Electro-thermal Coupling Model for Radial Temperature and Electric Field Distribution Computation and Experimental Research of 550kV RIP AC Oil-gas Bushings

Zhang Shiling¹, Song Wei¹, Yang Huaxia¹
¹State Grid Chongqing Electric Power Company Chongqing Electric Power Research Institute, Chongqing, 401123
zhangshiling@cq.sgcc.com.cn

Abstract. The condenser of 550kV RIP oil-gas bushings is in the solid structure of resin-epoxy impregnated paper(RIP), which has large difference with the oil-immersed one (OIP). Oil-gas bushings has compact configuration and heat conduction condition is harsh, while temperature distribution has direct relationship with bushings’ long-term stable operation performance, so it’s essential to carry out research in radial temperature within condenser during production of RIP oil-gas bushing prototype. In this paper, radial temperature distribution principle of bushing condenser under linear material conditions has been summarized by building electro-thermal coupling theoretical model of bushing condenser. The model has been generalized by electro-thermal coupling finite element mode under nonlinear material conditions, and electro-thermal coupling iterative computation process has also been proposed, then experimental measurement study in local temperature points of bushing condenser has been carried out. The study shows that plate model has advantages of high accuracy and simple form in calculating radial temperature distribution of bushing condenser; the hot-spot temperature of 550kV RIP oil-gas bushings is about 95℃ which appears near the center conductor; radial temperature of bushings under nonlinear material conditions is lower than that under linear material conditions and the thermal breakdown voltage of condenser under rated current is 538kV which is higher than the maximum operation phase voltage. This paper provides theoretical foundation for radial temperature computation within RIP bushing condenser and has some reference value for the design of HVAC RIP bushings.

1. Introduction
The construction of super / UHV substation in China is rapid, and the land resources and environment problems are increasingly prominent. Compared with the ordinary oil to air type bushing connecting the overhead soft conductor, the oil-gas bushing connecting transformer and the fully enclosed composite electrical equipment have great advantages in terms of the reliability, floor area and other technical indexes. Therefore, the research and development of AC 550kV capacitance dry-type oil and gas bushing has been carried out in China. The capacitance oil and the gas bushing is typical complex insulation structure, which has a central current carrying guide rod inside, and then formed into a solid core structure of epoxy impregnated paper through the process of rolling, casting and curing. During the bushing operation, the core has the comprehensive effects of electric, thermal and mechanical stress, while the electrical and mechanical stresses are left with a large margin in the early design stage, so the above two factors have little influence on the long-term operation performance of the bushing core. However, the heat inside the core of the bushing is mainly from the eddy current loss of the
central guide rod and the heating of the insulation medium joule. The dry type bushing capacitor core has no oil immersed oil channel convection channel, which is mainly through the internal radial conduction heat dissipation. Therefore, the 550kV capacitance dry oil and gas bushing bears the severe thermal stress, while the short-term and long-term insulation performance and dielectric breakdown characteristics of core are mainly determined by the heat stress. In view of this, the radial temperature distribution in the core of 550kV capacitance dry type oil and gas bushing is analyzed theoretically and experimentally.

