Study on transient electric field of multi-layer composite insulation structure during polarity reversal

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Abstract. Outgoing line device is an important structure of converter transformer. Multilayer composite insulation structure is widely used in the outgoing line device. Polarity reversal is special working state of converter transformer. In the process of polarity reversal, due to the influence of the space charge on the interface of composite insulation structure, there will be instantaneous high field strength, which threatens the normal operation of the outgoing line structure. In this paper, starting from the typical multi-layer composite insulation structure in the outgoing line device, the change rule of interface space charge and transient electric field in different polarity reversal time is analyzed under the condition of the equal temperature and temperature gradient. On this basis, the research object of the overall composite insulation structure of the outgoing line device is analyzed, and the change rule of the transient electric field in the process of polarity reversal is analyzed. The research in this paper can provide a theoretical basis for the development of the outgoing line structure of converter transformer.

1. Introduction
At present, there are many kinds of insulating media, including solid, liquid and gas insulating media [1, 2]. Application of multi-layer composite insulation media has appeared because of the complexity of the insulation media. However, with the increase of the complexity of the insulation media, the transient electric field of multi-layer composite insulation media, the nonlinear relationship between macro dielectric parameters and the frequency and temperature of the multi-layer composite insulation media, and existence of bubbles in the multi-layer composite insulation media are all characteristics of multi-layer composite insulation general problems of media [3-5]. It is necessary to conduct special research on the above phenomenon characteristics at the theoretical level, so as to have good guiding value for the application of multi-layer insulation medium in the insulation structure design of high-voltage power equipment [6, 7].

The contents of the paper are mainly divided into the following parts: 1) the distribution characteristics of the transient electric field of the double-layer composite medium are discussed in detail, and the transient electric field of the double-layer composite medium in the wide time domain is calculated quantitatively by using the finite element simulation method; 2) the application of the double-layer composite insulating medium to the multi-layer insulating medium is extended by using the classical analytical formula, which corresponds to the high-voltage bushing core, oil paper insulation structure of transformer and other applications; 3) test and analyze the macro dielectric constant of multi-layer insulation medium, and apply the fuzzy neural network to fit and analyze the macro dielectric constant, which can be applied to the finite element simulation calculation as a whole;
4) apply the macro dielectric constant of multi-layer insulation medium to analyze the micro gas between the insulation medium. In the case of bubbles, the distribution characteristics of electric field under DC and AC conditions are calculated respectively. The above research content makes quantitative analysis on the distribution characteristics of electric field of composite insulation medium at the certain level, which has certain theoretical guidance significance and engineering application value for the application and design of multilayer composite insulation medium in high-voltage power equipment [8-10].

2. Transient electric field simulation of double-layer composite medium

Under the action of DC voltage, electric field distribution inside the outgoing line structure depends on the conductivity of the insulating material, that is, the so-called resistance distribution. Under the action of the AC voltage, the electric field distribution is determined by the capacitance, which is a capacitance distribution. Under the action of polarity reversal voltage, the electric field distribution of the outgoing line structure is related to the resistivity and the capacitance, and it is the dynamic change process [11].

\[
E_x = -\frac{U}{d_1 + \frac{\varepsilon_1 d_1}{\gamma_1}} + \frac{2U}{d_1 + \frac{\varepsilon_2 d_2}{\epsilon_2}}
\]

\[
E_x = -\frac{U}{d_2 + \frac{\varepsilon_2 d_2}{\epsilon_2}} + \frac{2U}{d_2 + \frac{\varepsilon_1 d_1}{\gamma_1}}
\]

It can be seen from the formula that, at that time, the field strength shared by the oil gap at the moment of inversion is almost equal to a case of double step voltage. Then the field strength in the oil gap will gradually decrease, and the field strength in the paper will gradually increase. The transition process is determined by the discharge time constant of the two insulating materials. The time constant is the time when the field strength of the oil immersed paper reaches its maximum, and the smaller the transition process is, the shorter the transition process is. Generally, the transition process takes several minutes or even longer. When it is stable, its electric field distribution is DC electric field distribution. Using the finite element simulation software, the change of electric field in the polarity reversal of oil paper insulation structure is calculated as shown in Figure 2. Among them, the relative permittivity, resistivity and the thickness of transformer oil. The relative permittivity, resistivity and thickness of oil immersed insulating board. Assuming that the upper plate has polarity reversal voltage -and the lower plate is grounded, the discharge time can be obtained. The isopleth distribution of transformer oil and oil immersed insulating board at different times is shown in the following figure:
Figure 2. Equi-potential distribution during polarity reversal of oil paper insulation.

