Impact Factors in Calibration and Application of Field Mill for Measurement of DC Electric Field with Space Charges

Bo Zhang, *Member, IEEE*, Wenzhuo Wang, and Jinliang He, *Fellow, IEEE*

***Abstract*—The DC electric field is sometimes accompanied by space charges caused by the partial discharge in the air, which impacts DC electric field measurements. This paper describes the impact factors in the calibration and application of the field mill for measuring the DC electric field with space charges. First, the influence of the space charges on calibration results is evaluated and discussed. Then, both the impact of the height of the meter probe above the ground and the touch resistance between the ground and the meter on the measurement results are investigated. Correct calibration and application methods are presented. The results are expected to be of use to engineers for conducting accurate measurements of the DC electric field with space charges.**

***Index Terms*—Calibration, electric field, field meter, measurement, space charge.**

I. INTRODUCTION

DIRECT current (DC) electric fields exist in natural and artificial environments, such as thunderstorms or near high-voltage DC (HVDC) transmission lines [1]–[3]. Measuring the electric field is an ongoing and important research area [4]–[9]. Unlike in the case of a normal electrostatic field, the total electric field, either in a thunderstorm or near an HVDC transmission line, contains the contribution of space charges from partial discharge in the air [10]. Thus, when measuring DC electric fields, the effect of the space charges should be taken into account [11]–[14].

There are two types of DC electric-field meters that are widely used today: field mills and vibrating plate electric-field meters [11], [15]–[18]. Before measurement, the electric-field meters need to be calibrated. IEEE Std. 1227-1990 (R2010) recommends two kinds of parallel plate systems that could produce known electric fields separately, with and without space charges [11]. However, the IEEE Standard only specifies the parallel plate system that produces the field without space charges as well as its corresponding calibration method. For the apparatus that produces the field with space charges, the IEEE Standard only presents a schematic view of the developed apparatus as seen in [12], without discussing the factors that would be considered in the calibration. This may be because the apparatus that produces the field with space charges is more complicated in construction and operation than the space charge-free system [11], [12]. In addition, for ion-current densities no more than 0.1×10^{-6} A/m^2 and electric fields no less than 10 kV/m (which are the normal values near HVDC transmission lines), the measurement error due to space charges may be negligible [11]. In such situations, the simpler space charge-free system may be adequate for calibration purposes.

Although the calibration in space charge-free fields may be adequate for measuring electric fields near HVDC transmission lines, factors related to measurement results both in calibration and application need investigation. First, there is a need to specify when the gap between the calibration results with and without space charges cannot be neglected. Second, in field test, the electric-field meters are often placed directly on the ground, which will change the electric field to be measured. Because the distribution of the space charges and movement has also changed, the variations in the electric field may also be different from that of the space charge-free field. Thus, it is necessary to specify whether the calibration in the space charge-free field is still viable. Finally, the influence of the touch resistance between the ground and the meter, which may be very large in the field test, also needs to be studied since the resistance may block the discharge of the charges absorbed by the meter's shell.

This paper describes the construction of an apparatus that produces a field with space charges based on an idea presented in [12]. The field mill is used as an example to understand the influence of the space charges on the calibration results. Several other factors are also investigated, including the meter's height above the ground, and the touch resistance between the ground and the meter on the measurement results. The results are expected to be useful for engineers for accurate measurement of the DC electric field with space charges. Although different field mills have different calibration coefficients, the calibration method and conclusions will serve as good references.

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II. Field Mill and Calibration Apparatus

As shown in Fig. 1, the field mill is comprised of two identical metal discs with a number of fan-shaped holes. The two discs are placed coaxially with a little gap and are insulated from each other [9]–[11]. The lower disc called stator is fixed and grounded through a resistor, while the upper disc called the rotor is able to rotate with the shaft and is grounded directly. The total area of the stator exposed to the DC electric field varies with time. Since the induced charge Q on the stator is proportional to the exposed area and the DC electric field, an AC current flows through the resistor [9]–[11]:

$$i_{\mathrm{e}}(t) = \varepsilon_0 E n^2 A_0 \omega \sin n\omega t, \tag{1}$$

where ε_0 is the dielectric constant of the air, E is the DC field strength, n is the number of the fan-shaped holes on each disc, A_0 is the area of each hole, and ω is the rotating speed of the rotor. At the same time, the space charges are in motion due to the electric field, which forms a current in the air that reaches the stator through the fan-shaped holes on the rotor. The corresponding current flowing into the stator is thus [9]–[11]:

$$i_{\mathrm{j}}(t) = nA_0 J(1 - \cos n\omega t), \tag{2}$$

where J is the charge-current density, which is always perpendicular to the metal surface of the field mill as expressed in [10].

