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Research on the Calibration System of Noncontact Electrostatic Voltmeter by Using the Finite Element Analysis

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***Abstract*—Noncontact measurement of electrostatic voltage is required to study the charges in HVDC transmission system. The calibration platform of noncontact electrostatic voltmeter is studied. The electric field near the measurement probe is calculated by FEM. Based on the calculation, the edge effect and applied voltage of the calibrating plate electrode are analyzed.**

Keywords*—*calibration; electrostatic voltmeter; finite element method; noncontact measurement

I. INTRODUCTION

With the development of HVDC (high voltage direct current) transmission technology, the DC electrical equipment are widely used. Measurement of electrostatic voltage on the objects insulated from the ground is required [1-4]. In GIS (Gas insulated switchgear), the charged particles generated by the high voltage will be induced by the DC electric field, and then accumulated on the insulators [5-8]. The accumulated charges will distort the electric field nearby. The flashover voltage of insulators in GIS will be reduced, and the safe operation of the equipment may be influenced [9, 10]. Under the HVDC transmission lines, the ions generated by the corona discharge will accumulate on the insulated dielectrics or the potential floating conductors. The electric field near the ground may exceed the limitation value, and the electrostatic discharge may happen [11-15].

The electrostatic voltages can be measured by contact or noncontact methods. With respect to the floating potential conductor, the noncontact methods have the advantages of stability. The charges on the floating potential conductor will not be leaked by the internal resistance of measurement device [16-18]. On the surface of dielectrics, the charges cannot move freely. The noncontact method is necessary to measure the electrostatic voltage on the dielectrics [19-23].

The electrostatic voltmeter should be calibrated precisely before being used. The probe of noncontact electrostatic voltmeter should keep an appropriate distance from the calibrating source [24-26]. If the distance is too large, the precision of measured results will be influenced. By contrast, if the distance is too small, the surface charge distribution on the measured test sample will be influenced by the probe.

The edge effect will influence the calibration results, and the influence degree of edge effect depends on the distance between the calibration source and the measurement probe. In the IEC standard and the Chinese standard GJB/J 5972-2007 and JJF 1517-2015, the impact of edge effect is verified by experimental method. In this paper, this problem is studied by electric field calculation. The calculation model is presented by analyzing the measurement principle. The minimum radius and the maximum voltage of high voltage plate electrode is given.

II. METHODOLOGY

The calibration platform is illustrated in Figure I. A metal plate electrode is energized by the high voltage DC source, and the radius of the plate is *r*. The measuring probe of electrostatic voltmeter is put at the center of the metal plate. The measuring probe and the metal plate electrode are supported by insulating brackets. The distance between the electrode and the probe is *d*. In this calibration system, the measured signal of electrostatic voltmeter is liner transformed to the voltage on the metal plate electrode.

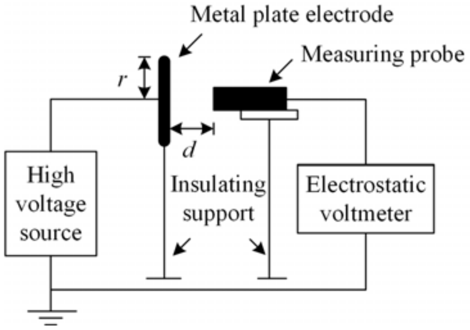


FIGURE I. THE CALIBRATION PLATFORM

The circuit model of the calibration system is shown in Figure II(A). When the probe is static, the distance is marked as d_0. The capacitance between the metal plate electrode and the vibrant plate in the probe is C_0, and the capacitance between the metal plate electrode and grounding outer surface of the probe is C'. The vibrating amplitude is Δd.

