Theoretical calculation model of insulation medium and eddy current heating under complex waveform of ±800kV converter transformer RIP bushing used in valve side

Zhang Shiling

1State Grid Chongqing Electric Power Company Chongqing Electric Power Research Institute, Chongqing, 401123
zhangshiling@cq.sgcc.com.cn

Abstract. Electrical and thermal properties of the converter transformer valve side RIP DC bushing interact with each other, so electrical insulation failure in operation is directly related to the thermal properties. It is essential to conduct quantitative analysis on the power loss of UHV converter transformer dry-type bushing. The total power loss of bushing consists of two parts, eddy heat from current-carrying structures and joule heat from bushing core. The actual current and voltage waveform imposed on the bushing contain many high frequency components. In this paper, the theoretical calculation model of bushing core joule heat and eddy heat is obtained from structure of HV converter transformer dry-type bushing. Then the temperature and frequency properties of epoxy impregnated paper used by dry-type bushing core are acquired by the experiments. Furthermore, based on the frequency domain FEM, the numerical calculation method for dry-type bushing power loss is proposed. In the end, the numerical results are used to analyze the factors that may lead to converter transformer dry-type bushing insulation failure in operation. The research result obtained in this paper is appropriate to compute thermal characteristic of bushing and is of directive significance to the operation, protection and accident analysis.

1. Introduction
At present, the technology of DC transmission and DC power grid is developing rapidly in China. At the same time, the design and manufacturing level of key equipment used in DC power grid has also been greatly improved. Take the dry bushing at valve side of ±800kV converter transformer as an example, its operation status directly affects the safety and stability of converter transformer and even the whole converter valve hall, the accidents caused by the sleeve have been reported repeatedly. In general, the electrical performance of dry-type bushing in actual operation is failure, but recent research shows that the electrical and thermal properties of dry-type DC bushing are interrelated, and the thermal state of bushing can directly affect its electrical performance[2,3]. Therefore, it is necessary to quantitatively analyze the loss from the perspective of the calorific value of the bushing body, and discuss the direct cause of insulation failure of dry DC bushing. There are many literature on the loss calculation of converter transformer body structure, but there are few reports on the quantitative analysis of dry bushing loss of UHV converter transformer [4-7].

The total loss of dry bushing of converter transformer is mainly composed of two parts: eddy current heating of bushing current carrying structure and Joule heating of dry bushing core medium. Eddy current heating is mainly related to the specific size of current carrying structure and current waveform, while dielectric heating is directly related to voltage waveform and intrinsic electrical
properties of insulating medium. The main difficulties in quantitative calculation of dry bushing loss of converter transformer are: the actual current and voltage through the bushing are non sinusoidal complex waveform, containing a large number of high-order harmonic components, which have enhanced effect on the eddy current heating and the Joule heating of bushing; on the other hand, the electrical performance of epoxy impregnated paper composite insulation unique to DC dry bushing core is very important. The material non-linearity should be taken into account in the calculation of Joule heating of medium in bushing core.

In this paper, the theoretical calculation model of eddy current heating of core medium and current carrying structure is derived through the specific structure of high-voltage converter dry-type bushing, and then the temperature and frequency nonlinear characteristics of epoxy impregnated paper composite insulation material for dry-type bushing core are obtained under laboratory conditions. Furthermore, based on the frequency domain finite element method, the numerical calculation method of converter dry bushing loss is proposed. Finally, the possible causes of insulation failure of dry bushing of converter transformer in actual operation are analyzed by using the above numerical calculation results, and the power frequency current value in the temperature rise test of converter bushing is corrected. The research results of this paper can be used to calculate the thermal performance of the converter bushing, and have a certain guiding significance for the field operation, maintenance and accident analysis of the high pressure dry bushing.

