Space-time distribution characteristic of electric field in oil of oil-pressboard insulation structure oil under impulse voltage

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Abstract. The space electric field distribution in oil under impulse voltage is very important for the design of transformer insulation. The existing research only focused on the characteristics of the electric field at a certain point in oil-pressboard insulation structure. To in-depth study of the space electric field distribution in oil under impulse voltage changes with time and space, the measurement platform for the space electric field in oil under impulse voltage was built. The space electric field distribution in transformer oil under lightning impulse voltage was measured, and its changes with time and space were analysed. The results indicate that: As the applied voltage increases, the measured field strength begins to be lower than the applied, and the difference between the maximum measured and applied field strength increase. The space electric field distribution in oil in the wavefront time stage gradually becomes uniform with the increase of time. In the tail time stage, the weakening effect of the space charge on the electric field in oil gradually weakens with the increase of time and the applied field strength is first higher than the measured and then gradually lower than it.

1. Introduction
The stability of the power system is directly affected by the safe operation of the transformer, so the insulation design of the transformer is very important. At present, simulation software is mainly used to analyse and calculate the electric field, lack of verification of measurement methods in oil.

Scholars have carried out research on the electric field distribution in liquids at different voltages. In 1983, M. Zahn used the Kerr effect method to measure the electric field distribution in water at the range of 8.8°C to 29.5°C under impulse voltage[1]. The study found that the distortion of space electric field is more serious when the temperature is lower. In the same year, E. Kelley measured the electric field distribution and space charge of transformer oil under AC voltage through the same method[2]. He found that there is no space charge effect under AC voltage. In 2017, Chengjun Cai measured the electric field changes in transformer oil from 25°C to 60°C under a lightning impulse voltage of 60kV. His found that as the temperature rises, the electric field at the measuring point shows a downward trend. However, he only measured one point in oil and didn’t give a law.

In summary, the existing research only focused on the characteristics of the electric field at a certain point in the oil-pressboard insulation structure. The platform for measuring the space electric field in oil under impulse voltage was built. The distribution of electric field in the transformer oil under lightning impulse voltage was measured, and its changes with time and space were analysed.
2. Experimental platform and measurement method

2.1. Electric field measurement platform and parameters

The Kerr effect method was adopted to measure the electric field. The measurement system was composed of optical devices, a photodetector, an experimental chamber, and an impact source. As shown in figure 1, the impact source output the standard lightning impulse voltage on the electrode and connected to the oscilloscope to record the voltage waveform through the capacitor voltage divider. The light beam emitted by the laser passed through the electric field area and was received by photodetector. The oscilloscope recorded the light intensity change of the whole wave process.

![Figure 1. Electric field measurement system under impulse voltage.](image)

The impact source was a 400kV impulse generator. The material of the experiment chamber was PMMA, with a length of 1080mm, a width of 200mm, a height of 170mm, and a thickness of 20mm.

The test medium was the Karamay #25 transformer oil, filtered three times with 0.45μm filter paper and dried at 85°C for 24 hours under vacuum conditions. The moisture content met the requirements of the moisture content in oil of the operating transformer, which was between 7.66~8.13μL/L.

2.2. Principle of electric field measurement in oil

Under the action of an applied electric field, the linearly polarized laser passed through the transformer oil and produced a phase difference $\theta$ between the components vertical and parallel to the electric field direction. The phase difference was only related to the Kerr constant of the medium, the length of the measuring area and the square of the electric field intensity. As shown below.

$$\theta = 2\pi B \int_0^L E^2(l)dl$$  \hspace{1cm} (1)

Where: $B$ is the Kerr constant of the medium to be measured, $m/V^2$; $E$ is the electric field intensity, $V/m$; $L$ is the length of the laser passing through the area to be measured, $m$.