At present, there are few literatures about the research on the temperature field inside the bushing core at home and abroad, and the existing data mainly focus on oil immersed bushing. Shibao in literature [1] Zhang analyzed the steady state, transient thermal performance and current overload capacity of high-pressure oil immersed bushing by using the cylinder model of bushing core. In document [2], v.raf studied the thermal stability of UHV oil immersed bushing by using core cone model, and got the core thermal impact voltage value of $U_{BT}$ under rated load flow. In document [3], n.s.jyothi built on the condition of material non-linearity by core plate model. The heat flow equation is established to analyze the radial temperature distribution and get hottest temperature value $T_{\text{max}}$. The above literature shows that the theoretical models of temperature distribution of core include flat plate, cylinder and cone model. The thermal breakdown voltage value $U_{BT}$ and the hottest point temperature value $T_{\text{max}}$ are two important parameters to evaluate the thermal performance of core. The nonlinear insulation material has a great influence on the temperature distribution and related parameters inside the bushing core. Based on this, this paper takes 550kV capacitance dry oil and gas bushing as the research object, and continues to carry out research and analysis from the following three aspects: ① three kinds of electric coupling theoretical models are established, namely, flat plate, cylinder and cone of bushing core. The model is simple and accurate by theoretical derivation. ② theoretical model is limited under the condition of the material non-linearity. In this paper, the above model is extended by the electric heating coupled finite element model, and the iterative flow path of the finite element electro-thermal coupling calculation is analyzed. ③ the model is used and actual structure size of 550kV capacitance dry-type oil and gas bushing core is determined. The radial temperature distribution was analyzed. The hottest point temperature value $T_{\text{max}}$ and the thermal breakdown voltage value $U_{BT}$ are calculated by using the nonlinear model. The temperature change in the local region of the bushing core is studied under the rated load flow of 5000A. In this paper, the model of thermal coupling is established and perfected to analyze steady radial temperature distribution of bushing. A complete theoretical formula and finite element method of electric coupling iteration are obtained, and the relevant temperature test analysis is carried out. The results have been successfully used in the prototype production of 550kV capacitance dry oil and gas bushing, and it has certain reference value for the design and development of other high voltage AC dry bushing.

2. Theoretical model of thermo-electric coupling for bushing

2.1. Establishment of theoretical model of thermoelectric coupling for bushing

550kV AC dry oil and gas bushing is of capacitive structure. The core body is shown in Fig. 1 (a). The intermediate metal part is the grounding flange. The core body is poured with special epoxy resin and insulating paper to form composite insulating medium. The core body is internally connected with the central metal guide rod, which simultaneously supports the voltage and current to realize power transmission. Under the power frequency condition, the heat generated by the bushing core is mainly composed of the eddy current loss of the central guide rod and the joule heating of the insulating medium. On the other hand, the axial dimension of the bushing core is much larger than the radial dimension, so the heat in the core mainly flows through the radial direction, and the axial heat flux can be ignored. Based on the above assumptions, the internal heat flow model of bushing capacitor core can be established, as shown in Fig. 1 (b).
In the cylindrical structure of Fig. 1 (b) ($r_1 < r < r_2$), $r_1$ and $r_2$ are the radius of the central guide rod and the insulating medium, respectively. In this model, the steady heat flux continuity differential equation can be expressed by equation (1):

$$\frac{1}{r} \frac{d}{dr} \left( r k \frac{dT(r)}{dr} \right) + \sigma \left( \frac{d\phi(r)}{dr} \right)^2 = 0 \quad (1)$$

In the formula (1), $k$ is the thermal conductivity of the insulating medium, $T(r)$, $\phi(r)$ are the temperature and potential values at the distance $r$ from the radial cross section of the core to the central axis, and the electric field intensity $E(r)$ can be expressed by formula (2):

$$E(r) = \frac{d\phi(r)}{dr} \quad (2)$$

$\sigma$ is the equivalent conductivity of insulating medium in the alternating electric field, which can be expressed by the relative permittivity $\varepsilon_r$ and loss tangent of insulating medium $\tan \delta$:

$$\sigma = 2\pi f \varepsilon_0 \varepsilon_r \tan \delta \quad (3)$$

In equation (1), the first term on the left of the equation represents the radial flow of heat, and the second term represents the heat production per unit volume in the insulating medium. It can be seen from the equations (1) to (2) that if the analytic solution of the second order differential equation in equation (1) is to be obtained, the specific expression of the electric field intensity $E(r)$ on the radial cross section of the capacitor core is needed.

According to the different types of $E(r)$ expressions, this paper proposes three theoretical calculation models for the electrothermal coupling of capacitor core, which are called plate model, cylinder model and cone model respectively: plate model (model 1) assumes that the local area of capacitor core is a plate structure, and the internal electric field intensity $E(r)$ is uniformly distributed in the radial direction; cylinder model (model 2) assumes that the capacitor core is an infinite cylinder structure, and $E(r)$ is in the radial direction. The cone model (model 3) simulates the cone-shaped
structure of the actual capacitor core of the bushing core, and $E(r)$ presents the U-shaped distribution in the radial direction, as shown in Figure 2. The expressions of $E(r)$ under the three models are listed in Table 1.