2. Theoretical calculation model of bushing medium and eddy current heating under complex waveform

2.1 Establishment of theoretical calculation model of bushing medium heating

The high-voltage dry-type DC bushing generally adopts the capacitive structure. The radial and axial field strength of the bushing is uniformly distributed through the metal plate inside the core body, and the metal plate is solidified in epoxy impregnated paper composite. The outline and basic parameters of the typical dry-type bushing capacitor core are shown in Figure 1.

![Fig.1 Typical outlet of RIP bushing condenser](image)

The Joule heating of the insulating medium under AC time-varying voltage can be characterized by formula (1):

\[
P_{ac}(\omega) = U_{\text{rms}}^2 \omega C(\omega) \tan \delta(\omega)
\]

In the above formula, \(U_{\text{rms}}\) is the RMS value of applied voltage (unit: V), \(\omega\) is the angular frequency (unit: rad/s), \(C\) is the real part of capacitance (unit: F), and \(\delta\) is the tangent value of loss angle. For capacitive bushing, assuming that its internal insulating medium is linear material, capacitance \(C_k\) of insulating medium between the \(k\)-th layer and \(k-1\) plate can be expressed as (2):
Where is the relative permittivity of the insulating medium, \( l_k \) is the length of the \( k \)th layer plate, and \( r_k \) and \( r_{k-1} \) are the radii of the \( k \)th layer and \( k-1 \) layer plate. Suppose that the whole bushing capacitance core contains \( n \)-layer plates, then its capacitance \( C \) can be calculated by formula (3):

\[
C = \frac{1}{\sum_{k=1}^{n} C_k}
\]  

(3)

The ohmic heating of insulating medium under DC condition can be characterized by (4):

\[
P_{dc} = \frac{U_{dc}^2}{R_{dc}}
\]  

(4)

Where \( U_{dc} \) is the applied DC voltage and \( R_{dc} \) is the DC resistance. For complex voltage waveforms with periodic variation in power system, Fourier decomposition can be used to realize the variation of complex waveform from the time domain to frequency domain. In all basic types, equation (5) can effectively characterize the contribution of each frequency component to the total voltage, that is, the total voltage can be decomposed into the superposition result of all frequency components, as follows:

\[
U(t) = U_{dc} + \text{Re}\left[\sum_{n=1}^{\infty} \sqrt{2} U_n e^{i\omega_n t + \phi_n}\right]
\]  

(5)

Where \( U_n \) is the effective value of the \( N \)th harmonic (unit: V), \( \phi_n \) is the phase value of the \( N \)th harmonic and \( \omega_n \) is the fundamental angular frequency (unit: rad/s). According to the Fourier decomposition result of equation (5), the total Joule heating amount of the insulating medium can be characterized by the algebraic superposition of the heating amount under the action of each harmonic voltage, as shown in equation (6):

\[
P_{ac}(\omega) = \sum_{n=1}^{\infty} |U_n|^2 n\omega C(n\omega) \tan \delta(n\omega)
\]  

(6)

Equation (6) shows that the relative permittivity and loss tangent of insulating medium are functions of harmonic frequency. And the classical dielectric physical theory shows that the above two electrical parameters of insulating medium are functions of frequency and temperature at the same time[2], that is, the Joule calorific value \( P_{ac} \) of dielectric has frequency and temperature non-linearity, which can be characterized by formula (7):

\[
\varepsilon_r = f_1(\omega, T) \quad \tan \delta = f_2(\omega, T) \quad P_{ac} = f_3(\omega, T)
\]  

(7)

The value range of neutralization \( T \) in equation (7) depends on the actual working environment of the insulating medium, and the specific values of the above two electrical parameters can be obtained in the laboratory. Assuming that the Joule calorific value of the insulating medium at the fundamental frequency (50Hz) is \( P_{ac50Hz} \), the Joule calorific value enhancement coefficient of dielectric is defined to characterize the influence of higher harmonics in complex voltage waveform:

\[
\lambda_1 = \frac{P_{ac}}{P_{ac50Hz}}
\]  

(8)
2.2 Establishment of eddy current heating theoretical model for bushing current carrying structure

![Image](229x609 to 365x686)

Fig.2 The cross-section of core and loading structure

The long and thin copper tube is generally used as the current carrying structure of high pressure dry bushing. The structure belongs to regular conductor, which can be solved analytically by theoretical formula. The actual copper tube current carrying structure is shown in Figure 2.

