Iterative Finite Element Method Applied to the Nonlinear Electric Field of ±400kV Converter Transformer Barrier System

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Abstract. The DC steady-state and the polarity reversal (PR) are typical states of composite insulation in converter transformer barrier system, and the insulation medium has the strong E-field and temperature nonlinear characteristic, so the DC steady-state and polarity reversal E-field will be affected by the variation of electric parameters under temperature gradient. The FEM was applied to the quantitative E-field analysis considering electric and temperature nonlinear factors simultaneously. First, the nonlinear relationship between conductivity with E-field and temperature of medium has been obtained by experiments. Then, the iterative FEM was proposed and verified by coaxial insulation with analytical solution. Finally, the full-scale model of ±400kV converter transformer barrier system has been established, the DC steady-state and polarity reversal E-field has been calculated with the proposed method. The results show that under linear and nonlinear conditions the E-field is quite different, and E-field non-linearity can inhibit the local high electric spot, temperature non-linearity can reduce the E-field in the high temperature area and increase that in the lower temperature area. Under the temperature gradient condition, the local high E-field spot is easy to occur in the PR process. The iterative FEM and calculation results can provide references for the design of converter transformer barrier system.

1. Introduction
Converter transformer is an important equipment in the DC transmission system, its operation state directly affects the reliability of power transmission, and the outlet device is an important insulation structure connecting the bushing tail of converter valve side and transformer winding[1-3]. For epoxy impregnated dry-type converter bushing, there are transformer oil, oil impregnated paper and resin impregnated paper at its tail. At the same time, there are many kinds of voltage types such as DC steady state, polarity reversal and so on in the operation of converter transformer. Therefore, the electric field distribution at the bushing outlet device is very complex, so it is necessary to conduct quantitative analysis to guide the insulation structure design of the outlet device.

Under DC steady-state voltage, the electric field in composite insulation is determined by dielectric conductivity, i.e. constant flow field. Under polarity reversal voltage, the electric field is determined by both dielectric constant and conductivity, i.e. transient field. The existing literatures generally simulate the DC steady-state and polarity reversal transient electric fields of the composite insulation structures under the linear conditions. Some literatures simulate the DC steady-state fields under the
condition of field varying non-linearity, but they are limited to simple insulation structures with single dielectric. In recent years, the research of related literature shows that the conductivity of transformer oil, oil impregnated paper and epoxy impregnated paper insulation is nonlinear with temperature and electric field[4-7]. Therefore, when calculating the electric field of insulation structure, it is necessary to take into account the temperature and field nonlinearity of the medium.

The eddy current heating of the valve side bushing of converter transformer in actual operation will establish temperature gradient distribution, and the DC steady-state and polarity reversal transient electric field will be distorted to the certain extent compared with isothermal condition. In order to analyze the difference quantitatively, a nonlinear iterative algorithm based on finite element method (FEM) is proposed in this paper[8-10]. The algorithm can take into account the field and temperature nonlinearity of the insulating medium at the same time. In this paper, the principle and process of nonlinear iterative algorithm based on FEM technology are described in detail, and the accuracy of the algorithm is verified by the coaxial cylinder structure with theoretical analytical solution. Furthermore, the temperature and field nonlinear experimental research of transformer oil, oil impregnated paper and epoxy impregnated paper composite insulation media is carried out. Finally, the whole model of a ±400kV converter transformer valve side bushing outlet device is established, and the influence of temperature change and field change nonlinearity on its DC steady-state and polarity reversal transient electric field distribution is analyzed in detail. The nonlinear finite element iterative algorithm and its calculation results presented in this paper can provide theoretical basis for the development of valve side bushing outlet device of converter transformer.

2. Algorithm principle and flow of nonlinear finite element method

2.1 Derivation of time domain finite element method for nonlinear electric field

In the finite element calculation of DC steady-state and polarity reversal transient electric field, the conductivity and dielectric constant of the generated element after meshing are set to be constant, because the volume of the element is much smaller than that of the whole model when mesh is sufficiently fine[11]. When there is no space charge in insulating medium, the potential satisfies Laplace equation:

$$\nabla \cdot (-\varepsilon_0 \varepsilon_i \nabla \varphi) = 0$$  \hspace{1cm} (1)

In equation (1), $\varepsilon_0$ is are the vacuum permittivity and $\varepsilon_i$ is the relative permittivity of the dielectric material respectively. According to Maxwell's current continuity equation, the nonlinear resistance materials are as follows:

$$\nabla \cdot J + \frac{\partial (\nabla \cdot D)}{\partial t} = 0$$  \hspace{1cm} (2)