If the probe and the plate electrode are close enough, the structure can be regarded as a parallel plate capacitance, and C' can be neglected. The capacitance of the vibrating system C is

$$C = \frac{\varepsilon S}{d_0 + \Delta d \sin wt} = \frac{C_0}{1 + \eta \sin wt} \tag{1}$$

Where ε is the permittivity in the air, ω and t are the vibrating frequency and time, respectively, S is the area of vibrating plate, and

$$\eta = \frac{\Delta d}{d_0} \tag{2}$$

The charge Q that stored in C is defined by

$$Q = C\left(U_M - U_E\right) \tag{3}$$

Where U_M is the voltage on the metal plate electrode, U_E is the voltage on the vibrating plate. In (3), the value of U_E is determined by the following equation

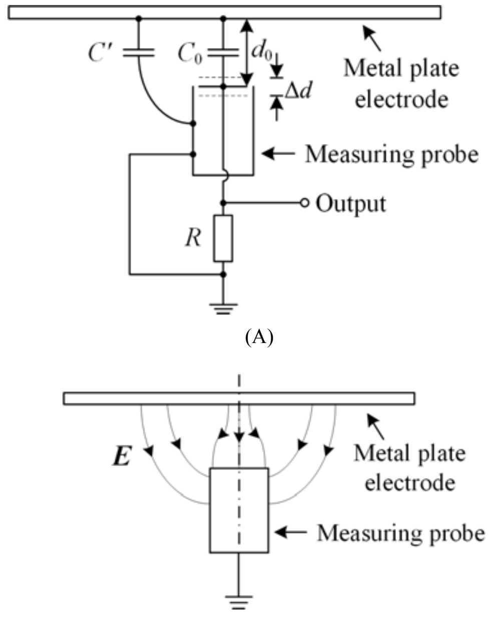
$$\begin{aligned} U_E &= R\frac{\mathrm{d}Q}{\mathrm{d}t} = R\frac{\mathrm{d}C}{\mathrm{d}t}\left(U_M - U_E\right) + RC\frac{\mathrm{d}\left(U_M - U_E\right)}{\mathrm{d}t} \\ &= R\frac{-\eta\omega C_0 \cos\omega t}{\left(1+\eta\sin\omega t\right)^2}\left(U_M - U_E\right) + RC\left(\frac{\mathrm{d}U_M}{\mathrm{d}t} - \frac{\mathrm{d}U_E}{\mathrm{d}t}\right) \end{aligned} \tag{4}$$

Where R is the resistance between the vibrating plate and the ground.

In (4), the value of U_M is determined by the voltage source, $\frac{\mathrm{d}U_M}{\mathrm{d}t} \approx 0$. The vibrating plate is very close to the metal plate electrode, $\eta = \frac{\Delta d}{d_0} = 1$, and $RC\frac{\mathrm{d}U_E}{\mathrm{d}t} \approx R\omega C_0 U_E = U_E$. Therefore, (4) can be simplified as

$$U_E = -U_M \eta R w C_0 \cos wt \tag{5}$$

It can be seen in (5) that U_E is proportional to U_M. When d is increased, the circuit model in (1) need to be modified, and the capacitance C' should be considered as well, so (5) cannot be used directly. However, the proportional relationship is still exist. The measured value on the "Output" port is produced by the electric field induction on the vibrating plate. Considering $U_E \approx 0$, and $\Delta d \approx 0$, the electromagnetic field model is provided in Figure II(B).



(A)

(B)

FIGURE II. THE PROBE OF A NON-CONTACT ELECTROSTATIC VOLTMETER NEAR A CONDUCTIVE PLATE: (A) CIRCUIT MODEL, (B) ELECTROMAGNETIC FIELD MODEL.

The fundamental equation in electrostatic field is the following Laplace equation

$$\nabla^2 \varphi = 0 \tag{6}$$

Where φ is the potential function in the space. The boundary conditions are

$$\begin{cases} \varphi\big|_{\Gamma_M} = U_M \\ \varphi\big|_{\Gamma_E} = 0 \\ \varphi\big|_{\Gamma_\infty} = 0 \end{cases} \tag{7}$$

Where Γ_M is the boundary of metal plate electrode, Γ_E is the boundary of the probe of electrostatic voltmeter, Γ_∞ represents the boundary of infinity.

