The temperature effect to the compound electric field distribution of oil-paper insulation

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Abstract. This paper adopts a typical double-layer oil-paper insulation structure model, and obtains the mathematical expression of electric field distribution of oil-paper composite insulation. On the basis of the mathematical expression of the electric field distribution of oil-paper combination insulation, the numerical calculation results of the electric field distribution of oiled paper composite insulation are obtained. It is found that the temperature has little effect on the field strength distribution in transformer oil and paperboard under high AC content, and the temperature is low in low AC content. It has a great influence on the distribution of field strength in oil-paper insulation, especially the field strength in transformer oil.

1. Introduction

The research work of electric field distribution of oil-paper insulation under the action of composite electric field is mostly carried out under room temperature conditions, but temperature is an important factor affecting transformer oil-paper insulation [1-6]. In recent years, there have been faults in the operation of transformers at lower temperatures. However, there is no research on the electric field distribution of oil-paper insulation under the electric field in the temperature range of high and cold regions, and the electric field distribution is used to study the breakdown and flashover of oil-paper insulation [7-12]. The study of characteristics is of great significance. This paper studies the influence of the temperature range (-40 °C~105 °C) in the alpine region on the electric field distribution of oil-paper insulation.

2. Experiment device

The coordination of the compound voltage source with different ac contents is needed in the test portion of the research work in this paper. The AC and DC test transformers are general-purpose equipments. The original conditions of the laboratory have met the test requirements. For this purpose, the AC-DC superposition test power supply is built.

Generally, the AC-DC superimposed voltage can be generated by two methods:

(1) Pre-plus DC voltage method, that is, first apply a DC voltage of a certain voltage amplitude, and then gradually increase the AC voltage until the sample breaks down

(2) The principle of pre-applied AC voltage method is similar to the former. For whatever the above methods, the breakdown voltage of the breakdown voltage may cause the phenomenon that the
breakdown voltage of the breakdown voltage is not fixed, and the requirement for qualitatively describing the relationship between the AC content and the breakdown voltage cannot be satisfied. To this end, the test used a fixed AC content percentage method to simultaneously boost the AC and DC power supplies. Using the existing AC and DC high voltage test transformers in the laboratory, through parallel combination, a power supply capable of generating a superimposed voltage is constructed. The circuit diagram of the device is shown in Figure 1.

![DC superimposed AC test circuit](image)

**Figure 1.** DC superimposed AC test circuit.

Figure 1 consists of a DC high voltage part and an AC high voltage part. It can be seen from the circuit principle in the above figure that the regulation of the voltage regulator can ensure that the AC content is kept at a fixed value, and the isolation capacitor and the high voltage silicon stack in the circuit can function to isolate the opposite side voltage.

The working voltage waveform of the output of the AC superimposed DC high voltage generating device is shown in Figure 2.

![AC and DC superimposed voltage waveform](image)

**Figure 2.** AC and DC superimposed voltage waveform.

In Figure 2, $U_{DC}$ is the average value of the DC component, $U_{AC}$ is the peak of the AC component. For convenience of presentation, the AC content in the AC-DC superimposed voltage is defined as:

$$
\eta = \frac{U_{AC}}{U_{AC} + U_{DC}} \times 100\%
$$

(1)
The DC content is \((1-\eta)\) and the voltage amplitude is expressed as:

\[ U = U_{AC} + U_{DC} \] (2)

The voltage amplitude \(U\) and the AC content \(\eta\) are used to describe the voltage relationship under various waveforms. As can be seen from the definition of equation (1), for the DC voltage \(\eta=0\), for the AC voltage \(\eta=1\); DC component \(\lambda=1-\eta\). For simplicity, the AC-DC superimposed voltage (or electric field) mentioned later in this paper includes both AC and DC voltage (or electric field).