$$J = \rho K E, \tag{3}$$

where ρ and K are the density and the average mobility of the space charges, respectively. Since $i_{\mathrm{e}}(t)$ is proportional to ω while $i_{\mathrm{j}}(t)$ is not, $i_{\mathrm{j}}(t) \ll i_{\mathrm{e}}(t)$ if ω is large enough. Then, according to (1), the DC electric field can be obtained from the measured current through the resistor.

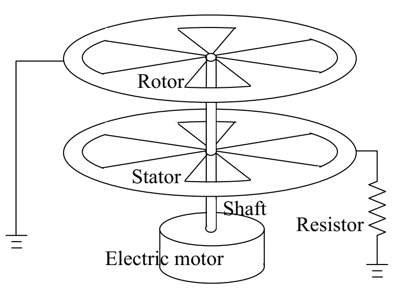

Fig. 1. Structure of the field mill [9].

The apparatus to generate a DC electric field with space charges is described in [11], [12] and shown in Fig. 2. Some charges generated by corona wires move downward to the first screen. Charges not collected on the first screen continue downward to the second screen, which is the top "plate" of a parallel-plate system. The charges that pass through the top plate travel a distance d to the bottom plate and form the current density J [11], [12]. The advantage of the apparatus is that it separates the region for measurement from that for corona generation, which avoids the interference on the measurement and makes the electric field and the ion current density controllable and computable. The expression for the electric field $E(z)$ between the parallel plates can be deduced from Poisson's equation in one dimension [11], [12]:

$$E(z) = \left[E_{\mathrm{T}}^2 + \frac{2J(d-z)}{K\varepsilon_0}\right]^{1/2} \tag{4}$$

where E_{T} is the electric field of the top plate. The relationship between E_{T} and the potential of the top plate V_{T} is derived by the integration of (4), as follows:

$$V_{\mathrm{T}} = \frac{K\varepsilon_0}{3J}\left[\left(E_{\mathrm{T}}^2 + \frac{2Jd}{K\varepsilon_0}\right)^{3/2} - E_{\mathrm{T}}^3\right]. \tag{5}$$

Since V_{T} and J can be measured [11], [19], E_{T} can be obtained from (5). Then, the electric field between the parallel plates can be determined from (4).

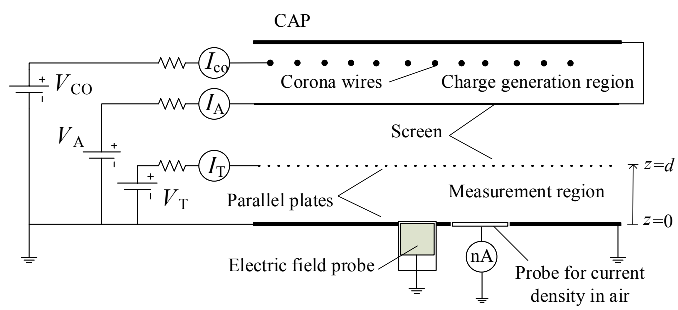

Fig. 2. Apparatus generating DC electric field with space charges [11], [12].

As shown in Fig. 3, a generator was constructed in this paper according to Fig. 2, which consisted of circular plates with a radius of 1 m. The measurement showed that within a radius of 30 cm the spread in J values at the bottom layer is less than ±3% when d = 0.25 m. As shown in Fig. 4, the field mill used in this work has a diameter 0.08 m with 18 holes on each disc; the rotating speed of its rotor is 90π rad/s.

Fig. 3. The apparatus constructed in this paper.

Fig. 4. A field mill.