Let the slender tubular conductor shown in Fig. 2, whose outer and inner radii are \( a \) and \( b \) respectively, carry alternating current. In this condition, the electric field intensity and current density have only axial component, and the magnetic field intensity is only circumferential component. Because of symmetry, the field quantity only changes with radius \( R \). Under the above conditions, Maxwell’s first equation of conductive medium is as follows:

\[
\nabla \times \mathbf{H} = \mathbf{J} = \gamma \mathbf{E} \tag{9}
\]

In equation (9), \( \gamma \) is the conductivity, and in the cylindrical coordinate system, there is:

\[
d\frac{H_\theta}{dr} + \frac{H_\theta}{r} = \gamma E_z \tag{10}
\]

According to Maxwell's second equation:

\[
\nabla \times \mathbf{E} = -j\omega\mu \mathbf{H} \tag{11}
\]

In equation (11), \( \mu \) is permeability, and equation (11) can be changed into equation (12):

\[
d\frac{E_z}{dr} = j\omega\mu H_\theta \tag{12}
\]

Substituting formula (12) into formula (10) gives the following result:

\[
\frac{d^2 E_z}{dr^2} + \frac{1}{r} \frac{d E_z}{dr} - j\omega\mu \gamma E_z = 0 \tag{13}
\]

Then \( k = \sqrt{j\omega\mu\gamma} \), (13) can be rewritten as follows:

\[
\frac{d^2 E_z}{d(kr)^2} + \frac{1}{kr} \frac{d E_z}{d(kr)} - E_z = 0 \tag{14}
\]

The solution of equation (14) can be written as follows:

\[
\dot{E}_z = \hat{C} I_0(kr) + \hat{D} K_0(kr) \tag{15}
\]

In equation (15), \( I_0(kr) \) and \( K_0(kr) \) are the first and second kinds of distorted zero order Bessel functions, respectively. \( \hat{C} \) and \( \hat{D} \) are constants determined by boundary conditions, and the magnetic field intensity can be determined by equation (12):
According to the law of total current, the boundary condition of magnetic field on the conductor boundary is as follows:

$$\left. \frac{\partial H}{\partial r} \right|_{r=a} = \frac{i}{2\pi a} H(a)$$

(17)

The AC impedance of the current carrying conductor can be obtained as follows:

$$Z = R_0 \frac{K(a^2 - b^2) I_a(ka)K_b(kb) + K_a(ka)I_b(kb)}{2a} I_a(ka)K_b(kb) - K_a(ka)I_b(kb)$$

(18)

The real part of the formula (18) is the AC resistance of the tubular conductor, taking the real part of the formula (18) as the AC resistance of tubular conductor, the eddy current heating of dry bushing current carrying structure can be characterized as:

$$W_{ac} = I^2 \text{Re}(Z) = I^2 (R_0 \lambda_2) = (I^2 R_0) \lambda_2 = W_{ac} \lambda_2$$

(19)

Where (19) $\lambda_2$ is the enhancement coefficient relative to the direct current calorific value. The current waveform of high-voltage dry bushing of converter transformer is periodic non-sinusoidal complex waveform, and the eddy current calorific value can be obtained by superposition principle, that is, the actual current waveform is decomposed by Fourier transform, as shown in formula (20):

$$I(t) = \text{Re}[\sum_{n=1}^{\infty} \sqrt{2} I_n e^{i\omega rt + \phi_n}]$$

(20)

The frequency $\omega_1$ and the effective value $I_1$ of each harmonic of the actual current are obtained, and the eddy current calorific value under each harmonic is calculated by substituting them into (18) and (19), and the total eddy current calorific value $W_{ac}$ is obtained by superposition. Assuming that the eddy current calorific value of the bushing current carrying structure at the fundamental frequency (50 Hz) is $W_{ac,50Hz}$, $\lambda_2$ the eddy current calorific value enhancement coefficient is defined to characterize the influence of higher harmonics in the complex current waveform:

$$\lambda_3 = W_{ac} / W_{ac,50Hz}$$

(21)

Under the actual complex current waveform, the enhancement coefficient of eddy current calorific value of dry bushing of converter transformer is $K = \lambda_3 \lambda_2$.

