High Temperature Insulation Design of Capacitive Wall Bushing for High-temperature Solid Electrical Heat Storage Devices

WANG Zhe1,*, FU Qitong2, FAN Jinpeng3, and XING Zuoxia4

1School of Electrical Engineering, Shenyang University of Technology, Shenyang, 110870, China

Corresponding author: 15640042003@163.com

Abstract. The temperature resistance and voltage level of the wall bushing are the key factors restricting the increase of the heat storage capacity of the solid electrical heat storage device. Therefore, by studying the electrical insulation and heat insulation principles of the wall bushing of the solid electrical heat storage device, a new type of capacitive solid electric heat storage device wall bushing suitable for 66~500 kV high voltage and 800 ℃ high temperature was designed, and its internal insulation parameter calculation method considering the influence of high temperature was proposed. The analysis of the bushing through the multi-physics coupling field of temperature field, force field and electric field shows that high temperature deformation does not affect the electrical insulation of the capacitor core. However, in order to reduce the pressure of the outer insulation layer of the bushing, a deformation margin of 3% of the radius of the ground electrode plate still needs to be left. The change of relative dielectric constant will enhance the field strength at the edge of the capacitor core plate and deteriorate the electric field distribution of the bushing. Therefore, when calculating the internal insulation, it is necessary to set a partial discharge calculation margin of 1.4 times and the ratio of the length of the internal and external steps of the capacitor core furnace to 86%. As the voltage level increases, the effect of high temperature on the electric field distribution of the bushing becomes weaker.

1. The introduction

With the increasing proportion of new energy in China's energy structure, high temperature solid electric heat storage device (HTSEHS) is used to convert new energy power generation into heat energy for storage and utilization, which has a more significant effect on improving the utilization rate of new energy power generation[1-2]. In the improvement of HTSEHS capacity, the temperature of heat storage and the voltage level of power supply are improved at the same time, which also puts forward higher requirements for the wall bushing of high temperature solid electric heat storage device. To develop a kind of wall bushing with higher temperature resistance and insulation performance has become an important research content in the development of HTSEHS.

At present, the research on high temperature insulation design of through wall bushing at home and abroad is mainly to study the variation of electric field at high temperature according to the distribution characteristics of temperature field and the high temperature characteristics of insulation materials. Zeng D and radakovic Z[3-4] established the thermal model of the casing by hot spot measurement, and studied the optimization method of the heat transfer structure of the casing. Zhang S
and Zhang Shiling[5-7] used the RC thermal network method to calculate the transient temperature distribution of the bushing whose material properties are related to temperature, and to analyze the transient temperature of the high voltage bushing. Jyothi N S[8] and others analyzed the temperature field of epoxy resin impregnated wrinkly paper (RIP) dry high voltage bushing, and proposed the calculation method of maximum thermal voltage based on rip AC conductivity. Lin Shen[9-11] studied the conductivity change of oil paper bushing under the influence of temperature, carried out heat flow coupling calculation for Joule heat and eddy current loss, and analyzed the influence of temperature on oil paper bushing insulation. Zhang Shiling[12-13] and others studied the dry DC bushing using SF6, analyzed the relationship between insulation medium and temperature, and deduced the decoupling model of temperature field and electric field. Chi Minghe[14] studied the influence of temperature on the electric field distribution under composite voltage by conducting experiments on the resistivity and conductivity characteristics of oil paper insulation and combining with simulation. However, the existing research on high temperature bushing is mainly for high temperature insulation of DC bushing below 120℃. For the 800℃ high temperature and AC environment in this paper can not meet.

In order to improve the voltage level of wall bushing for high temperature solid electric heat storage device (WDHTSEHS), this paper focuses on the design of a kind of bushing which can withstand the voltage of 66-500kV. The high temperature insulation characteristics of WDHTSEHS are studied. The influence of deformation and relative permittivity on the insulation function of capacitor core is analyzed, and the reasonable optimization method is proposed.