Figure 3. Dynamic change process of E-field strength of oil paper insulation during polarity reversal.

Under the polarity reversal voltage, the electric field distribution of the flat oil paper insulation system is in the process of dynamic change, the specific change rule: before the polarity reversal, the electric field strength in the transformer oil is kV/mm, and the electric field strength in the oil immersed paper is kV/mm, at this time, the electric field is distributed according to the resistivity. At the moment of polarity reversal, the electric field strength of the transformer oil is 18.6kV/mm, and the electric field strength in the oil paper is kV/mm, the transformer oil bears most of the field strength, which is the same as the calculation result of the formula. At this time, the electric field distribution is leisurely, and the field strength in the oil is equivalent to twice the step voltage. It is known that in the process of polarity reversal, the field strength in the oil decreases gradually, and the field strength in the oil immersed paper increases gradually. At about 500s, the transition process is completed, and the field distribution tends to be stable. After the field distribution is stable, the electric field strength of transformer oil is about 0.3kV/mm, and the electric field strength in the oil immersed paper is 14.7kV/mm. At this time, the electric field distribution in the oil immersed paper insulation system is the same as that in the steady-state DC electric field, it is distributed according to the resistance which is shown in Figure 3. To sum up, at the moment of polarity reversal, the electric field distribution in transformer oil is very concentrated, which may lead to partial discharge or even breakdown. Therefore, sufficient insulation margin shall be reserved for the outgoing line structure design of ± 800kV converter transformer to ensure the safe and reliable operation of the equipment during polarity reversal.

3. Extension of transient electric field in multi-layer composite medium

Two-layer media model of epoxy impregnated paper:

\[
\begin{align*}
\text{div}(\varepsilon_1 E_1(x)) &= 0 \\
\text{div}(\varepsilon_2 E_2(x)) &= 0 \\
\int_0^l E_1(x)dx + \int_0^d E_2(x)dx &= V \\
\varepsilon_1 E_1(x) - \varepsilon_1 E_1(x) &= \sigma_t \\
\gamma_2 E_1(x) - \gamma_1 E_1(x) &= 0
\end{align*}
\]
According to the latter two formulas, interface charge of two-layer dielectric model can be calculated:

\[ \sigma_i = E_i(x) \frac{\varepsilon_i \gamma_i}{\gamma} - \varepsilon_i \]  

(3)

It is easy to obtain the current density \( J \):

\[ J = \frac{\gamma_i \gamma V}{\gamma d_i + \gamma d_i} \]  

(4)

\( E_p(x) \) is the Poisson electric field with interface charge and no space charge accumulation in the insulator. For four layers of media:

\[ E_{P1}(x) = \frac{(-\sigma_1) d_2 e_2 e_1 + (\sigma_1 + \sigma_2) d_2 e_2 e_4 + (\sigma_1 + \sigma_2 + \sigma_3) d_2 e_2 e_3}{e_2 e_2 e_2 e_2} \]

\[ E_{P2}(x) = \frac{(-\sigma_1) d_2 e_2 e_1 + (+\sigma_1) d_2 e_2 e_4 + (\sigma_1 + \sigma_2 + \sigma_3) d_2 e_2 e_3}{e_2 e_2 e_2 e_2} \]

\[ E_{P3}(x) = \frac{\sigma_1 d_3 e_3 e_2 + (\sigma_3 - \sigma_1) d_3 e_3 e_2 + (\sigma_1 + \sigma_2) d_3 e_3 e_2}{e_2 e_2 e_2 e_2} \]

\[ E_{P4}(x) = \frac{\sigma_1 d_4 e_4 e_2 + (\sigma_3 - \sigma_1) d_4 e_4 e_2 + (\sigma_1 + \sigma_2) d_4 e_4 e_2}{e_2 e_2 e_2 e_2} \]

\( E_{L}(x) \) is the Laplace electric field without interface charge. For four layers of media:

\[ E_{L1}(x) = \frac{e_2 e_2 e_2}{d_2 e_2 e_2 + d_2 e_2 e_2 + d_2 e_2 e_2} \]

\[ E_{L2}(x) = \frac{e_3 e_3 e_3}{d_3 e_3 e_3 + d_3 e_3 e_3 + d_3 e_3 e_3} \]

\[ E_{L3}(x) = \frac{e_4 e_4 e_4}{d_4 e_4 e_4 + d_4 e_4 e_4 + d_4 e_4 e_4} \]

\[ E_{L4}(x) = \frac{e_4 e_4 e_4}{d_4 e_4 e_4 + d_4 e_4 e_4 + d_4 e_4 e_4} \]