3. Frequency and temperature dependent nonlinear characteristics of medium in bushing core

3.1 Morphology and electrical properties of the sample

The main insulation of dry-type bushing core is the epoxy impregnated paper composite medium. The observation results under polarized light (PLM) and scanning microscope (SEM) are shown in Fig. 3. It can be seen that corrugated paper is evenly distributed in pure epoxy. The mechanical toughness of the bushing core can be effectively enhanced by the orderly arrangement of the crepe paper cellulose.
The dielectric properties of the samples were tested by the concept80 broadband dielectric spectrum test system. The maximum test frequency range is 10^9 Hz ~ 3 GHz. The temperature control system is used to measure the temperature non-linearity of the sample. The maximum temperature controllable range is -150 °C~500°C, and the accuracy is 0.01°C. According to the operation experience data of the converter dry bushing, the maximum temperature range that the core can experience is generally between -40°C and 160°C, so the temperature range studied in this paper is between -40°C and 160 °C, and the temperature interval set in the spectrum measurement is 5°C. After each temperature point is stable, set the test frequency range of 10^1 Hz ~ 10^9 Hz.

3.2 Dielectric spectrum test results of core composite insulation
The non-linear relationship between the real part of the dielectric constant and the tangent of the loss angle of the core composite insulation and the frequency \( f \) and temperature \( T \) is shown in Fig. 4. It can be seen that the above two electrical parameters increase with the increase of temperature \( T \) and the decrease of frequency \( f \), but there are many peaks and troughs on the three-dimensional surface, so the nonlinear characteristics are difficult to be quantitatively characterized by classical explicit function \( f(\omega,T) \). The frequency and temperature nonlinearity of epoxy impregnated paper composite insulation are further discussed through two-dimensional curve.
For the real part of the dielectric constant, its value is larger in the low frequency region (10^{-1}Hz), and tends to be stable in the high frequency region (10^6Hz). The change of loss tangent with frequency is complex, but it is stable in high frequency region (10^6Hz). The brief explanation is as follows: in the low frequency region, which is far less than 1 (when the relaxation time is fixed), all kinds of polarization can be established in time, so the relative permittivity tends to be static. In the relaxation region, the period of the applied electric field can be compared with the relaxation time, and the dielectric loss increases while the dielectric loss decreases significantly. In the high frequency region, that is, it is far more than 1, the relaxation polarization can not be established, the polarization is all contributed by the displacement polarization, and the relative permittivity is close to the relative permittivity of optical frequency. The above two electrical parameters are also closely related to temperature, which is mainly reflected by the correlation between relaxation time and temperature of the relaxation polarization. The relaxation time is approximately exponentially proportional to the temperature $T$ ($k$ is the Boltzmann constant, $u$ is the activation energy of the molecule, which is basically independent of the temperature) [8-10].

4. Frequency domain finite element calculation of bushing loss under complex waveform

4.1 Actual waveform and discrete frequency spectrum of converter bushing

In order to obtain the voltage and current waveforms of the bushing at the valve side of the converter, the transient analysis software is used to model and calculate the DC system. The rated voltage of the system is 800kV and the converter is 12 pulse. The phase to ground potential waveform of Y/D and Y/Y converter valve side bushing at the rectifier side under rated conditions (limited to the space, take Y/Y as an example) and current waveform are shown in Figure 5.
The discrete frequency spectrum shown in Figure 6 can be obtained by discrete Fourier analysis of the actual voltage and current waveform.