| E($r$) expressions in different models |
|----------------------------------------|
| **Model 1** | **Model 2** | **Model 3** |
| $E(r)$ | $\frac{U_m}{r_2 - r_1}$ | $\frac{U_m}{r \ln \left( \frac{r}{r_1} \right)}$ | $\frac{U_m (L_1 + L_2)}{2 \ln \left( \frac{r}{r_1} \right)}$ |

In Table 1, $U_m$ represents the highest operating phase voltage of the bushing during operation. In model 3, $L_1$ and $L_2$ are the lengths of the zero layer of the bushing capacitor core and the grounding plate, respectively, as shown in Figure 2, and the detailed derivation process of $E(r)$ is shown in reference [4-8]. It can be seen from table 1 that $E(r)$ in model 3 is closest to the actual radial electric field distribution of bushing capacitor core, but the expression is more complex. Model 1 has the simplest expression, but the electric field distribution is quite different from the actual situation. Model 2 belongs to the transition between model 1 and 3. This paper will use the above three models in the following content to deduce the theoretical expression of radial temperature field distribution $T(r)$ in bushing capacitor core in detail under condition of electro-thermal coupling, and make a comparative study. By substituting $E(r)_i$ ($i$ is the model number) in Table 1 into equations (1) to (2), equation (4) can be obtained:

$$\frac{1}{r} \frac{d}{dr} \left( r \sigma \frac{dT(r)}{dr} \right) + \sigma E(r)^2 = 0 \quad (4)$$

### 2.2. The radial temperature distribution of different electrothermal coupling theoretical models in linear medium

The high nonlinear relationship between the equivalent AC conductivity of insulating medium and the radial temperature $T(r)$ in the bushing capacitor core makes it difficult to solve the second order differential equation in formula (4), because in most cases, there is no closed solution. In view of this, the following contents are discussed in two situations: (1) it will be treated as a constant, namely, the specific value obtained by formula (3) by using the tangent of the relative dielectric constant and loss angle of insulating medium at room temperature. (2) it will be treated as the function of temperature, as shown in formula (5).

$$\sigma = \sigma_0 f \left( T(r) \right) \quad (5)$$

Where $\sigma_0$ is the conductivity value of insulating medium at room temperature. For model 1, equation (6) can be obtained:

$$T_1(r) = C_{11} + C_{12} \ln(r) - m \left( \frac{r}{2(r_2 - r_1)} \right)^2 \quad (6)$$

For model 2, equation (7) can be obtained:

$$T_2(r) = C_{21} + C_{22} \ln(r) - m \left( \frac{\ln(r)}{\ln \left( \frac{r_2}{r_1} \right)} \right)^2 \quad (7)$$

For model 3, equation (8) can be obtained:
\[ T_i(r) = C_{31} + C_{32} \ln(r) - m\left(\frac{M \ln(r)}{N}\right) + \frac{Mb \ln(b - N \ln(r))}{N} - \frac{M \ln(b - N \ln(r)) \ln(r)}{N} \] (8)

Thus \( M = \left(\frac{L_1 + L_2}{2}\right)^2 \), \( N = \frac{L_2^2 - L_1^2}{\ln\left(\frac{r_2}{r_1}\right)} \), \( b = L_2 + N \ln r_i \).

Equations (6) to (8) respectively give the radial temperature distribution of bushing capacitor core under the above three models:

\[ m = \sigma \frac{U_i^2}{k} \] (9)

\( C_{ij}(i=1\sim3, j=1\sim2) \) is the undetermined coefficient, which can be determined according to the boundary conditions. Considering the actual operation condition of 550kV AC dry oil and gas bushing analyzed in this paper, the boundary conditions of the theoretical model are described by formula (10):

\[
\left\{
\begin{aligned}
&\frac{dT_i(r)}{dr} \bigg|_{r=r_1^+} = -\frac{P_1}{2\pi r_k}, \\
&T_i(r) \bigg|_{r=r_2^-} = T_a
\end{aligned}
\right.
\] (10)