In conclusion, the Laplace electric field without space charge in \( N \)-layer medium can be expressed by the following general formula:

\[ E_{L}(x) = \frac{V / \varepsilon_i}{\sum \frac{d_i}{\varepsilon_i}} (i = 1, \ldots, N) \]  

(7)

For the Poisson electric field with interface charge and assuming no space charge accumulation in the insulator, it can be given by matrix type. For four layers of media:

\[
\begin{bmatrix}
E_{L1} \\
E_{L2} \\
E_{L3} \\
E_{L4}
\end{bmatrix} = 
\begin{bmatrix}
0 & -\sigma_1 & (\sigma_1 + \sigma_2) & (\sigma_1 + \sigma_2 + \sigma_3) \\
\sigma_1 & 0 & -\sigma_2 & (\sigma_1 + \sigma_2) \\
\sigma_1 + \sigma_2 & \sigma_2 & 0 & -\sigma_3 \\
\sigma_1 + \sigma_2 + \sigma_3 & \sigma_2 + \sigma_3 & \sigma_3 & 0
\end{bmatrix} 
\begin{bmatrix}
d_1 \\
d_2 \\
d_3 \\
d_4
\end{bmatrix} 
\]

\[
\begin{bmatrix}
\lambda_{L1} \\
\lambda_{L2} \\
\lambda_{L3} \\
\lambda_{L4}
\end{bmatrix} = 
\begin{bmatrix}
\frac{d_1}{\varepsilon_1} + \frac{d_2}{\varepsilon_2} + \frac{d_3}{\varepsilon_3} + \frac{d_4}{\varepsilon_4} \\
\frac{d_2}{\varepsilon_2} + \frac{d_3}{\varepsilon_3} + \frac{d_4}{\varepsilon_4} \\
\frac{d_3}{\varepsilon_3} + \frac{d_4}{\varepsilon_4} \\
\frac{d_4}{\varepsilon_4}
\end{bmatrix} 
\]

(8)

For \( N \)-layer media, the interface charge density is as follows:

\[ \sigma_i = E_i(x) \frac{\varepsilon_i \gamma_i}{\gamma_{i+1}} - \varepsilon_i (k = 1, \ldots, N - 1) \]  

(9)
The Poisson electric field distribution of n-layer medium can be expressed by the following general formula: $\sigma_j + \sigma_{j+1} + \cdots + \sigma_j = S_j$ ($j > i$). First of all, let ($j > i$), in which the composite effect of interface charge density on Poisson electric field of n-layer medium can be expressed by symmetric matrix. From this matrix, it can be seen that interface charge has mutual influence on Poisson electric field of n-layer medium, so the composite Poisson electric field of n-layer medium should be analyzed from the perspective of system.

\[
\begin{bmatrix}
E_{p1}' \\ E_{p2}' \\ \vdots \\ E_{px,y}' \\ E_{pj}' \\
\end{bmatrix} = \begin{bmatrix}
0 & -S_{11} & -S_{12} & \cdots & -S_{1x} & \cdots & -S_{1(x-1)} \\
S_{11} & 0 & -S_{22} & \cdots & -S_{23} & \cdots & -S_{2(x-1)} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
S_{xi} & S_{xi} & S_{xi} & \cdots & 0 & -S_{x(2x-1)} & -S_{x(x-1)} \\
\vdots & \vdots & \vdots & \ddots & 0 & -S_{x-1,x-1} & -S_{x-1,x} \\
0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\
\end{bmatrix} \begin{bmatrix}
d_1 / \varepsilon_1 \\
d_2 / \varepsilon_2 \\
\vdots \\
d_{y-1} / \varepsilon_{y-1} \\
d_y / \varepsilon_y \\
\end{bmatrix}
\]

(10)

Further $E_{pk}'$ amendments are required:

\[
E_{pk}' = \frac{E_{pk}}{\sum_{i=1}^{x} \frac{d_i}{\varepsilon_i}}
\]

(11)

4. Dielectric properties of the multi-layer composite media

There is the direct relationship between the macroscopic electrical properties and the microstructure of multilayer composite media. Figure 4 shows the microscopic observation results of the multi-layer composite dielectric under the electron scanning microscope. It shows that the composite insulating media are closely connected and there are small bubble defects under the microscopic conditions (the bubble may be in the vacuum environment).