In equation (2), $j$ is the conduction current density, $D$ is the potential shift vector, and $j$ and $E$ satisfy equation (3):

$$J = \gamma(E,T) \cdot E$$  \hspace{1cm} (3)

Where $\gamma(E,T)$ is conductivity, which is a nonlinear function of electric field strength and temperature, so the potential $\varphi$ satisfies the nonlinear scattering equation:

$$\nabla \cdot [-\gamma(E,T) \nabla \varphi] = \frac{\partial}{\partial t} [\nabla \cdot (\varepsilon_0 \varepsilon_i \nabla \varphi)]$$  \hspace{1cm} (4)

$\varepsilon_i$ is the relative permittivity of the nonlinear resistance material. The corresponding finite element equation is as follows:

$$K(\varphi) \cdot \varphi = P(\varphi)$$  \hspace{1cm} (5)
In equation (5), $K(\phi)$ is the nonlinear stiffness matrix of order $n \times n$; $\phi$ is the potential column vector of order $n$; $\rho(\phi)$ is the sum of the column vector of order $n$ generated by the first kind of boundary conditions and the equivalent charge density. Equation (5) holds only when conductivity is linear (i.e. independent of field strength and temperature). If the conductivity has field and temperature non-linearity, it can be calculated according to equation (5) only if the mean value of each element is the same everywhere and the two conditions are known. Under the assumption that the conductivity of the cell is a constant, the key is whether the value is consistent with the real value, otherwise the calculated potential is not credible. In this paper, the iterative method is used to solve this problem: first, the initial value of each finite element element is given, and then the potential and field strength $E$ of each point in the field are obtained, and the new value is obtained from the nonlinear relationship of conductivity with field strength and temperature. In this way, the iterative calculation is repeated until the difference between the potential or field strength values of two adjacent solutions is less than a given accuracy\[12-15\]. The judgment condition is shown in equation (6), and $N$ is the total number of finite element elements.

\[
\max \left\{ \phi^{k+1} - \phi^k \middle|_{k=1-N} \right\} \leq \varepsilon \quad \text{or} \quad \max \left\{ \gamma(E^{k+1}, T^{k+1}) - \gamma(E^k, T^k) \middle|_{k=1-N} \right\} \leq \varepsilon
\] (6)

In equation (6), $\phi^k$, $E^k$, and $T^k$ are the potential, field strength and temperature values after the $k$-th iteration.

### 2.2 Newton Raphson iterative algorithm

For the actual composite insulation structure, the number of finite element elements is large, and the simple iterative method is easy to oscillate and diverge when the field strength, temperature and non-linearity are high, the iteration format is as follows:

\[
[J^k](\Delta \phi^{k+1}) = -[K \gamma(E^k, T^k)](\Delta \phi^k)
\] (7)

In equation (7), $[J^k]$- the Jacobian matrix used in the $k$-th iteration is shown in equation (8):

\[
J = \begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_n} \\
\frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_n} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \cdots & \frac{\partial f_n}{\partial x_n}
\end{bmatrix}
\] (8)

The formula is the square matrix of the order $n \times n$, and the function $f$ is the nonlinear relationship of conductivity with temperature and field strength in the local region of the finite element element:

\[
\sigma = f(E, T)
\] (9)

The Newton Raphson method for solving nonlinear equations can speed up the iterative convergence process, because the "damping coefficient" $P_k$ can be introduced to effectively reduce the increment of each iteration, so as to prevent oscillation and promote convergence, the correction formula of each iteration step to the local conductivity of the element is shown in equation (10):

\[
\gamma^{k+1} = \gamma^k + P_k [\gamma(E^{k+1}, T^{k+1}) - \gamma^k]
\] (10)

The value of damping coefficient $P_k$ needs to be determined by trial method, generally between 0 and 1. Figure 1 is the geometric explanation of the oscillation: curve 1 and curve 2 are the values of the electric field strength, the temperature and conductivity defined by equation (9), which are the finite element elements with the higher and lower electric field strength respectively. Curve 3 shows
the nonlinear characteristics of the superposition field change and the temperature change of medium conductivity. The intersection of the two kinds of curves is the convergent solution of the finite element element, represented by \( A \) and \( B \) in the Figure. If \( \sigma_0 \) is taken as the initial iteration value, the strong oscillation will occur before the final solution (point \( A \)) is reached under the conditions of high temperature, high field strength and strong conductivity non-linearity. Figure 1 can also explain the effect of initial value on oscillation and iteration times. Generally speaking, the closer the initial value is to the final value, the better. For convenience of calculation, the conductivity at room temperature and zero field strength can be taken as the starting point.