III. Influence of Space Charges on Calibration

In this section, the influence of space charges on calibration is investigated through a comparison between the calibration coefficient in space charge-free apparatus and the apparatus with space charges. The calibration coefficient is the ratio of the real value of the electric field to the reading of the field mill.

A. Calibration in Space Charge-Free Field

Space charge-free field is the most widely used method for calibrating field meters. Take V_{co} and V_{A} away, and a space charge-free field can also be generated in the measurement region just by V_{T} as shown in Fig. 2, which also satisfies the requirements of the IEEE Standard [11]. By adjusting V_{T}, different space charge-free fields can be obtained since $E = V_{\text{T}}/d$. Fig. 5 shows the calibration coefficient in different DC space charge-free fields. In the measurement interval, the largest difference among the calibration coefficients is less than 1.5%, which could also result from a measurement error. Thus, it can be seen that the calibration coefficient remains at 2.45 as a constant within the range of 10 to 50 kV/m for the field mill used in this paper.

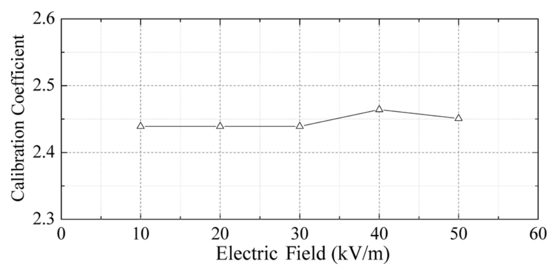

Fig. 5. Calibration coefficient in space charge-free field.

B. Calibration in Electric Field with Space Charges

Put V_{co}, V_{A}, and V_{T} in Fig. 2 into use, and an electric field with space charges can be generated. First, V_{co} should be large enough to make corona. Then, V_{A} is adjusted to change the space charges passing through the first screen. V_{T} is also adjusted to change the space charges passing through the second screen and the electric field under it. V_{A} and V_{T} are adjusted together to make both the space charges and the total electric field controllable, which can be calculated by (4) and (5). Since only positive charge was investigated, the average mobility of the charge K was 1.4×10^{-4} m^2/V·s [20]. The distance between the two parallel plates d was 0.165 m.

Fig. 6 shows the calibration coefficient at different charge current densities when the total electric field at the bottom plate E_0 remains at 30 kV/m. It can be seen that the calibration coefficient increases gradually with the charge-current density, although the measured electric field remains constant. At other electric fields, the same variation can be obtained as shown in Fig. 7, where the relative calibration coefficient is defined as the ratio of the calibration coefficient with space charges to that without space charges. The stronger the electric field, the smaller will be the variation.

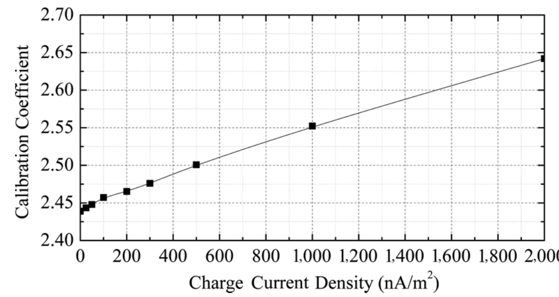

Fig. 6. Variation of calibration coefficient in 30 kV/m electric field.

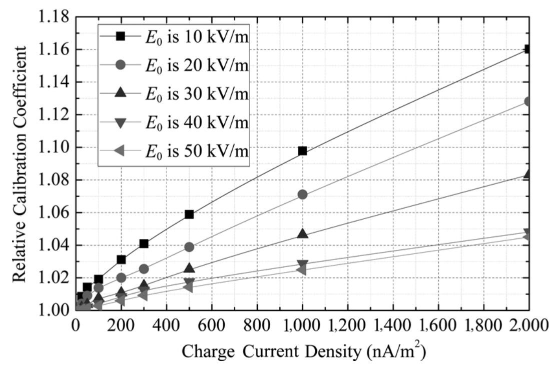

Fig. 7. Relative calibration coefficients at different electric fields and charge-current densities.