In FEM (Finite Element Method), the equivalent variable problem of Laplace equation (6) is

$$\begin{aligned} J[\varphi] &= \iint \frac{\varepsilon}{2}\left[\left(\frac{\partial \phi}{\partial x}\right)^2 + \left(\frac{\partial \phi}{\partial y}\right)^2\right] dxdy \\ &= \frac{1}{2}[\varphi]^T[K][\varphi] = \min \end{aligned} \tag{8}$$

Where $J[\varphi]$ is the second-order energy functional, $[K]$ is the coefficient matrix of the total electric field energy. According to the extreme value theory of function, there is

$$\frac{\partial J}{\partial \varphi} = 0 \tag{9}$$

And the discrete form is

$$[K][\varphi] = [f] \tag{10}$$

Where f is the energy source in the electric field. In the FEM analysis, the space is meshed by second order triangular element, as shown in Figure III(A).

The charge on the vibrating plate is

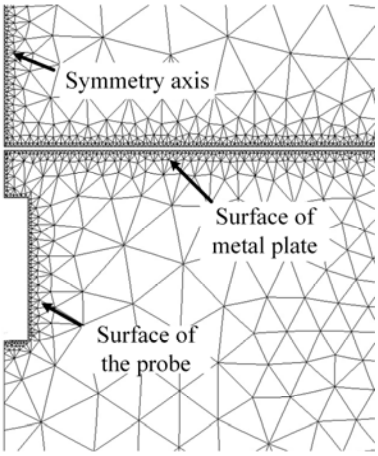
$$Q = \int_{s} \varepsilon E dS = \varepsilon E \cdot S \propto E \tag{11}$$

Therefore, the variation of output signal can be determined by calculating the electric field on the vibrating plate.

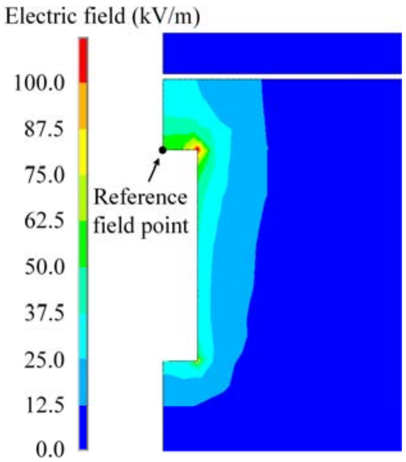
III. VERIFICATION

The calculation area in Figure II(B) can be simplified as a 2D symmetrical model. The length of the electrostatic voltmeter probe is 7.5 cm, and the radius is 2.5 cm. In the following calculation, r=50 cm, d=2.5cm.

The calculation result is shown in Figure III(B). The electric field near the edge of probe is larger than other areas. The electric field distribution shows that the structure cannot be simplified to be a parallel plate capacitor. At the sharp edges of probe, the electric field is significantly distorted. In the practice, these sharp edges can be designed to be smooth edges. Therefore, the center of the probe is chosen to be the reference field point, the electric field on this point is studied.



(A)



(B)

FIGURE III. FEM ANALYSIS OF THE PROBE, (A) MESHES. (B) CALCULATED ELECTRIC FIELD DISTRIBUTION.

IV. DISCUSSION

The influence of the radius of metal plate electrode r on the electric field on the reference point is indicated in Figure IV. With the increasing of r, the electric field on the probe is increased at first, and then reaches a certain value. When the probe is far away from the metal plate electrode, the electric field strength is decreased.

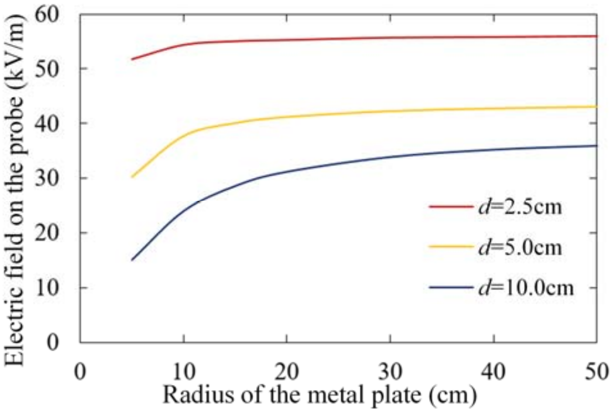


FIGURE IV. INFLUENCE OF BOUNDARY EFFECT ON THE ELECTRIC FIELD

The gradient of the electric fields E' in Figure IV is defined as

$$E' = \frac{\mathrm{d}E}{\mathrm{d}r} \tag{12}$$

E' reflects the edge effect of the metal plate electrode. The calculation results are shown in Figure V. The values of E' are reduced to 0 with the increase of r. It means the edge effect of metal plate electrode will be weaken by increasing the length of r. The farther the distance, the more serious the edge effect.