2. Design principle and structure

2.1 Design principle
The inner part and outer part of WDHTSEHS have different working environment. The wall is in a high temperature environment, and the temperature is above 800 ℃. The sleeve outside the wall is in the atmospheric environment. Because the high temperature solid electric heat storage device operates in winter, the atmospheric environment temperature can reach minus 20 ℃, and the temperature difference between the inside and outside of the device can reach more than 800℃. It is necessary to design the insulation and heat insulation of bushing separately. The schematic diagram is shown in Figure 1. The conductive rod is the high potential end of the bushing, and the flange is the low potential end of the bushing[15]. The power line at the flange is the densest with the largest field strength, which is prone to flashover or air breakdown. Therefore, the electric field at the flange must be improved to make the electric field distribution more uniform[16].

![Figure 1. Insulation principle of wall bushing](image)

Conducting rod and electric heating element conduct heat transfer through heat conduction; the surface of bushing carries out convective heat transfer with the air in the device and thermal radiation heat transfer with the heat storage body; the outside wall bushing dissipates heat by convective heat in outdoor, so the structure of bushing needs to be improved to prevent heat transfer in these two aspects[17].

2.2 Geometric configuration
As shown in Figure 2, a kind of capacitive bushing designed in this paper is mainly composed of conducting pole, outer insulating layer, capacitor core, impregnated insulating medium, heat resisting ring and voltage equalizing device.
Dry type capacitor core impregnated with high temperature resistant epoxy resin is used as internal insulation, and aramid fiber is used as manufacturing material of capacitor core to improve voltage level, high temperature resistance and initial partial discharge voltage of wall bushing[18]. Using SF6 as the filling medium between the outer insulating layer of the bushing and the capacitor core can improve the corona discharge resistance, withstand certain high temperature and protect the capacitor core[19]. Two layers of opaque quartz material are sandwiched with alumina ceramic material. The better mechanical properties and thermal vibration resistance of quartz material are used to prevent the casing from cracking due to repeated temperature rise and fall. Alumina ceramic material is used to prevent SF6 corrosion. Two layers of vacuum cavity are formed between the outer insulation layers for heat insulation, and can also prevent flashover[20].

The heat resisting ring in Figure 3 is used to absorb the heat transferred from the electric heating element to the bushing. Alumina ceramic is selected as the heat storage material of the heat resistance ring, and aluminum silicate fiber with low thermal diffusivity is used as the heat insulation material to make the temperature of the heat resistance ring evenly distributed.

In Figure 3, the true cavity is used to realize the radial heat insulation of the casing. On the basis of heat insulation, it can also prevent corona or gas breakdown[21]. In order to reduce the influence of the cushion block on the insulation effect of the vacuum layer, the double-layer vacuum cavity structure is adopted.

3. Parameter calculation and finite element model

3.1 Calculation of insulation parameters

The parameter calculation in this paper is based on the wall bushing with rated voltage of 66kV, and the main technical indexes are shown in Table 1.

| Item                              | Number | Unit |
|----------------------------------|--------|------|
| Un                               | 66     | kV   |
| In                               | 1000   | A    |
| Tn                               | 800    | ℃    |
| Tmax                             | 900    | ℃    |
| SF6 Pmin                         | 0.35   | Mpa  |
| SF6 Pn                           | 0.4~0.6| Mpa  |
| SF6 Pmax                         | 0.8    | Mpa  |
| Power frequency withstand voltage test | 160   | kV   |
| Lightning impulse withstand voltage test | 380   | kV   |
| Insulator's pollution level      | 1      | kV   |

The insulation calculation of WDHTSEHS includes internal insulation calculation and external insulation calculation. The main purpose of insulation calculation in capacitive bushing is to calculate the size of capacitor core. In this paper, through high temperature insulation analysis, the initial values of field strength safety margin and length ratio of inner and outer steps for WDHTSEHS internal insulation calculation are given. Through high temperature insulation analysis, the initial values of field strength safety margin and length ratio of inner and outer steps for WDHTSEHS internal insulation calculation are given.