The calibration result verifies the conclusion in the IEEE Standard [11]. For charge-current densities no more than 0.1×10^{-6} A/m^2 and electric fields no less than 10 kV/m, calibration in the space charge-free field is acceptable, which results in an error of no more than 10%. Since the electric field and the ion-current density near HVDC transmission lines should be no larger than 30 kV/m and 100 nA/m^2, respectively, the measurement error introduced by calibration in the space charge-free field is no more than 2%, which is negligible. However, if the electric field is weaker while the charge-current density is larger, then the error introduced by calibration in the space charge-free field should be taken into consideration. In this situation, the nonlinear interpolation method can be used to find a suitable calibration coefficient, as illustrated in Fig. 7:

1) First, the charge current density is measured.
2) Next, an initial calibration coefficient is selected.
3) E_0 is calculated based on the selected calibration coefficient and the reading of the meter.
4) At the same time, another E_0 can be obtained from Fig. 7 according to the measured charge-current density, and the selected calibration coefficient with the help of the interpolation method.
5) If the two E_0s are quite different from each other, a new calibration coefficient is selected.

Steps 3) to 5) are repeated until the two E_0s differ from each other by amounts smaller than a specified tolerance.

C. Discussion of Calibration Results

Theoretically, $i_{\text{e}}(t)$ in (1) is determined by the electric field while $i_{\text{j}}(t)$ in (2) is determined by charge current density.

Thus, if $i_\mathrm{e}(t) \ll i_\mathrm{j}(t)$, the influence of the space charges on the measurement result of the field mill can be neglected. When comparing (1) and (2), it can be seen that the ratio of the coefficients of the two equations is:

$$s = \frac{nA_0 J}{\varepsilon_0 E n^2 A_0 \omega} = \frac{J}{\varepsilon_0 E n \omega}. \tag{6}$$

Since $\varepsilon_0 = 8.85\times10^{-12}$ F/m, $n = 18$, and $\omega = 90\pi$ rad/s for the field mill used in this paper, and E is from 10 kV/m to 50 kV/m and J is from 0 A/m^2 to 2×10^{-6} A/m^2 in the above test, according to (6), s is between 0 to 4.44×10^{-3}, which shows that $i_\mathrm{j}(t) \ll i_\mathrm{e}(t)$ in all of the above tests, and thus the influence of the space charges is negligible. However, the test results in Fig. 7 show that the influence is not particularly small. When E is smaller than 10 kV/m and J is greater than 1×10^{-6} A/m^2, the difference between the calibration coefficient in the space charge-free field and in electric field with space charges is greater than 10%. Since theoretical analysis cannot explain the calibration result, there should be other reasons.

The main factor that makes the calibration error large for the field with space charges may be the wind from the rotor of the field mill. When the field mill disc rotates, there is slight wind movement (the vibrating plate electric-field meters can also generate wind). The wind can blow away the space charges above the meter, which makes the real electric field near the meter smaller than the theoretically calculated one. The charge-current density is also smaller than that measured nearby. The calibration coefficient in the electric field with space charge density is, therefore, greater than the theoretical one, and greater than that in the space charge-free field where the wind has no effect.

The extent of the wind's influence is determined by two factors. One is wind strength, and the other is charge density in the air. In order to reduce the influence of the former factor, the disc of the meter should be flat, and the shaft should not vibrate. For the latter factor, it can be seen from (3) that the charge-current density is proportional to the charge density. Thus, a large charge-current density means a large charge density. The total electric field on the bottom plate E_0 consists of two parts. One is the field due to the voltage source V_T. The other is the field due to the space charges. Thus, small E_0 with large space charge density means the contribution from the space charges is great. At the same time, the larger the space charge density, the greater will be the effect from the wind, and thus large space charge density means the same wind exacts more interference on the electric field. Thus, for the same charge-current density, when E_0 is small, the contribution from the space charges is greater, and the effect of space charges on the calibration coefficient is also great. For the same E_0, when J is great, the contribution from the space charges will be equally great, and the effect of space charges on the calibration coefficient is also great. For the calibrated field mill, wind velocity is a constant (the rotation speed of the disc is a constant). Thus, the relative calibration coefficient will increase with increase in charge-current density, as shown in Fig. 6 and Fig. 7.