The reference value of E'=0.05 is also marked out in Figure V. When d=2.5 cm, 5 cm and 10.0 cm, the radius of metal plate electrode should not less than 15cm, 35cm and 50cm, respectively.

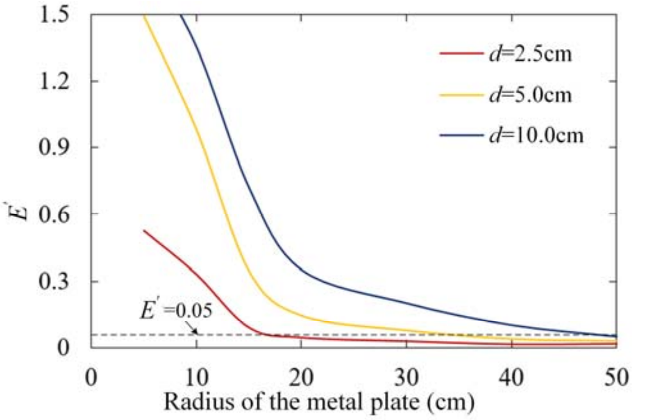


FIGURE V. GRADIENT OF THE RADIUS OF PLATE WITH ELECTRIC FIELD

Except for the edge effect, the voltage on the metal plate electrode also should be limited. If the electric field on the surface of probe exceed the threshold value, corona discharge or spark discharge will happen, and the measurement device might be destroyed. In extremely uneven electric field, 3kV/cm is an empirical limitation value of discharge. The electric field at the reference field point is proportional to the voltage on the metal plate electrode, as shown in Figure VI. In order to confine the electric field strength on the reference field point under 3kV/cm, the voltage on the metal plate should less than 5.5kV, 7kV and 8.5kV when d=2.5cm, 5.0cm and 10.0cm, respectively.

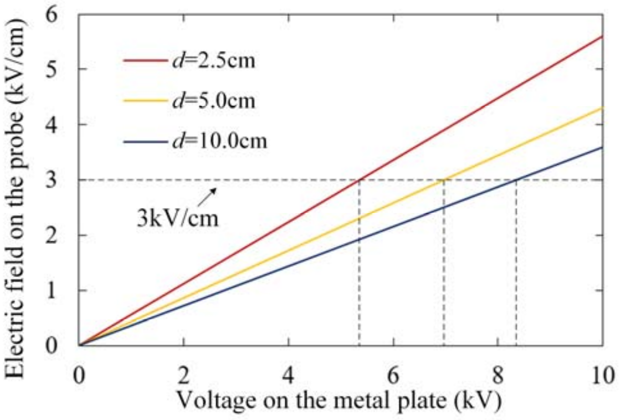


FIGURE VI. INFLUENCE OF VOLTAGE ON THE PROBE SURFACE ELECTRIC FIELD

V. CONCLUSION

The calibration system of noncontact electrostatic voltmeter is studied in this paper. Based on the analysis of measurement principles, the electromagnetic field model is presented. Compared with the circuit model, the electromagnetic field model is more suitable for studying the size of metal plate electrode and the applied voltage in the calibration system.

By using FEM analysis, the electric fields near the calibrating electrode and the measurement probe are calculated. When the distances are 2.5cm, 5.0cm and 10.0cm, respectively, the radius of plate should not less than 15cm, 35cm and 50cm, respectively, and the voltage on the metal plate electrode should not exceed 5.5kV, 7kV and 8.5kV, respectively.

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