![Figure 4. Multi-layer composite dielectric under the electron scanning microscope.](image)

From the dielectric spectrum characteristics of multilayer composite oil paper insulation system, it can be seen that the dielectric parameters of pure insulating board and oil impregnated insulating board, including the loss tangent, AC conductivity and temperature, frequency change significantly, and loss tangent value appears more significant loss peak in the high frequency and high temperature areas. Conductivity and frequency change are not sensitive, mainly closely related to temperature change. Through the 3D graph, it can be found that tangent value of loss angle has multi peak characteristics with temperature and frequency. However, in the process of using the above multi data relationship, the data points obtained through the experiment are all discrete data lattice, so how to get the rest of the data points in the wide range of temperature domain and frequency domain has good application value. In this paper, fuzzy neural network is applied to interpolation calculation, and the
interpolation fitting effect is shown in Figure 5. The figure shows that the interpolation effect of FNN is good, and only significant interpolation error occurs in the low frequency region which is shown in Figure 6.

![Figure 5. The relationship between dielectric parameters and temperature and frequency of multilayer composite insulation.](image)

![Figure 6. Fitting error of fuzzy neural network.](image)

The main reason for complex peak value of the above macroscopic dielectric parameters, frequency and temperature is that the bubble in the composite medium distorts the E-field distribution nearby. In order to further analyze electric field distortion of oil paper insulation, when there are bubbles between the multi-layer media. The surface electric field distribution of two typical bubble topologies is shown in Figure 7. It can be seen that the high field strength region is mainly distributed at end of the bubble.

In the calculation, the single bubble between the plates is considered for the solid modeling. In the calculation, the load voltage between the plates is 27kV, which is calculated in two cases of AC and
DC. The main parameters of the calculation model are as follows: width between the upper and lower plates=3mm, plate length = 30mm, long axis length of elliptical bubble=0.5mm, length of short axis of elliptical bubble=0.25mm which is shown in Figure 8.

Figure 7. Surface electric field distribution of two typical bubble topologies.

Figure 8. Calculation model of bubbles between plates.

Because the length of the electrode plate is long enough, the influence of the edge effect at the end of the electrode plate on the potential and electric field distribution around the bubble can be ignored. Considering that when the angle between the bubble and the horizontal plane changes, the potential and electric field distribution around the bubble will change greatly, the different potential and electric field distribution around the bubble will be considered in the calculation. Bubbles between plates may occur in both AC and DC conditions, so the following will be divided into AC and DC cases for calculation, and the calculation results under AC.

Figure 9. Electric field and potential distribution of bubbles between plates (AC).
The above is the calculation results when the angle between the bubble and the horizontal plane is 0°, 45° and 90°. The electric field distribution is shown in Figure 9. It can be seen from the figure that the electric field distortion around the bubble is relatively serious. There are two high field strength areas and two low field strength areas. The electric field intensity inside the bubble is uniform, about 17628 V/mm, 15032 V/mm and 11886 V/mm. It can be seen from the figure that the equipotential line between the plates deflects at the interface between the bubble and epoxy, and the equipotential line inside the bubble is even.

**Figure 9.** The relationship between maximum E-field intensity and the rotation angle of bubbles.

The relationship between the maximum electric field intensity of bubbles and the rotation angle is shown in Figure 10. It can be seen from the figure that when the included angle is 0°, that is, when the bubbles are in the horizontal direction, the maximum electric field intensity of bubbles is the largest, about 17500 V/mm. When the bubbles are in the vertical direction, that is, when the included angle is 90°, the maximum electric field intensity of bubbles is the smallest, about 12000 V/mm. The following is the calculation results when the angle between the bubble and the horizontal plane is 0°, 45° and 90°. The electric field distribution is shown in Figure 11. It can be seen from the figure that the electric field distortion around the bubble is relatively serious. There are two high field strength areas and two low field strength areas. The electric field intensity inside the bubble is uniform, about 24729 V/mm, 19800 V/mm and 13150 V/mm. It can be seen from the figure that the equipotential line between the plates deflects at the interface between the bubble and epoxy, and the equipotential line inside the bubble is even.