Figure 6 shows that the voltage and current withstood by the valve side bushing not only contain DC and fundamental frequency (50Hz) AC components, but also have a large number of the high-order harmonics with large amplitude. If only DC and fundamental frequency components are considered in the quantitative analysis of Joule heating of core medium and eddy current heating of current carrying structure, the calculated results will be quite different from the actual situation. However, in the numerical calculation of the actual bushing loss, considering the calculation cost, it is impossible to get the higher harmonic component of infinite terms, so it is necessary to truncate the harmonic number. In this paper, the first 150 harmonics of voltage and current waveform are obtained and used to recover the original waveform. The truncated waveform, original waveform and fundamental frequency waveform are compared with Figure 7. It can be seen that the difference between the truncated waveform and the original waveform is small, while the fundamental waveform is smoother than the former two, mainly because the fundamental component ignores the influence of many higher harmonic components.
Fig. 7  Comparison for three types of voltage and current

Under linear condition, the Joule calorific value of the bushing core and eddy current calorific value of the current carrying structure can be quantitatively calculated by the formula (6) and formula (19), respectively. However, the above theoretical model is no longer applicable when considering frequency variation, temperature variation and harmonic nonlinearity. In this paper, the traditional calculation method of bushing loss is extended by frequency domain finite element method, and the finite element model of bushing core and current carrying structure is shown in Figure 8. Firstly, the theoretical model is used to calculate the bushing loss under linear medium and fundamental frequency, and the calculation results are compared with those of frequency domain finite element method to verify its effectiveness. Then, it is extended to the quantitative calculation of bushing loss under the conditions of temperature variation, frequency variation nonlinearity and multi-harmonic.

Fig. 8  Calculation model for frequency-domain FEM

5. Calculation process and results of converter dry bushing loss

5.1 Calorific value of bushing core under isothermal condition

The isothermal condition means that the whole core of bushing is at constant temperature $T_{con}$. The calculation environment of single frequency $f_i$ is defined as the physical environment of harmonic field. For the problem studied in this paper, the first 150 harmonic components are taken, that is, 150 physical environments need to be defined, and the input quantity of each physical environment is the frequency $f_i$ and voltage peak $U_i(i=1~150)$ obtained by Fourier decomposition. The harmonic field method is used to solve each physical environment. After the calculation, the real part of the result is extracted, and the heating power of each element is $W_{mi}(m=1~K, i=1~150)$. $K$ is the total number of elements in the finite element model. The calorific value $P_{mi}(m=1~K, i=1~150)$ of each unit can be obtained by multiplying the calorific power $W_{mi}$ of each unit by the volume $V_{mi}(m=1~K)$. The linear superposition of the calorific value of 150 physical environments is the core dielectric loss under
isothermal $T_{\text{con}}$. According to the above calculation process of bushing dielectric loss, change the value of $T_{\text{con}}$ in the temperature range of -40°C~140°C with 5°C as the step, that is, the relationship between the calorific value of bushing core and temperature under isothermal condition is obtained, as shown in Figure 9.

Figure 9 shows that under the actual voltage waveform, the calorific value of bushing medium is greater than that under fundamental frequency voltage, and the ratio (i.e. the enhancement coefficient of medium heating) is slightly different at each temperature point, with an average value of 1.607. Under the actual voltage waveform, the calorific value of bushing medium in the temperature range [-40°C, 100°C] shows the downward trend, while calorific value of bushing medium in the temperature range [100°C, 140°C] rises sharply. Therefore, $T_{\text{cri}}$ can be used as the intrinsic critical temperature of bushing medium. Figure 9 shows that the critical temperature of the thermal stability of bushing core medium is near 100°C. The qualitative description is as follows: in the temperature range of -40°C to 100°C, if the temperature value increases, the Joule calorific value $P$ of the medium in the bushing core will decrease, which can effectively inhibit the further increase of the medium temperature. On the other hand, if the temperature value increases in the range of 100°C to 140°C, the Joule calorific value $P$ of the medium will increase sharply, which makes the medium temperature rise sharply, and the above "positive feedback effect" can be applied. It leads to thermal breakdown of the medium.

