temperature are also suitable for extreme ambient temperature conditions.

4. Conclusions

(1) The internal components of thyristor valve of the controllable arrester have the characteristics of the equivalent capacitance changing with temperature and voltage. The test results show that the temperature characteristics of the equivalent capacitance of the resistor are more significant. When the temperature changes from -20°C to 60°C, the maximum rise of the equivalent capacitance of the resistor is 44.63%. The junction capacitance of the thyristor decreases exponentially with the increase of voltage. When the voltage changes from 0kV to 5kV at 20°C, the attenuation of the junction capacitance reaches 59.87%.

(2) The maximum nonuniform coefficient of potential distribution can be reduced from 1.141 to 1.070 by paralleling 400pF capacitors in layer 1–16th of thyristor valve, and the maximum nonuniform coefficient difference between the first and second sections can be reduced to 5.00%. When the equalizing capacitance increases to 700pF, the voltage of the second section exceeds that of the first section, and the maximum nonuniform coefficient is 1.064, which appears at the beginning of the second section.

(3) Under the extreme temperature conditions that may occur in the operating environment of thyristor valve of the controllable arrester, the potential distribution of thyristor valve is slightly different from that at room temperature. The change of equivalent capacitance between resistors and thyristors caused by ambient temperature has little effect on the potential distribution, which can verify that the voltage equalizing measures adopted at room temperature are also suitable for extreme ambient temperature conditions.

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