3. Analysis

In order to study the electric field distribution of oil-paper insulation, a typical double-layer oil-paper insulation structure model is adopted in this paper, the relative dielectric constant, electrical conductivity and thickness of cardboard and oil are respectively \(\varepsilon_p, \gamma_p, d_p\) and \(\varepsilon_o, \gamma_o, d_o\). The equivalent circuit is shown in Figure 1. Respectively, the voltage at both ends of the oil-paper composite insulation structure is \(U\), and the equivalent voltage, capacitance and resistance at both ends of the cardboard and oil are \(U_p, C_p, R_p\) and \(U_o, C_o, R_o\) [1-6].

![Diagram of oil-paper insulation model and equivalent circuit.](image)

The space charge on the oil-paper interface before the installation of the voltage is zero, that is, the equivalent circuit shown in Figure 3 is in the zero state. When the voltage is applied, according to Ohm's law and the first-order circuit, we obtain:

At any time, the voltage on the board is:

\[ u_p = \frac{R_o}{R_p + R_o} U_{dc} + \left( \frac{C_o}{C_p + C_o} - \frac{R_o}{R_p + R_o} \right) U_{dc} e^{-\frac{t}{\tau}} + u_{ac} \left( \frac{C_o}{C_p + C_o} \right) \] (3)

The voltage on the oil is:

\[ u_o = \frac{R_o}{R_p + R_o} U_{dc} + \left( \frac{C_p}{C_p + C_o} - \frac{R_o}{R_p + R_o} \right) U_{dc} e^{-\frac{t}{\tau}} + u_{ac} \left( \frac{C_p}{C_p + C_o} \right) \] (4)

In the formula, \(\tau = \frac{1}{R_p} + \frac{1}{R_o}\), is the time constant.

Mathematical expression of electric field distribution of oil-paper composite insulation

It can be known from formula (1):

\[
\begin{aligned}
    u_{dc} &= (1-\eta)U \\
    u_{ac} &= U_{ac} (\sin \omega t) = \eta U \sin(\omega t)
\end{aligned}
\] (5)

Substituting equation (5) into equations (3) and (4) yields:
\[ u_p = \frac{R_p}{R_p + R_o} (1 - \eta) U + \left( \frac{C_p}{C_p + C_o} - \frac{R_p}{R_p + R_o} \right) U e^{-\tau} + \frac{C_o}{C_p + C_o} \eta U \sin(\omega t) \]
\[ = \frac{R_p}{R_p + R_o} U + \left( \frac{C_p}{C_p + C_o} - \frac{R_p}{R_p + R_o} \right) U e^{-\tau} \] (6)

\[ u_o = \frac{R_o}{R_p + R_o} U + \left( \frac{C_p}{C_p + C_o} - \frac{R_p}{R_p + R_o} \right) U e^{-\tau} \]
\[ + \left[ \frac{C_o}{C_p + C_o} \sin(\omega t) - \frac{R_o}{R_p + R_o} - \left( \frac{C_p}{C_p + C_o} - \frac{R_p}{R_p + R_o} \right) e^{-\tau} \right] \eta U \] (7)

Since the model shown in Figure 1 belongs to a flat-plate type capacitor, and so, \( C = \varepsilon \frac{s}{d} \) and \( R = \rho \frac{d}{s} \) there are:

\[
\begin{align*}
R_p &= \frac{\rho_p d_p}{s} \\
R_o &= \frac{\rho_o d_o}{s} \\
R &= \frac{\rho d}{s}
\end{align*}
\]
\[
\begin{align*}
R_p + R_o &= \frac{\rho_p d_p + \rho_o d_o}{s} \\
R &= \frac{\rho d}{s}
\end{align*}
\]
\[
\begin{align*}
C_p &= \frac{\varepsilon_p d_p}{s} \\
C_o &= \frac{\varepsilon_o d_o}{s}
\end{align*}
\]
\[
\begin{align*}
C_p + C_o &= \frac{\varepsilon_p d_p + \varepsilon_o d_o}{s}
\end{align*}
\]