Without considering the influence of high temperature, the minimum insulation thickness of bushing is 1.2mm. When the initial field strength of partial discharge is 2MV/m, the number of insulation layers of bushing can be calculated as 16.

According to the calculation of external insulation, the length of bushing Lg is 700 mm and the creepage distance is 1056 mm. The grounding electrode plate is 10% higher than the discharge distance of the outer tube of the device, and the zero electrode plate is 20% lower than the discharge distance of the outer tube of the device. If the length ratio of the inner and outer steps of the device is 100%, the length of the inner step of the device is 3 cm.
3.2 Geometric configuration
By setting the inner diameter of the outer insulating layer of the bushing as 95 mm, the thickness of the vacuum layer as 8 mm, and the heat transfer power of the conductive rod as 1500 W, the volume of the heat resistance ring can be calculated as 32×106 mm3. If the ratio of the height of the dome to the radius of the bottom is 1.2 and the number of thermal storage layers is designed to be 6, the structural parameters of the thermal barrier ring are shown in Table 2.

| H     | Ra   | Rb   | Insulation thickness | Thickness of external insulation layer |
|-------|------|------|----------------------|----------------------------------------|
| 280 mm| 146 mm | 235 mm | 5 mm                | 20 mm                                   |

3.3 Finite-element-model
The finite element models of temperature field and electric field are included in this paper. The governing equations of partial convective heat transfer in temperature field are as follows:

The heat transfer inside the casing is heat conduction heat transfer. Because the casing is a cylindrical model, its finite element model is as follows:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + q = \rho c \frac{\partial T}{\partial t}
\]

Where R is the radius, z is the axial length, t is the time, λ is the thermal conductivity, Ts is the solid temperature, q is the heat generation rate per unit volume, ρ is the density, and c is the specific heat capacity.

In order to study the deformation of casing at high temperature, the total strain is expressed as follows in the period of time t:

\[
\varepsilon(t) = \varepsilon_c(t) + \varepsilon_T(t)
\]

The instantaneous electric field of through wall bushing can be considered as stable field, and it can be considered as electrostatic field in finite element calculation. In cylindrical coordinates, the Poisson equation of potential can be expressed as:

\[
\nabla^2 \phi = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \phi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial \theta^2} + \frac{\partial^2 \phi}{\partial z^2} = -\frac{\rho_b}{\varepsilon}
\]

Where \( \phi \) is the potential, \( \rho_b \) is the bulk charge density and \( \varepsilon \) is the dielectric constant.

4. High temperature characteristic analysis
COMSOL is used to analyze the temperature field of through wall casing in high temperature environment. Figure 3 shows the temperature field distribution of the through wall bushing after
heating for 7h under radiation heat transfer. The end temperature of the conductive rod of the through wall bushing has the greatest impact on the high temperature safety of the whole device. SF6 gas and capacitor core can withstand the high temperature of 500℃ and 370℃ respectively, which is the key to the temperature safety analysis of WDHTSEHS. According to the simulation results shown in Figure 5(a), the maximum temperature of SF6 gas is 384.59℃, which meets the temperature resistance requirements and has a temperature safety margin of about 1.3, and the maximum temperature of capacitor core is 264.32℃, which meets the temperature resistance requirements and has a temperature safety margin of about 1.4. Compared with figure 3 (b), the maximum temperature of SF6 gas can be reduced by 630.1℃ by the heat blocking ring, and the cooling effect is obvious.

The temperature gradient distribution of WDHTSEHS is shown in Figure 6. The temperature gradients of the bushing and the insulation wall are not taken into account in the temperature gradient diagram. According to the calculation, the maximum temperature gradient of the pad is 16.19℃/mm, and the maximum temperature gradient of the edge of the capacitor core is 5.28℃/mm. It is proved that the temperature gradient of the bushing pad is the largest and the volume of the pad is small, which only affects the deformation, but does not affect the insulation and electric field distribution of the bushing. The temperature gradient of capacitor core Zero plate and grounding plate accessories is large, which has the greatest influence on the electric field distribution.