In the above formula, \( P_1 \) is the eddy current loss of the center guide rod per unit length. \( T_a \) is the ambient temperature of the capacitor core. By combining (10) and (6) ~ (8), the concrete expression of \( C_{ij} \) can be derived. Under the three models, radial temperature distribution \( T_i(r) \) of bushing capacitor core is composed of two terms, the first term \( \bar{T}_1(r) \) is the temperature rise caused by eddy current loss, and the second term \( \bar{T}_2(r) \) is the temperature rise caused by joule heating of insulating medium. For \( \bar{T}_1(r) \), it has the same expression under three models, namely:

\[ \bar{T}_1(r) = \frac{P_1}{2\pi k} \ln\left(\frac{r_2}{r}\right) + T_a \] (11)

For \( \bar{T}_2(r) \), the expressions are different under the three models, which are listed in equations (12) to (14):

\[ \bar{T}_2(r) = m\left(\frac{r_2^2 - r^2}{4} + \frac{r_1^2 \ln\left(\frac{r^2}{r_2^2}\right)}{2}\right) / (r_2^2 - r_1^2) \] (12)

\[ \bar{T}_2 = m \frac{\ln\left(\frac{r_2}{r_1}\right) \ln\left(\frac{r_1}{r}\right)}{r \left(\ln\left(\frac{r_2}{r_1}\right)^2\right)} \] (13)

\[ \bar{T}_3 = m \frac{M}{N} \left(\frac{b}{N} - N \ln r - \ln b + N \ln r_i \right) \ln\left(\frac{r_2}{r}\right) + \ln\left(\frac{r_2}{r}\right) \ln\left(b - N \ln r_i\right) \] (14)

It can be seen from formula (12) ~ (14) that the temperature rise caused by joule heating of insulating medium is the nonlinear function of radius \( r \). Through further analysis, it is found that the
temperature rise is the largest near the central guide rod of bushing \((r=r_1)\), and decreases when it is far away from the central guide rod. In fact \(T_i(r)\) \((i=1\sim3)\) can be represented by the general formula (15) under the three models.

\[ T_i = m f_i(r) \quad (15) \]

In the above formula, \(m\) represents the inherent properties of the insulating medium used in the bushing capacitor core, and \(f_i(r)\) represents the structural characteristics of the bushing core. In the design of the bushing, it is necessary to ensure that the internal temperature rise of the core body meets the control requirements, which can improve the operation reliability and prolong the service life. It can be seen from formula (15) that when the structure size of bushing capacitor core is fixed \((f_i(r)\) is constant), the coefficient \(m\) will directly affect temperature rise of bushing in steady-state operation. It can be seen from formula (9) that \(m\) is proportional to the square of \(U_m\). Therefore, for 550kV AC dry oil and gas bushing, the temperature rise caused by the joule heating of insulating medium is more significant, which needs to be quantitatively analyzed by the above three electrothermal coupling models. On the other hand, \(m\) is proportional to \(\frac{\sigma}{k}\), which puts forward requirements for the inherent characteristics of insulating medium: the AC equivalent conductivity at room temperature should be as small as possible and the conductivity should be as high as possible. The thermal coefficient should be as large as possible, so that the steady-state temperature rise of dry bushing core can meet the control requirements.

2.3. Limitation and extension of electro-thermal coupling theory model in nonlinear medium

In the following, above-mentioned electrothermal coupling theoretical model is extended to consider the temperature nonlinear characteristics of the properties of the insulating materials, which can be obtained by combining equations (4) and (5):

\[ \frac{1}{r} \frac{d}{dr} \left( r k \frac{dT(r)}{dr} \right) + \left( \sigma_0 f(T(r)) \right) E(r)^2 = 0 \quad (16) \]

In general, the variation law of the function of AC conductivity and temperature of different insulating media is different, that is, the function \(f\) has different expressions. The existing literature generally uses following formula to express the relationship between equivalent conductivity and temperature [9-11], that is:

\[ \sigma = \sigma_0 e^{\alpha T} \quad (17) \]

Where \(\alpha\) is the temperature coefficient of equivalent conductivity of insulating medium of bushing capacitor core. Taylor series is used to expand the function \(f\):

\[ e^{\alpha T} = 1 + \alpha T + \frac{(\alpha T)^2}{2} + \frac{(\alpha T)^3}{6} + \frac{(\alpha T)^4}{24} + \cdots \quad (18) \]