![Fig.1 Iterative oscillation and damping effect](image)

### 2.3 Iterative algorithm flow of nonlinear finite element for composite insulation

The above analysis shows that the principle of Newton Raphson iterative method is to form the system of linear algebraic equations with Jacobian matrix as coefficient, iterative difference of approximate solution vector as the unknown vector, and the residual vector as right end vector, from which the approximate solution of the each iteration can be obtained. For the composite insulation structure, the nonlinear finite element method should be further improved to be suitable for the bushing outlet device of converter transformer\([16,17]\). For epoxy impregnated paper dry (RIP) bushing, there are three kinds of composite insulating media near the outlet device, including transformer oil, oil impregnated paper (OIP) and rip bushing core. The iterative calculation flow of the nonlinear finite element is shown in Figure 2. The newton raphson iterative method is used in iterative process: first, an initial conductivity is set for each unit, and then the temperature field distribution is calculated by the load current of the current carrying conductor in the center of the bushing, and the electric field distribution is calculated according to the applied voltage, and the local conductivity of each unit is adjusted according to the calculated temperature value and the field strength value, and the temperature field and electric field calculation are continued until accuracy control is met system requirements. Array \( ELMAX\_OIP, ELMAX\_RIP, ELMAX\_Oil \) is used to access the total number of the units in oil impregnated paper, epoxy impregnated paper and transformer oil area, \( EE \) array is used to load the electric field strength of each unit, \( JJ \) array is used to load Joule heating caused by leakage current of each unit, \( TT \) array is used to load the temperature value of each unit. If the convergence criterion (6) is satisfied in the iteration process, the loop program is exited and the corresponding post-processing is performed.

### 3. Selection of temperature and field dependent nonlinear coefficients of single insulating medium

At present, the epoxy impregnated paper dry bushing is widely used in the valve side of converter transformer. Therefore, in the compact space of outlet device, there are mainly three kinds of insulating media: epoxy impregnated paper, oil impregnated paper and transformer oil. Now, the temperature and field nonlinear characteristics of the above three kinds of single insulating media are
studied respectively. The test results are shown in Figure 2. Figure 2 shows that the conductivity of single insulating medium changes significantly with temperature and field strength, so the temperature and field strength have great influence on the DC steady state and polarity reversal transient electric field in composite insulating medium. The existing literature shows that the temperature and field dependent nonlinear parameters of conductivity can be fitted simultaneously by equation (11):

$$\sigma = \sigma_0 e^{\alpha T + \beta E}$$  \hspace{1cm} (11)$$

Where $\sigma_0$ is the conductivity value (unit: S/m) at $t = 0 \, ^\circ\text{C}$ and $E = 0\, \text{kV/mm}$, $\alpha$ is the temperature dependent nonlinear coefficient and $\beta$ is the field dependent nonlinear coefficient[18]. The parameters of three kinds of insulation media are fitted and listed in Table 1.
| Coefficient             | \(\sigma_0\)    | \(\alpha\) | \(\beta\) |
|------------------------|------------------|-------------|------------|
| Transformer oil        | 3.06e-14         | 0.0667      | 0.5185     |
| Cardboard              | 3.20e-17         | 0.0969      | 0.0400     |
| Glue impregnated paper | 7.66e-16         | 0.0564      | 0.0320     |

4. Numerical verification of nonlinear finite element method

The above nonlinear finite element iterative calculation process is verified by the coaxial insulation structure with the analytical solution. The coaxial structure is shown in Figure 3, and the iterative algorithm results are compared with the analytical results. In Figure 3, \(I\) is the current carrying capacity of conductor (unit: \(A\)), \(R\) is the resistivity of conductor (unit: \(\Omega \cdot m\)), \(\lambda\) is the thermal conductivity of insulating medium (unit: \(\text{w/(m\cdot k)}\)), and \(T_s\) is the boundary temperature of insulating medium (unit: \(^\circ\text{C}\)). It is assumed that the field and temperature dependent nonlinear characteristics of the insulating medium in the above model are as follows (12):

\[
\rho = \frac{\rho_0 e^{-\alpha T}}{E^{-\beta}} \quad (12)
\]