4.1 Wall bushing deformation
The structure mechanics analysis of through wall casing is carried out. The boundary between flange and wall is set as fixed boundary, and the boundary of other parts of casing is set as free boundary. As shown in Figure 5, the deformation at the end of the bushing is serious. The maximum deformation at the conductive rod is 1.78mm, and the maximum stress is 14.4 $\times$ 10⁸ N/m². This is due to the large thermal expansion coefficient of the conductive rod and the high temperature in the device, which is related to the cylindrical structure of the bushing. In addition, the maximum displacement of the capacitor core is 1.57mm and the maximum stress is 8.39 $\times$ 10⁸ N/m².

Figure 6 shows the displacement curve of the edge of the bushing plate in the device, taking the radial positions of the edges of the 3rd, 6th, 9th, 12th and grounding plates. It can be seen from figure 6 that the total displacement of the electrode plate near the conductive rod is large, and the displacement of the outer edge of the capacitor core is greater than the internal displacement.
largest, and the peak stress appears at the position of the cushion block, indicating that the bushing near the cushion block bears the deformation pressure of the bushing. It can be seen from Figure 7 (b) that the displacement of the outer insulation layer of the bushing is mainly radial displacement, which is calculated as 1% of the vacuum thickness, and has little effect on the bushing. It can be seen from Fig. 7 (c) that the displacement of the outer insulating layer of the bushing is mainly caused by the cushion block, so the displacement is distributed near the cushion block. The maximum displacement is 0.35mm, and the radial displacement is close to the axial displacement. The radial displacement is 3.18% of the thickness of the vacuum layer, and the axial displacement is 2.49% of the length of the cushion block, which has little impact on the safety of the bushing. The casing far away from the flange is mainly a small radial displacement component.

It can be seen from Figure 7 (d) that the deformation of the outer insulation inner layer of the bushing in the flange part is large, and the main component of the inner Bushing in the flange part is the radial displacement component, and the main component of the outer Bushing in the flange part is the axial displacement component. This is because the distance between the outer insulation inner layer and the capacitor core is close, and it is easy to deform due to the influence of the capacitor core. The displacement direction of the outer insulation inner layer is similar to that of the capacitor core, the direction of thermal expansion of the capacitor core is related. After calculation, the maximum displacement of the outer insulation inner layer is 0.84 mm, the maximum radial displacement is 0.79 mm, which is 10% of the thickness of the vacuum layer, and the maximum axial displacement component is 0.65 mm, which is 6.5% of the length of the cushion block.

**Figure 7.** Displacement curve of outer insulation layer

To sum up, the deformation of WDHTSEHS is related to the thermophysical properties, temperature field distribution and structural design of the material. The deformation of the outer insulation inner layer is greatly affected by the deformation of the capacitor core, and the axial displacement component of the deformation of the capacitor core is the main displacement. Therefore, only the deformation of capacitor core can be considered in WDHTSEHS design.

4.2 Relative permittivity of through wall bushing

Figure 8 shows the relative permittivity distribution of the bushing of WDHTSEHS capacitor core after 7 hours of radiation heat transfer. It can be seen from the figure that the relative permittivity distribution of the capacitor core has a large gradient on one side of the device. The average value of
the relative permittivity of the capacitor core is 3.57 and the maximum value is 7.18 after 7 hours of radiation heat transfer, which has a great local influence. Compared with the normal temperature, the average value of the relative permittivity of each layer increases slightly, but the maximum value increases greatly, which indicates that the effect of high temperature on the relative permittivity is mainly local.