In general \(\alpha T < 0.01\), the first two terms of formula (18) can be used to approximate the original function \(f\) with higher accuracy:

\[ \frac{1}{r} \frac{d}{dr} \left( r k \frac{dT(r)}{dr} \right) + \left( \sigma_0 (1 + \alpha T(r)) \right) E(r)^2 = 0 \quad (19) \]

By substituting the expression of \(E(r)\) in Table 1 into equation (19), the radial temperature control equations of the three models can be obtained under the condition of material non-linearity. Through analysis, it is found that the analytic solution of equation (19) is obtained under three different models (different \(E(r)\) expressions), and the calculation of the formula is complicated, even does not exist at all. In model 1, the solution of equation (19) can be expressed as follows:
Where \( \lambda = \frac{\sigma_0}{k} \left( \frac{U_m}{r_2 - r_1} \right)^2 \), the general solution of equation (20) is as follows:

\[
T_4(r) = C_{41}J_0(r\sqrt{\alpha \lambda}) + C_{42}Y_0(r\sqrt{\alpha \lambda}) - \frac{1}{\alpha}
\] (21)

Among them, \( J_0(x) \) , \( Y_0(x) \) are zero order Bessel functions of the first and second kind respectively. \( C_{41} \), \( C_{42} \) can be obtained by simultaneous expression of the boundary value condition (10). The expression is complicated and the derivation process is omitted. In model 2 and 3, there is no closed form analytical solution to equation (19). On the other hand, the relationship between AC conductivity and temperature of insulating medium used in 550kV AC dry oil and gas bushing is experimentally measured, and the results are shown in Fig. 3.

Fig.3 Relationship between conductivity and temperature of bushing condenser

It can be seen from Figure 3 that the conductivity changes in a U-shape in the range of 0 ~ 110°C. The conductivity rises abruptly in the range of 110 ~ 140°C, and the above change relationship cannot be fully characterized by equation (17). This paper proposes to fit the functional relationship between conductivity and temperature by equation (22).

\[
\sigma = \sigma_1 e^{\alpha_1 T} + \sigma_2 e^{\alpha_2 T}
\] (22)

According to the experimental data of insulation medium used in 550kV AC dry oil and gas bushing, it can be determined as follows: \( \sigma_1 = 6.624 \times 10^{-13} \text{S/cm}, \) \( \alpha_1 = -0.01015; \) \( \sigma_2 = 3.3 \times 10^{-16} \text{S/cm}, \) \( \alpha_2 = 0.06816, \) it can be determined that the fitting effect is good. The above analysis shows that the thermoelectric coupling model can not be used to further analyze the radial temperature distribution of bushing capacitor core under the condition of material non-linearity, and other analysis methods are needed to promote the thermoelectric coupling model of bushing. In this paper, the solid model of the bushing capacitor core is established by using the finite element analysis, and the material attribute definition and mesh generation are realized in the calculation environment. The finite element model of the bushing core is shown in Figure 4.
In order to realize the coupling calculation of the electric field and thermal field, this paper uses the iterative calculation method of physical environment: the physical calculation environment of electric field and temperature field is established respectively. According to equations (10) - (14) and (22), the initial radial temperature distribution $T(r)$ and the conductivity value at radius $r$ of the bushing are determined. In the electric field calculation environment, the harmonic field analysis function is used to calculate electric field distribution in the insulating medium according to the obtained conductivity, and the joule calorific value caused by leakage current is extracted. In the temperature field calculation environment, the boundary condition equation (10) is applied, and the dielectric value obtained in the harmonic field analysis is calculated. The joule calorific value is loaded into the temperature field analysis model to calculate the radial temperature distribution of the cross section of the bushing capacitor core, and the insulating material properties are obtained by interpolation with the calculated temperature value. According to the modified properties, electric field distribution and joule calorific value are calculated again under physical environment of electric field calculation, and the temperature field distribution is corrected by substituting them into the temperature field calculation environment. The calculated temperature difference meets control accuracy requirements[12-18].