IV. Influence of Height on Field Mill

In the on-site test of the electric field of HVDC transmission lines, the meters are often placed directly on the ground for convenience, which is not the same as in calibration where the surface of the meter is at the same level as the ground. The meter can change the electric field nearby, and the electric field to be measured on the surface of the meter is different from that on the ground surface. Although the above situation can also be considered at the calibration stage just by placing the calibrated meter on the bottom plate for the space charge-free field, the distribution of the space charges and their movement for the field with space charges, also change. As a result, the variation of the electric field may be different from that of the space charge-free field. Thus, the calibration result in the space charge-free system may not be used any more.

This section explains how the field meter was calibrated when placed directly on the ground using the apparatus in Fig. 3. The measurement results based on three calibration methods were compared to identify those that were acceptable.

Method 1: Uses the calibration coefficient that is also obtained in the space charge-free field, but the meter is placed directly on the ground plate.

Method 2: Uses the calibration coefficient 2.45 obtained in the space charge-free field when the surface of the meter is on the same level as the ground plate, as shown in Fig. 5.

Method 3: Uses the calibration coefficient obtained in the field with space charges when the surface of the meter is on the same level as the ground plate.

Method 3 is seen as offering the most accurate results since it is based on a real situation set up, and all factors have been considered. However, this method presents difficulties in operations while the other two have fewer challenges.

In the ranges of the electric field and the ion-current density near HVDC transmission lines, because the calibration result in the space-charge-free field is almost the same as that in the electric field with space charge if the meter is on the same level with the ground plate, the calibration result in the electric field with space charge is omitted. Fig. 8 shows the measurement results of a field meter with a radius of 4 cm and a height of 2 cm when the distance of the parallel plates $d = 0.265$ m.

In Fig. 8, different electric fields are generated by adjusting V_T. It can be seen that for all the electric fields, Method 1 can achieve almost the same result as Method 3, while the result from Method 2 is much greater than others, which means that if the meter is placed directly on the ground in the on-site test, the corresponding calibration should also be performed by placing the calibrated meter on the bottom plate. The calibration in space charge-free field, thus, is adequate for accurate measurements even for the field with space charges. In this set up, since the field meter makes the electric field on the surface greater than that when the meter does not exist, the corresponding calibration coefficient should be smaller than when the surface of the meter is on the same level with the ground plate. Thus, if the calibration coefficient in Fig. 5 is used, the measured result will be greater than the real one.

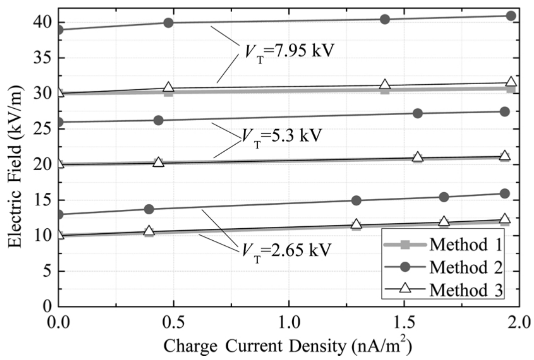

Fig. 8. Measurement results when the meter is placed above the ground plate.

Fig. 9 shows the measurement results by field meters with different heights, which is realized by changing the distance of the top surface of a probe to the electrode plate. It can be seen that regardless of the height, if the calibration occurs by placing the corresponding meter on the bottom plate, the result is always the same. If the calibration coefficient in Fig. 5 is used, the higher the field meter is, the greater the measurement error.

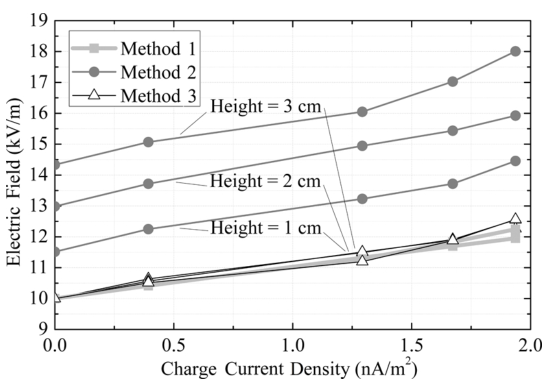

Fig. 9. Influence of the height of the field meter's top surface.