**Figure 11.** The relationship between maximum E-field intensity and the rotation angle of bubbles (DC).
The relationship between the maximum electric field strength and rotation angle of bubble is shown in Figure 12. It can be seen from the figure that when the included angle is 0 °, that is, when the bubble is in horizontal direction, the maximum electric field strength of bubble is the largest, about 25000V/mm. When the bubble is in vertical direction, that is, when the included angle is 90 °, the maximum electric field strength of bubble is the smallest, about 13000V/mm.

![Figure 12. The relationship between the maximum electric field intensity and the rotation angle of bubbles (AC and DC).](image)

As can be seen from Figure 12, the maximum electric field strength of bubbles in DC is always higher than that in AC. In case of power flow reversal in DC system, 800kV UHV converter transformer shall bear polarity reversal impulse voltage. At this time, the electric field distribution in the outgoing line area of converter transformer is very concentrated, so insulation strength under polarity reversal test voltage shall be examined in type test. In this paper, the finite element method is
used for the first time to analyze the electric field distribution of the insulation structure of 800kV UHV converter transformer outgoing line under polarity reversal voltage, which is 1124kV. The open type outgoing device is shown in Figure 13, which is composed of the multi-layer coaxial straight cylindrical paper cylinder. The structure is simple and easy to produce. At the same time, the oil circuit is smooth, the oil flow range is large, and the heat dissipation effect is good. However, the improvement effect of the open outlet device on the electric field concentration near the equalizing ball is limited. The insulation structure of closed outgoing line device is conducive to improving the phenomenon of concentrated electric field distribution near the equalizing ball. However, the flow range of the structural oil is small, and the heat dissipation is relatively poor. At the same time, the shaped cardboard is not well formed in the actual engineering manufacturing, and the mechanical strength cannot be effectively guaranteed.

![Figure 13](image)

**Figure 13.** Structure diagram of open outlet device.

At the moment of polarity reversal, the electric field distribution of the outgoing line area of the converter transformer is determined by the permittivity and resistivity of material. It can be seen that the distribution of the equipotential lines in the outgoing line area at the moment of inversion is quite different from that at AC voltage and DC voltage. The electric field at the end of the bushing is particularly concentrated. At this time, the space charge at each interface will discharge and charge at different speed and through different paths, which may lead to the situation that the local field strength is too high at the certain time. This also explains the reason why the outgoing line structure is prone to failure at the moment of polarity reversal. Then, the electric field distribution of the outgoing line area enters into the transition process, and the transition time is determined by the time constant of its insulation structure which is shown in Figure 14. At that time, the electric field distribution of the outgoing line device basically reaches the steady state, and the distribution of the equipotential lines in the outgoing line area is very close to that under DC voltage.

**Figure 14.** Variation curve of maximum electric field intensity in different structures.

At the moment of polarity reversal, the electric field distribution of the outgoing line area of the converter transformer is determined by the permittivity and resistivity of material. It can be seen that the distribution of the equipotential lines in the outgoing line area at the moment of inversion is quite different from that at AC voltage and DC voltage. The electric field at the end of the bushing is particularly concentrated. At this time, the space charge at each interface will discharge and charge at different speed and through different paths, which may lead to the situation that the local field strength is too high at the certain time. This also explains the reason why the outgoing line structure is prone to failure at the moment of polarity reversal. Then, the electric field distribution of the outgoing line area enters into the transition process, and the transition time is determined by the time constant of its insulation structure which is shown in Figure 14. At that time, the electric field distribution of the outgoing line device basically reaches the steady state, and the distribution of the equipotential lines in the outgoing line area is very close to that under DC voltage.

**5. Conclusions**

1. There is the significant transient process in the process of polarity reversal in the double-layer insulating medium. The electric field is distributed according to the AC voltage at the moment of polarity reversal voltage and the DC voltage after the transient process. The transient process takes about 500s.
2. The matrix form of classical analytical formula can be used to reasonably extend the multi-layer insulating medium, and the electric field strength value in each layer of insulating medium can be effectively calculated according to the classical formula.
3. The fuzzy neural network can effectively fit the multi peak three-dimensional distribution surface of the dielectric constant with temperature and frequency, and only in the low frequency region, the interpolation error is significant.
(4) The relationship between the maximum electric field intensity and the rotation angle of bubbles is significant under AC and DC. The maximum electric field intensity of bubbles under DC is always higher than that under AC.

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