3. Calculation example of radial temperature distribution of 550kV dry oil and gas bushing
The structural parameters of 550kV dry oil and gas bushing core are shown in Table 2. In the table, $n$ is the number of layers of electrode plate inside the bushing core. $L_1$, $r_1$, $L_2$ and $r_2$ are the length and radius of the zero layer of bushing capacitor core and grounding electrode plate, respectively. The maximum operating phase voltage of the bushing is 317kV, and the rated current carrying capacity is 5000A. The prototype manufactured according to the structural parameters of bushing core is shown in Figure 5.

| Structural parameters | $L_1$(mm) | $L_2$(mm) | $r_1$(mm) | $r_2$(mm) | $n$ |
|-----------------------|-----------|-----------|-----------|-----------|-----|
| Numerical value       | 3075      | 1025      | 67.5      | 205       | 56  |

Fig.5 Outlet of 550kV oil-gas bushing condenser
According to the structure parameters of the bushing core in Table 2 and the expression of $E(r)$ in Table 1, the radial electric field distribution curve in the bushing capacitor core under the above three models can be obtained. The curve obtained in model 3 is the actual radial electric field distribution of the core, which is closer in model 1 than in model 2. Considering the skin effect of guide rod and the variation of system current during the operation of bushing, the radial temperature rise of bushing core caused by eddy current loss under different ampacity is shown in Figure 6. According to equation (11), the eddy current loss heating of the central guide rod has the same temperature rise distribution under the three models. In the calculation, the thermal conductivity $K$ of the insulating medium is 0.12w/m/k, and the ambient temperature $T_a$ of the core body is 20 ℃. It can be seen from Figure 6 that the eddy current loss causes uneven radial temperature rise inside the bushing core. The maximum temperature rise point is near the guide rod in the center of the core, and the temperature rise changes about ±20 ℃ within the range of ±1000A ampacity fluctuation. At the same time, the ambient temperature $T_a$ has direct impact on the radial temperature rise inside the core. If the 550kV dry oil and gas bushing operates in the poor heat dissipation environment, the insulation medium of the core will run at a high temperature and accelerate aging, which is not conducive to the long-term safe and stable operation of the bushing.

On the other hand, according to formula (12) ~ (14), the radial temperature rise of bushing caused by joule heating of the insulating medium inside the core is shown in Figure 7, in which the insulating medium is assumed to be linear medium, and the AC equivalent conductivity is 5.442e-13s/cm (at 20 ℃). Figure 7 shows that the maximum radial temperature rise caused by joule heating of the core
insulating medium is also near the central guide rod, which is about 22 °C in model 2 and 15 °C in model 1 and 3. Compared with the maximum temperature rise of 80 °C caused by eddy current loss, the eddy current loss of the central guide rod accounts for a larger proportion of the temperature rise, followed by the joule heating of the insulating medium, but due to its highest value. The operation voltage $U_m$ is high, so the latter cannot be ignored. Among the three models mentioned in this paper, the temperature rise of model 2 is higher, and the difference between model 1 and model 3 is very small. The reason is that the radial electric field distribution curves of the two models are close, so model 1 has high accuracy and the calculation process is simple. Considering the material nonlinear characteristics of core insulation medium under model 1, it can be seen from equation (21) that the eddy current loss of guide rod and the temperature rise caused by joule heating of medium cannot be quantitatively analyzed respectively. Therefore, the above-mentioned thermoelectric coupling finite element model of bushing is used to carry out numerical calculation according to the iterative process. The radial temperature distribution of bushing core at 4000A and 5000A is shown in Figure 7.

It can be seen from Figure 7 that the radial temperature distribution of bushing core obtained by considering nonlinear characteristics of materials under different ampacity is lower than the calculated value under linear condition, mainly because the conductivity of insulating medium used in 550kV dry oil and gas bushing has a minimum value in the range of 0~110 °C. When the bushing runs in this temperature range, the joule calorific value of the medium is reduced compared with that at room temperature of 20 °C, so the temperature appreciation is reduced, which can be used as a reference. It can be seen that the nonlinear property of the material can make bushing run stably in this temperature range. Considering the eddy current loss, medium heating and material nonlinear characteristics, $T_{\text{max}}$, the hottest spot inside the bushing core at rated current, is near the center guide rod, which is about 95 °C, meeting the design requirement that the operating hottest spot temperature is lower than 120 °C.