Thus, in the situation where the field meter is put above the ground surface, the calibration coefficient in the space charge-free system can still be used when the calibration is also done when the corresponding meter is placed on the bottom plate. Fig. 10 shows the variation of the calibration coefficient with the height of the field meter's top surface. The higher the field meter is, the smaller the calibration coefficient.

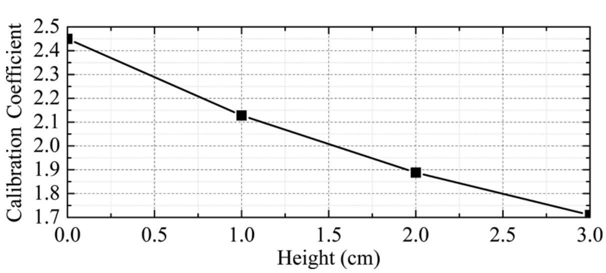

Fig. 10. Calibration coefficients of field meters with different height.

V. Influence of Touch Resistance to Ground

Because the field mill rotor is insulated from the stator, it should be grounded to discharge the absorbed charges, or else the charges may change the measured electric field. Thus, in the on-site test, another factor that may affect the measurement result is the uncontrollable touch resistance between the field meter and the ground since the resistance may block the discharge of the charges absorbed by the meter. In order to investigate this factor, a resistor was added between the shell of the meter and the ground in the calibration. Fig. 11 shows the calibration coefficients in the electric fields with different space charges.

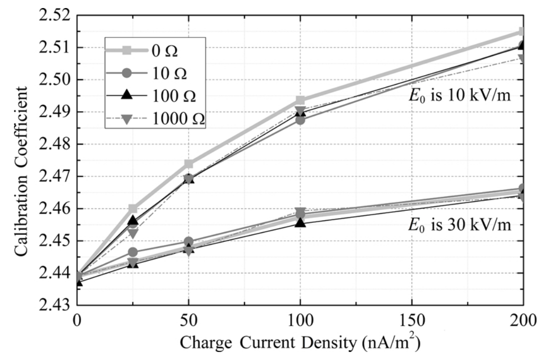

Fig. 11. Influence of touch resistance on measurement result.

It can be seen that the measurement results are almost the same for different touch resistances, which means that the touch resistance has almost no effect on the measurement result. This may be because the equivalent resistance of the air in the field with space charges is still much larger than the touch resistance. This result makes the meter easy to be used in the on-site test since there is no special requirement for both touch resistance and grounding resistance. However, grounding for the field meter is necessary. Results from our experiments show that the reading of the field mill was not stable due to the accumulated space charges in the field meter if the meter was insulated from the ground. In fact, the above resistances will reduce the discharge speed of the accumulated charges on the probe. If they are large, it will take a long time to discharge the accumulated charges until dynamic equilibrium is reached.

VI. Conclusion

In this paper, first, the influence of the space charges on calibration results for DC electric field measurement was evaluated and discussed. Then, both the influence of the height of the meter above the ground and that of the touch resistance between the ground and the meter on measurement result was investigated. Following conclusions can be drawn:

1) For charge-current densities no more than 0.1×10^{-6} A/m^2 and electric fields no less than 10 kV/m, calibration in space charge-free field is acceptable, which results in an error no more than 10%. But if the electric field is weak, while the charge current density is large, the error introduced by calibration in the space charge-free field would be greater. The wind from the rotor of the field

mill could amplify the influence of the space charges. Thus, the disc of the meter should be kept flat, and the shaft should not vibrate.

2) For the situation where the surface of the field meter is higher than the ground surface in the on-site test, the calibration coefficient in the space charge-free system can still be used when the calibration is also done by placing the corresponding meter on the bottom plate having the same height. The higher the field meter is, the smaller the calibration coefficient.
3) In the on-site test, there is no special requirement for both touch resistance and grounding resistance of the field meter shell. However, grounding for the shell of the field meter is necessary to discharge the accumulated space charges in the field meter.

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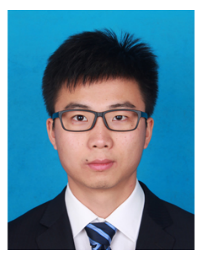

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