\(\rho_0\) is the resistance coefficient under reference temperature and field strength (unit: \(\Omega \cdot m\)); \(\rho\) is the resistance coefficient under temperature \(T\) and field strength \(E\) (unit: \(\Omega \cdot m\)). Without considering joule heating of insulating medium, through a series of formula derivation, the radial field strength and the temperature distribution \(E(r)\)、\(T(r)\) of the coaxial structure considering the field variation and temperature variation non-linearity are shown in formula (13):

\[
\begin{align*}
E(r) &= (\varphi \delta r^{-\delta} \ln(r_\delta r_0)) / (r_\delta r_0^{-\delta}) \\
T(r) &= T_c - (T_c - T_s) \ln(r_0 r) / (\ln(r_0 r_\delta))
\end{align*} \quad (13)
\]

\(T_c\) is the temperature of the current carrying conductor (unit: \(^\circ\text{C}\)), \(r_0\) is the radius of current carrying conductor, \(r_\delta\) is the insulation radius, and \(\varphi\) is the conductor potential, there is the formula (14):

\[
\begin{align*}
\delta &= (\beta + \gamma) / (\beta + 1) \\
\gamma &= (\alpha I^2 R) / (2\pi \lambda)
\end{align*} \quad (14)
\]

The iterative process from the nonlinear finite element method is shown in Fig. 4, where the value of "damping coefficient" \(P_k\) is 0.55. Due to the arbitrariness of the initial value, the solution of \(E(R)\) after the fifth iteration will have the large deviation[19]. The numerical solution of \(E(R)\) will gradually approach the analytical solution by continuously modifying the distribution of the conductivity of the element. After 20 iterations, the difference between the numerical solution and the analytical solution is less than the allowable error, and the \(E(R)\) distribution is very close to the real distribution of the analytical solution.
In order to further illustrate the relationship between the damping coefficient $P_k$ and the convergence process, $P_k$ takes a series of values in the $(0,1)$ interval, and takes an element in the insulating medium as the observation point. Fig. 5 shows the convergence and oscillation curves of the local field strength of the element in 25 iterations. When $P_k = 0.3$, the finite element iterative calculation tends to have a better convergence effect in the first five steps.

The premise of deriving the theoretical formula (13) to (14) is to ignore the joule heat of insulating medium caused by the leakage current. If joule heat is taken into account, there is no closed form analytical solution. At this time, the numerical solution can still be obtained by finite element iterative algorithm. The calculation results are shown in Figure 6. It can be seen from the figure that joule heating of the insulating medium has significant effect on the distribution of $E(r)$, $T(r)$: the radial temperature increases and the in-homogeneity of field strength distribution increases.
Fig. 6 also shows the nonlinear iterative numerical calculation of the finite element method. Fig. 6 also shows that nonlinear iterative numerical algorithm of the finite element method is in good agreement with the classical analytical formula without considering the joule heating condition of the medium, which verifies the accuracy of the algorithm, and provides an effective numerical analysis for the further analysis of the electric field and temperature distribution of the composite insulation structure under the condition of temperature variation and field variation superposition non-linearity analysis method. The results show that the proposed method is in good agreement with the classical analytical formula without considering Joule heating, which verifies the accuracy of the algorithm and provides effective numerical analysis method for further analysis of electric field and temperature distribution of the composite insulation structure under the condition of temperature variation and field variation superposition non-linearity.

Fig. 7 Comparison between outlet model and real object
5. Nonlinear electric field calculation of composite insulation

5.1 Outlet device of converter valve side bushing

The comparison between the calculation model and the real object of the bushing outlet device at the valve side of converter is shown in Figure 7. The model includes three kinds of composite insulation media, namely transformer oil, oil impregnated paperboard and epoxy impregnated paperboard. Taking the dry bushing outlet device of ±400kV converter transformer as an example, the DC steady-state operation voltage is 646kV and the polarity reversal voltage is 460kV. The selection of nonlinear coefficient of temperature change and field change of each single insulating medium is the same as Table 1. The nonlinear electric field of the composite insulation is discussed in three cases: 1) DC steady-state field of the composite insulation under temperature gradient condition; 2) transient field of the polarity reversal of the composite insulation under temperature gradient condition. Joule heating caused by leakage current is considered in the calculation.

5.2 DC steady state field of composite insulation under temperature gradient

During the type test of the outgoing line device, the composite insulation at the end of the bushing basically maintains the isothermal state, but in the actual operation of the outgoing line device, due to the certain amount of current flowing through the central current carrying structure, the eddy current heating will establish the temperature gradient distribution. Therefore, it is necessary to analyze the electric field distribution law of the composite insulation under the condition of field variation and the temperature variation superposition nonlinearity through nonlinear finite element iterative algorithm. The hot spot temperature of the outlet device is set as 80 ℃ (calculated according to the flow rate) and the ambient temperature is set as 20 ℃. Similarly, the convergence curve of local field strength of a unit in RIP, OIL and OIP insulation medium is shown in Figure 8. After the first 11 iterations, the composite insulation tends to be stable, which proves that nonlinear finite element iterative algorithm also has good convergence for composite insulation under condition of field variation and temperature variation superposition nonlinearity.