5.2 Calorific value of bushing core under non isothermal condition

The loads and boundary conditions applied in the physical environment of the thermal field include the flow rate $I$ of bushing current carrying structure, the ambient temperature $T_a$ and the Joule heating power $W_i(i=1~K)$ of each unit $(i=1~K)$. After the thermal field calculation, the temperature value $W_i(i=1~K)$ of each unit is introduced into the harmonic field calculation, and the material properties of each unit can be nonlinear interpolated according to the calculation results of the temperature field, and then the Joule heating power $W_i(i=1~K)$ of each unit medium is recalculated through the modified material parameters. If $W'_i=W_i$, the "open-loop" flow chart under the isothermal condition can be transformed into a "closed-loop" structure, which can effectively take into account the frequency-dependent and temperature-dependent nonlinear characteristics of the medium[11-16]. The above calculation process couples the temperature field with the harmonic field to form the closed-loop iterative mode as shown in Fig. 10. For the core of UHV converter tube in this paper, the convergence can be achieved by 4 ~ 5 iterations. In order to further analyze the thermal stability of the bushing core in actual operation, when the current carrying structure of the bushing is at rated current carrying rate, the ambient temperature $T_a$ of bushing core is gradually increased. In this process, the characteristic
curve of the calorific value $w$ of the bushing core and the ambient temperature $T_a$ is obtained, as shown in Figure 10(a). It can be seen that the characteristic curve of bushing core loss also has a "U" shape change under non-isothermal conditions. Similarly, $T_{crl}$ is defined as the turning point. Figure 10(b) shows that the transition temperature decreases with the increase of ampacity. On the other hand, according to the equivalent thermal circuit of the bushing core, equation (22) is obtained:

$$\left(T_s - T_c\right)/T = W_R$$

Where $T_s$ is the surface temperature of the bushing core, $T$ is the thermal resistance of the surrounding medium, $W_R$ is the heat emitted to the surrounding medium, so the heat dissipation curve of the bushing core is a straight line, as shown in Figure 10(b). There are two intersections $A$ and $B$ between the heat dissipation curve and the heat generation curve, and with the increase of bushing ampacity, the corresponding temperature value at point $A$ is unchanged, while the corresponding temperature value at point $B$ shows a downward trend.

### 6. Conclusion

Through the quantitative analysis of the loss of dry bushing at valve side of ± 800kV converter, the following conclusions can be obtained:

1. The electrical performance parameters of epoxy impregnated paper composite used in dry bushing core have significant frequency and temperature nonlinearity. It is difficult to consider the above nonlinear factors in the theoretical calculation model of bushing dielectric loss and eddy current loss, so the frequency domain finite element method is needed to expand the traditional calculation method.

2. The voltage and the current waveforms of the converter bushing contain more higher harmonic components, which can aggravate the bushing loss. Under the given waveform and bushing structure, the heat enhancement coefficient of medium is 1.607 and that of eddy current is 1.417. For other dry bushings, the proposed loss calculation process can be used for quantitative analysis according to the specific structure size, material characteristics and operation waveform.

3. The loss characteristic curve obtained under the isothermal condition of the bushing core can characterize the inherent thermal characteristics of the epoxy impregnated paper composite, while the loss characteristic curve under non-isothermal condition can characterize the thermal stability of the bushing: in actual operation, the external environment temperature of the bushing can be controlled near $T_c$, so as to minimize the calorific value of the bushing. However, the electrothermal breakdown during the operation of the bushing core may be due to the increase of the bushing current carrying capacity or the external ambient temperature, which leads to the "instability zone" of the bushing loss characteristic curve.

4. The calculation of eddy current loss of bushing current carrying structure by frequency domain finite element method can effectively save calculation time and has high accuracy. In the temperature
rise test, the current value of power frequency test can be corrected to make the calorific value of bushing test equivalent to that of actual operation.

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