The instantaneous values of the voltages on the board and oil obtained by substituting (8) into (6) and (7) are:

\[ u_p = \frac{\rho_p d_p}{\rho_p d_p + \rho_o d_o} U + \left( \frac{\varepsilon_p d_p}{\varepsilon_p d_p + \varepsilon_o d_o} - \frac{\rho_p d_p}{\rho_p d_p + \rho_o d_o} \right) U e^{-\tau} \]
\[ + \left[ \frac{\varepsilon_o d_o}{\varepsilon_p d_p + \varepsilon_o d_o} \sin(\omega t) - \frac{\rho_o d_o}{\rho_p d_p + \rho_o d_o} - \left( \frac{\varepsilon_p d_p}{\varepsilon_p d_p + \varepsilon_o d_o} - \frac{\rho_p d_p}{\rho_p d_p + \rho_o d_o} \right) e^{-\tau} \right] \eta U \] (9)

\[ u_o = \frac{\rho_o d_o}{\rho_p d_p + \rho_o d_o} U + \left( \frac{\varepsilon_o d_o}{\varepsilon_p d_p + \varepsilon_o d_o} - \frac{\rho_o d_o}{\rho_p d_p + \rho_o d_o} \right) U e^{-\tau} \]
\[ + \left[ \frac{\varepsilon_p d_p}{\varepsilon_p d_p + \varepsilon_o d_o} \sin(\omega t) - \frac{\rho_p d_p}{\rho_p d_p + \rho_o d_o} - \left( \frac{\varepsilon_o d_o}{\varepsilon_p d_p + \varepsilon_o d_o} - \frac{\rho_o d_o}{\rho_p d_p + \rho_o d_o} \right) e^{-\tau} \right] \eta U \] (10)

Because it is in steady state, \( t \to \infty \), so \( e^{-\tau} = 0 \), the above formula is reduced to:
When $\sin(\omega t) = 1$, $u_p$ and $u_o$ get the maximum value, at this time,

$$
egin{align}
    u_p &= \frac{\rho_p d_p}{\rho_p d_p + \rho_o d_o} U + \left[ \frac{\varepsilon_p d_p}{\varepsilon_p d_p + \varepsilon_o d_o} \sin(\omega t) - \frac{\rho_p d_p}{\rho_p d_p + \rho_o d_o} \right] \eta U \\
    u_o &= \frac{\rho_o d_o}{\rho_p d_p + \rho_o d_o} U + \left[ \frac{\varepsilon_o d_o}{\varepsilon_p d_p + \varepsilon_o d_o} \sin(\omega t) - \frac{\rho_o d_o}{\rho_p d_p + \rho_o d_o} \right] \eta U
\end{align}
$$

(11)

Due to the characteristics of the distribution of the composite electric field between oil and paperboard, and the equivalent parallel impedance value is much larger than the capacitive reactance value, it is considered that the AC and DC electric fields can be linearly superimposed in engineering. Assuming that the electric field distribution in the medium is uniform, the electric field strengths $E_p$ and $E_o$ in the oil-impregnated paperboard and transformer oil can be obtained from $E=U/d$:

$$
egin{align}
    E_p &= \frac{\rho_p}{\rho_p d_p + \rho_o d_o} (1-\eta) U + \frac{\varepsilon_o d_o}{\varepsilon_p d_p + \varepsilon_o d_o} \eta U \\
    E_o &= \frac{\rho_o}{\rho_p d_p + \rho_o d_o} (1-\eta) U + \frac{\varepsilon_p d_p}{\varepsilon_p d_p + \varepsilon_o d_o} \eta U
\end{align}
$$

(13)

It is known from the above that $\rho$ and $\varepsilon$ are both functions of the temperature $T$, so the field strengths $E_p$ and $E_o$ in the paperboard and oil are both a function of the temperature $T$ and the alternating current content $\eta$.

4. The calculation results of oil-paper composite insulation electric field distribution numerical

The expression of the resistivity and the relative dielectric constant as a function of temperature is brought into the formula (13) by taking the fitting, taking $U=150$ kV, $d_p=1$ mm, $d_o=1.5$ mm, The trend of $E_p$, $E_o$ with $\eta$ and $T$ is shown in Figure 4.