However, due to the temperature gradient distribution near the outlet device, the DC steady-state field distribution of RIP, OIL and OIP is significantly different from that under isothermal condition. The temperature distribution of the outlet device and the distorted DC steady-state field in the three kinds of dielectric are shown in Figure 9.
Figure 9 shows that the high-temperature area at the end of the bushing is concentrated near the central current carrying guide rod, the position of the DC steady-state maximum electric field shifts to the low-temperature area. The electric field of the barrier in OIP insulation is higher than that covered by the grading ball, while the maximum electric field strength in the RIP insulation of the bushing core is concentrated near the flange. The electric field strength near the central guide rod is lower, which is contrary to the electric field distribution law under isothermal condition, so it is difficult to obtain the maximum electric field strength at the temperature. The insulation strength at low temperature should be strengthened under ladder condition.

5.3 Transient field of polarity reversal in composite insulation under temperature gradient
At $0^+ s$, $U(T)$ steps from zero to $-U_m$, and the duration is $t_1 s$. Then at $T_1$, $U(T)$ steps from $-U_m$ to $U_m$, and duration is $T_2$. Therefore, there are 1# and 2# transient processes in the whole polarity reversal process. Under isothermal and temperature gradient conditions, potential distribution change process of composite insulation at the end of bushing in $(0-T_2)s$ is shown in Fig. 10, where $T_1=40000 s$ and $T_2 = 80000 s$ are set, and the change process of composite insulation equi-potential line during polarity reversal of $0^+ s$ and $t_1 s$ is focused. Similarly, the hot spot temperature of the outlet device is set at 80 ℃ (calculated according to the flow rate), and the external ambient temperature is set at 20 ℃.
At $0^\circ$s, electric field distribution of the composite insulation at the end of the bushing is determined by the dielectric constant of each medium, which has little relationship with the temperature, so the equipotential distribution is basically the same under isothermal and temperature gradient conditions; at $t_1$, the electric field distribution of the composite insulation is determined by the dielectric constant...
and conductivity of each medium, and the conductivity is closely related to the temperature, so the equipotential distribution is different under isothermal and temperature gradient conditions. In order to quantitatively analyze the variation of field strength with time in the process of polarity reversal under the two conditions, the variation of field strength with time in RIP, OIP and OIL is shown in Figure 11. Figure 11 shows that in the process of polarity reversal, when there is a temperature gradient, the "overshoot" of field strength in RIP medium is greater than that under constant temperature, and the steady-state field strength in OIP medium is greater than that under constant temperature, which indicates that the test of composite insulation of outlet device is more severe under the condition of temperature gradient, and the insulation accident at the end of bushing is more likely to occur.

6. Conclusion
1) In this paper, based on the finite element method and Newton Raphson method, a finite element iterative algorithm for solving nonlinear electric field distribution is proposed, and the algorithm is improved to make it suitable for composite insulation system. Through the coaxial insulation structure with analytical solutions, it is found that the analytical solutions of radial temperature and field intensity distribution are in good agreement with the numerical solutions, which proves the accuracy and effectiveness of the algorithm. It is found that the conductivity is a function of temperature and field strength, and the exponential function can well fit the test data.

2) The nonlinear finite element iterative algorithm is applied to the composite insulation of the actual outgoing line device, and the algorithm also has good convergence under the condition of considering the superposition nonlinearity of temperature variation and field variation. The results show that: the electric field distribution law under the nonlinear and traditional linear conditions is significantly different, and the electric field nonlinearity has a certain field strength suppression effect on the high field strength region, while the temperature nonlinearity causes the field strength to decrease in the high temperature region and increase in the low temperature region, so the insulation strength in the low temperature region should be strengthened. In addition, under the condition of temperature gradient, the transient field of composite insulation polarity reversal in rip and OIP media is prone to local high field strength, which is more prone to bushing tail insulation accident than under the condition of constant temperature;

3) The DC steady-state field and polarity reversal transient field of composite insulation obtained by nonlinear finite element iterative algorithm are more consistent with the characteristics of insulating materials and actual operating environment, which effectively improve the traditional linear electric field calculation method. At the same time, the algorithm can be directly applied to the electric field simulation of composite insulation structure of other power equipment.

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