![Figure 8](image)

**Figure 8.** Distribution diagram of relative dielectric constant after 7h of radiant heat transfer

5. Analysis of electric field thermal characteristics of WDHTSEHS

5.1 Electric field thermal characteristics of wall bushing

In this section, we will study the influence of relative permittivity and geometry on the electric field of through wall bushing under high temperature difference. Figure 9 shows the influence of the change of relative permittivity and geometric structure on the electric field intensity at the edge of the capacitor core plate. At high temperature, with the increase of relative permittivity of the insulation material of the capacitor core, the maximum electric field intensity at the edge of each plate will increase. When the geometric structure of the bushing changes, the electric field intensity at the edge of the plate will decrease due to the increase of the radial thickness of the plate.

Figure 10 shows the influence of relative permittivity change and geometric structure change on the electric field strength of the capacitor core along the step. The change of relative permittivity has a great influence on the electric field strength of the capacitor core along the step. At high temperature, the electric field strength distribution along the step will change greatly. The electric field strength of the capacitor core along the inner side of the step will decrease, and the electric field strength on the outer side will increase. When the geometry of the capacitor core changes, the overall electric field strength decreases, which can improve the anti flashover ability of the bushing.

![Figure 9](image)

**Figure 9.** Thermal characteristics of the electric field intensity distribution at the edge of the plate

It can be seen from Figure 9 and Figure 10 that the influence of high temperature on the electric field intensity along the step of the capacitor core is slightly greater than that on the edge of the electrode plate. The reason is that the diameter of the capacitor core is relatively small relative to the length of the bushing, the gradient of the electric field intensity along the radial direction is small, and the total change value of the relative permittivity and the shape variable of the capacitor core along the axial direction is small, so the influence on the electric field intensity at the edge of the electrode plate is small. In addition, the influence of relative permittivity on the electric field strength of capacitor core is much greater than that of deformation, so the partial discharge calculation of capacitor core can improve the safety margin in the insulation design of bushing.
Figure 10. Thermal characteristics of axial electric field intensity distribution of capacitor core along steps

Figure 11. Thermal characteristics of electric field distribution on bushing surface

Figure 11 shows the influence of the change of relative permittivity and geometric structure on the electric field distribution of the through wall bushing. It can be seen from the figure that the electric field inside and outside the through wall bushing device changes, indicating that high temperature has an impact on the electric field distribution of the through wall bushing. According to the calculation, when the relative permittivity changes, the potential of the bushing increases as a whole, the maximum potential of the bushing in the device increases by 4495.45V, and the maximum potential of the outer sleeve of the device increases by 595.35V, which indicates that the change of the relative permittivity has a deterioration effect on the electric field distribution of the bushing at high temperature. When the geometric structure is deformed, the electric potential of the casing is also enhanced as a whole. The maximum electric potential of the casing in the device is increased by 201.37V, and the maximum electric potential of the casing in the device is increased by 26.28V, indicating that the geometric structure deformation has a deterioration effect on the distribution of the casing inside and outside the device at high temperature.

6. Conclusion
Through the research of capacitive WDHTSEHS, the following conclusions are drawn.

(1) The temperature difference between inside and outside of the bushing can reach 400 °C, which can effectively protect the dry-type capacitor core.

(2) Through the analysis of high temperature insulation characteristics, it can be seen that high temperature will cause bushing deformation and relative dielectric constant change, and the influence of high temperature on bushing capacitance core is far greater than that on external insulation of bushing. The results show that the distortion caused by deformation is far less than that caused by the change of relative permittivity. Therefore, the influence of deformation can be ignored in the calculation of the internal insulation of the bushing, and a deformation margin of 3% of the radius of the grounding plate can be reserved to reduce the extrusion of the capacitance core deformation on the external insulation of the bushing.

(3) According to the internal insulation calculation method, considering the distortion of bushing field strength and electric field distribution caused by high temperature, taking 66kV bushing internal insulation calculation as an example, setting the safety margin of 1.4 times of partial discharge calculation can effectively offset the increase of capacitor core plate field strength, and setting the plate length of capacitor core device as 86% of the outer part of the device can effectively improve the electric field distribution of bushing Cloth. With the increase of voltage level, the distortion caused by high temperature will be smaller.

7. References
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