Figure 4. Field strengths in transformer oil and oil-impregnated cardboard under different AC content and temperatures.
When the AC content is constant, the field strength of the paperboard generally decreases with the increase of temperature. When the temperature is constant, the field strength of the paperboard increases monotonously with the decrease of the AC content and the change of the field strength in the oil is just the opposite. This is because the electric field distribution at high AC content mainly depends on the relative dielectric constant ratio of the oil paper, while the electric field distribution at low AC content mainly depends on the resistivity ratio of the oil paper. In the figure, the maximum field strength of the paperboard appears at low temperature and low AC content ($\eta = 0$, $T = -20 ^{\circ}C$), while the maximum field strength in the oil occurs at high temperature and high AC content ($\eta = 100\%$, $T = 100 ^{\circ}C$). Therefore, when designing the converter transformer, attention should be paid to the insulation margin at high temperature and high AC content for the oil gap. For the insulation board, attention should be paid to the insulation margin under low temperature and DC conditions.

In order to quantify the rate of change of field strength, this paper calculates the field strength growth rate $v$ in paperboard and oil based on 20 $^{\circ}C$, which is defined as:

$$v = \frac{E_T - E_{20}}{E_{20}} \times 100\%$$

(14)

Where: $E_T$ represents the field strength at a temperature of $T$, and $E_{20}$ represents the field strength at a temperature of 20 $^{\circ}C$, and can be obtained by Figure 4. The growth rates of field strength in paperboard and oil are shown in Tables 1 and 2, respectively.

**Table 1.** Growth rate of field strength in paperboard at different temperatures and AC content Unit: %.

| AC content | Temperature $^\circ C$ | 0%  | 20%  | 40%  | 60%  | 80%  | 100% |
|------------|------------------------|-----|------|------|------|------|------|
|            | -40                    | 2.17| 4.93 | 5.16 | 5.5  | 6.07 | 7.33 |
|            | -20                    | 2.91| 6.32 | 6.13 | 5.83 | 5.32 | 4.3  |
|            | 0                      | 1.33| 2.83 | 2.74 | 2.61 | 2.39 | 1.93 |
|            | 20                     | 0   | 0    | 0    | 0    | 0    | 0    |
|            | 40                     | 0.74| 1.4  | 1.1  | 0.66 | -0.09| -1.6 |
|            | 60                     | -1.72| -2.16| -2.23| -2.35| -2.54| -2.93|
|            | 80                     | -7.42| -13.99| -13.01| -11.54| -9.06| -4.06|
|            | 100                    | -29.5| -44.5| -40.6| -34.7| -34.9| -5   |

**Table 2.** Growth rate of field strength in oil at different temperatures and AC content Unit: %.

| AC content | Temperature $^\circ C$ | 0%  | 20%  | 40%  | 60%  | 80%  | 100% |
|------------|------------------------|-----|------|------|------|------|------|
|            | -40                    | -53.1| -17.9| -9.7 | -5.9 | -3.9 | -2.5 |
|            | -20                    | -38.9| -22.9| -11.5| -6.2 | -3.4 | -1.4 |
|            | 0                      | -32.5| -10.3| 5.1  | -2.8 | -1.5 | -0.7 |
|            | 20                     | 0   | 0    | 0    | 0    | 0    | 0    |
|            | 40                     | -18.2| -5.1 | -2.1 | -0.7 | 0.05 | 0.55 |
|            | 60                     | 24.3 | 7.9  | 4.2  | 2.6  | 1.6  | 1.01 |
|            | 80                     | 181.7| 50.8 | 24.4 | 12.5 | 5.7  | 1.4  |
|            | 100                    | 721.6| 161.7| 76.2 | 37.8 | 15.9 | 1.7  |
5. Conclusions
The conclusion is that the temperature has little effect on the field strength distribution in transformer oil and paperboard under high AC content. While the temperature at low AC content has a great influence on the field strength distribution in oil-paper insulation, especially the effect on the field strength in transformer oil is more significant.

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