The Kerr constant $B$ \cite{3} of the liquid medium can be expressed as follows.

$$B = \frac{N(\Delta \alpha)^2}{30kT\lambda e_0}$$  \hspace{1cm} (2)

Where: $N$ is the number of molecules per unit volume in the medium; $\Delta \alpha$ is the parameter that characterizes the anisotropy of the polarizability; $k$ is the Boltzmann constant; $T$ is the absolute temperature; $\lambda$ is the wavelength of the incident light; $e_0$ is the dielectric constant of the liquid.
The laser passed through the polarizer and the analyser. The angle of the polarizer is 45°, of the analyser is 135°, and the relationship between the output and input light intensity is shown as follows.

\[
\frac{I_o}{I_i} = \sin^2 \left( \frac{\pi}{2} \left( \frac{E}{E_m} \right)^2 \right)
\]  

(3)

Where: \( I_i \) is the input light intensity; \( I_o \) is the output light intensity; \( E_m \) is the applied field intensity corresponding to the first maximum value of the light intensity. \( E_m \) is only related to the Kerr constant and the length of the electric field, as shown in equation (4).

\[
E_m = (2BL)^{\frac{1}{2}}
\]  

(4)

When the output light intensity changes with the increase of the electric field, \( E_m \) is a reference value. When the electric field value reaches \( \sqrt{n}E_m \), \( \sqrt{3}E_m \), \( \sqrt{5}E_m \) …… \( \sqrt{n}E_m \) successively, the light intensity is the maximum value, and \( n \) is an odd number.

When the light intensity is weakened, the formula for electric field intensity is shown as follows:\[4\].

\[
\frac{E}{E_m} = \left[ n - 1 + \frac{2}{\pi} \arcsin \left( \frac{I_o}{I_i} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}}
\]  

(5)

When the light intensity increases, the formula for electric field intensity is shown in (6).

\[
\frac{E}{E_m} = \left[ n + \frac{2}{\pi} \arcsin \left( \frac{I_o}{I_i} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}}
\]  

(6)

Transformer oil Kerr constant was measured by AC modulation\[5\], which is \( B = 2.30 \times 10^{-15} \text{ m/V}^2 \).

2.3. Experimental method

Because the steeper the wavefront, the stricter the requirements for the gradient distribution of the transformer longitudinal insulation electric field, so standard lightning impulse voltage was chosen as the experimental voltage form, and wavefront/tail time of the impulse voltage was 1.0/44µs.

![Figure 2. The point of space electric field measurement.](image)

Stainless steel flat electrodes were used in the model. In figure 2, the electrode length is 1m, the width is 80mm, and the thickness is 10mm. It is chamfered by 5mm. The distance between the electrodes is 5mm, the distance between each measuring point is 1mm, the distance between point P1 and ground electrode is 0.5mm, and the distance between point P5 and high-voltage electrode is 0.5mm. Five measurement points were measured to achieve the space electric field distribution in oil.
Figure 3. The measured value of applied voltage and light intensity.

Figure 4. Electric field strength in oil under 30kV lightning impulse voltage.

The entire wave process collected by the oscilloscope is shown in figure 3. According to formula (1)–(6), the actual electric field can be calculated. As shown in figure 4, under the lightning impulse voltage of 30kV, the measured field strength is consistent with the applied electric field.

3. Experimental results and analysis

3.1. Influence of applied voltage on electric field

As the applied voltage increases, the measured electric field strength begins to be lower than the applied field strength. As shown in figure 5 and figure 6, the difference between the maximum measured and applied field strength at 60kV is 2.64kV/mm, and at 90kV is 4.88kV/mm. This is mainly because there are tiny tips and burrs on the surface of the electrode. After applied voltage is increased, local field strength of the electrode surface reaches $10^8$V/m. The electrode injects electrons into the oil under the influence of the applied voltage[6], which weakens the electric field in the oil.

The wave front time of lightning impulse voltage is determined by the time of 30% and 90% of applied peak voltage. The half-peak time is determined by the time of 50% applied peak voltage, and the 100% applied voltage is peak applied voltage, as shown in figure 7. Therefore, the electric field distribution at these four moments was mainly discussed. The applied voltage is all 90kV.
3.2. Time and space distribution of electric field in oil

Figure 8 shows changes of the measured electric field in oil with time and space in the 90kV lightning impulse front time stage. When applied field strength is 0.36μs, the space electric field distribution is uneven. The difference of measured maximum and minimum value is 3.2kV/mm. Simultaneously, the applied field strength is 11.4kV/mm, the field strength at points P1 and P2 is lower than 11.4kV/mm, and at points P3, P4, and P5 is higher than it. This is because of space charge, which enhances the field strength of P3, P4, P5 points. As time increases, the space electric field distribution gradually becomes uniform. At 1.2μs, maximum difference of the space electric field decreases to 1.8kV/mm, the field strength difference is 0.44 times smaller than that at 0.36μs, but the electric field distribution in oil is still uneven. At this time, the applied field strength is 17.8kV/mm, and the measured field strength in the oil is still lower than it. This phenomenon may be because the influence of space charge injection, migration and accumulation on the electric field distribution has not yet reached a stable stage.