The thermal breakdown voltage ($U_{bT}$) of the bushing core can be further analyzed according to the thermoelectric coupling finite element model of the bushing: the current carrying capacity and the ambient temperature of the bushing center guide bar are set constant, and the voltage value is gradually increased to $U_{mi}$ on the basis of the maximum operating phase voltage ($U_m$) and applied to the iteration process of the nonlinear thermoelectric coupling finite element model, and the hottest point temperature ($T_{\text{max}}$) in the core is extracted in each cycle. If $T_{\text{max}}(k=1,\ldots,j)$ and $T_{\text{max}}(k=1,\ldots,j)$ decrease in sequence and converge to the fixed value, the bushing core can keep thermal stability under the voltage $U_{mi}$. The results show that the thermal breakdown occurs when the voltage is $U_{mi}$.

The relationship between the temperature $T_{\text{max}}$ of the hottest spot inside the core and the applied voltage $U_m$ is shown in Figure 8.

![Fig.8 Relationship between the hottest spot temperature with applied voltage](image)

It can be seen from Figure 8 under current carrying capacity of 4000A and 5000A, the temperature of the hottest spot of the core in the stable region is basically unchanged with the increase of the
applied voltage. When the applied voltage increases to certain critical value $U_{BT}$, the temperature of the hottest spot rises sharply and enters the unstable region, which is the thermal breakdown voltage. In fact, the abnormal high temperature in the unstable region does not exist, because the thermal breakdown of the bushing core has occurred. The results show that the thermal breakdown voltage of the core is 538kV and 628kV respectively under the current carrying capacity of 5000A and 4000A, which is larger than highest operating phase voltage of 317kV. The reason of thermal breakdown is that the conductivity of the insulating medium increases exponentially in the range of 110 ~ 140 ℃. If the local temperature inside the core body enters the temperature range with the increase of applied voltage, the conductivity of the insulating medium increases sharply, resulting in a sharp rise in the calorific value of the medium, which in turn causes the conductivity to increase again, forming a positive feedback effect. If the thermal capacity is constant, it will inevitably lead to heat accumulation and thermal breakdown in the core.

4. Conclusion
This paper takes 550kV dry oil and gas bushing as the research object, establishes the theoretical model of thermo-electric coupling of bushing, obtains the radial temperature distribution of core body under linear material, and popularizes theoretical model of thermo-electric coupling under nonlinear condition by using finite element model. Finally, the experimental measurement of local temperature point is carried out, and the following conclusions can be drawn:

(1) The models of plate, cylinder and cone are established to describe the radial heat flow in the core, and the specific expressions of radial temperature distribution $T(r)$ are derived. Among the three models, the plate model has the advantages of high accuracy and simple form compared with other models, which is more suitable for calculating the radial temperature distribution of bushing core. Then, the electrothermal coupled finite element model is used to extend above model under nonlinear conditions, and the electrothermal coupled finite element iterative algorithm is realized.

(2) For the actual 550kV oil and gas bushing, through the analysis of three theoretical models, it is found that the temperature rise caused by eddy current loss of the center guide rod is about 80 ℃, which is greater than that caused by Joule heating of the medium by about 15 ℃. The hottest point $T_{max}$ of the bushing core appears near the center guide rod, which is about 95 ℃. It is found that the radial temperature distribution $T(r)$ of the bushing core is smaller than that of the linear medium, and the thermal breakdown voltage ($U_{BT}$) of the bushing core is about 538kV at rated current carrying capacity, which is higher than the maximum operating voltage ($U_m$) of the bushing.

(3) Through the local temperature measurement test of 550kV oil and gas bushing, it is found that: temperature of each local measurement point is gradually changing and finally stable. And the hottest point is in the core center guide rod and related metal accessories. The maximum temperature is about 100 ℃, which is close to 95 ℃ calculated by the electrothermal coupling model.

(4) The electrothermal coupling model proposed in this paper is suitable for the calculation of the radial temperature field of the cross section of the bushing core. Compared with the conical model considering the axial heat dissipation, the temperature calculation in this paper is more rigorous. If it is necessary to further analyze the axial temperature distribution of the core, the calculation model should be improved according to the actual situation.

References
[1] LIU Zhen-ya. Ultra-high voltage power grid[M]. Beijing, China: China Economy Press, 2005.
[2] Zhu Fang, Zhao Ziyu, Liu Qichang, Ju Jichun. A New Design Method for Condenser Body of H.V. Transformer Bushing[J]. Journal of Xi’an Jiaotong University, 1989, 23(1): 77-100.
[3] Xie Heng-kun. Electrical insulation design principles [M]. Beijing, China: Mechanical Industry Press, 1992.
[4] N.S.Jyothi, T.S.Ramu, Manoj Mandlik. Temperature distribution in resin impregnated paper
insulation for transformer bushing[J]. IEEE Transaction on Dielectrics and Electrical Insulation, 2010, 17(3): 931-938.

[5] Shibao Zhang. Evaluation of thermal transient and overload capability of high-voltage bushings with ATP[J]. IEEE Transactions on Power Delivery, 2009, 24(3): 1295-1301.

[6] V.Raff, M.G.Daniels. Considerations for thermal stability of oil impregnated EHV condenser bushings[J]. IEEE Transaction on power apparatus and systems, 1985, PAS-104(1): 200-206.

[7] N.S.Jyothi, T.S.Ramu, Manoj Mandlik. Temperature distribution in resin impregnated paper insulation for transformer bushing[J]. IEEE Transaction on Dielectrics and Electrical Insulation, 2010, 17(3): 931-938.

[8] Xie Heng-kun. Electrical insulation design principles [M]. Beijing, China: Mechanical Industry Press, 1992.

[9] M.Clemens, E.Gjonaj, P.Pinder, T.Weiland. Numerical simulation of coupled transient thermal and electromagnetic fields with the finite integration method[J]. IEEE Transactions on Magnetics, 2000, 36(4): 1448-1452.

[10] Zheng Libing, Han Li, Liu Jun, Wen Xuhui. Investigation of the temperature character of IGBT failure mode based on 3D thermal-electro coupling FEM[J]. Transaction of China Electrotechnical Society, 2011, 26(7): 242-246.

[11] Su Xiuping, Lu Jianguo, Liu Guojin. Thermal field simulation analysis of miniature DC electromagnetic relays[J]. Transactions of China Electrotechnical Society, 2011, 26(8): 185-189.

[12] Ch.Chakradhar Reddy, T.S.Ramu. Estimation of thermal breakdown voltage of HVDC cables-A theoretical framework[J]. IEEE Transaction on Dielectrics and Electrical Insulation, 2007, 14(2): 400-408.

[13] Lei Ming, Liu Gang, Qiu Jingsheng et al. Real-time core temperature calculation of single-core cable by nonlinear finite element method[J]. Power System Technology, 2011, 35(11): 163-168.

[14] Han S.J., Zou J., Gu S. Q et al. Calculation of the potential distribution of high voltage metal oxide arrester by using an improved semi-analytic finite element method[J]. IEEE Transactions on Magnetics, 2005, 41(5): 1392-1395.

[15] Daniel Weida, Thorsten Steinmetz, Markus Clemens. Electro-quasistatic high voltage field simulations of large scale insulator structures including 2D models for nonlinear field-grading material layers[J]. IEEE Transactions on Magnetics, 2009, 45(3): 980-983.

[16] MENG Qingmin. A Temperature Field and Heat Circuit Integrated Numerical Calculation Method for Underground Cable Temperature Field[J]. Power System Technology, 2009, 33(20): 193-196.

[17] FU Yongchang, ZHANG Wenbin, CHEN Tao. Calculation on temperature field and current-carrying capacity of irregularly arranged cables[J]. Power System Technology, 2010, 34(4): 173-176.

[18] TU Weimin, CUI Guomin, LI Yu, HU Xiangbai et al. Internal streaming simulation of oil-immersed transformers and on-line fault prediction method[J]. Power System Technology, 2010, 34(5): 195-200.