Figure 9 shows the distribution of the measured electric field in oil over time and space during the tail time of the lightning impulse wave. As figure 9 showed that the electric field in oil is uniformly distributed at the tail time of the lightning impulse. The applied field strength is 15.9kV/mm at 10μs. The measured maximum and minimum electric field difference is only 0.3kV/mm, and the space charge weakens the electric field in oil. As time increases, the average value of the measured field strength in oil is 6.8kV/mm at 50μs. At this time, the difference between the applied and measured field strength is 1.3kV/mm. As the voltage drops, the weakening effect of space charges on the electric field in oil also

Figure 7. Data time in lighting impulse voltage wave process.

Figure 8. The variation of measured electric field with time and space in oil within front time of the lightning impulse.

Figure 9. The variation of measured electric field with time and space in oil within tail time of the lightning impulse.
The applied field strength is 2.2kV/mm at 150µs, the space electric field distribution in oil is uniform, the actual field strength average value is 3.0kV/mm, the field strength in oil is 0.8kV/mm higher than the applied field strength, this phenomenon is caused by space charge.

4. Conclusion

In this research, the Kerr effect method was used to measure the space electric field distribution in transformer oil under lightning impulse voltage, and on this basis, the space electric field in oil under impulse voltage was analysed over time and space. The experiment results indicate that:

1) As the applied voltage increases, the measured field strength begins to be lower than the applied field strength, and the difference between the maximum measured and applied field strength increases. This is mainly because after the applied voltage increases, the metal electrode injects electrons into the oil under the influence of the applied voltage, which weakens the electric field in oil.

2) In the 90kV lightning impulse voltage front time stage, the space electric field distribution in oil gradually becomes uniform with the increase of time. The difference between the maximum and minimum measured space field strength in oil at 0.36µs is 3.2kV/mm, and at the peak of 1.2µs is reduced to 1.8kV/mm. This phenomenon may be because the influence of space charge injection, migration and accumulation on the electric field distribution has not yet reached a stable stage.

3) In the 90kV lightning impulse voltage tail time stage, the electric field in oil is distributed uniformly. The weakening effect of the space charge on the electric field in oil gradually weakens with the increase of time. The applied field strength is first higher than the measured field strength and then gradually decreases to lower than the measured field strength.

In order to benefit the design of the transformer insulation, the actual measurement of the electric field in transformer oil is necessary. This research was only carried out at room temperature, and the measurement of the space-time distribution of electric field in oil under impulse voltage at different temperatures needs further study.

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References

[1] Zahn, M., Takada, T., Voldman, S. (1983) Kerr electro optic field mapping measurements in water using parallel cylindrical electrodes. J. Appl. Phys., 54: 4749-4761.
[2] Kelly, E.F., Hebner, R.E. (1983) Electrooptic measurement of the electric field distribution in transformer oil. IEEE Trans. Power App. Syst., 102: 2092-2097.
[3] Imai, K., Kanematsu, A., Nawata, M. (1991) Kerr constant frequency dependence in liquid nitrogen. In: Proceedings of the 3rd International Conference on Properties and Applications of Dielectric Materials. Tokyo. pp. 280-283.
[4] Qi, B., Zhao, X.L., Zhang, S.Q. (2017) Measurement of the electric field strength in transformer oil under impulse voltage. IEEE Trans. Dielectr. Electr. Insul., 24: 1256-1262.
[5] Ustundag, A., Gung, T.J., Zahn, M. (1998) Kerr electro-optic theory and measurements of electric fields with magnitude and direction varying along the light path. IEEE Trans. Dielectr. Electr. Insul., 5: 421-442.
[6] Lopez, V.J.A., Jimenez, T.J.A., Cartujo, P. (1991) Analysis of the effects of constant-current Fowler-Nordheim-tunneling injection with charge trapping inside the potential barrier. J. Appl. Phys., 70: 3712-3720.