Design and Analysis of Power Frequency Electric Field Sensing Unit with Reduce Edge Effect

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Abstract. The performance of the electric field sensing unit determines the sensitivity, linearity and range of the electric field sensor. In this paper, a kind of alternating electric field sensing unit based on parallel capacitance was been introduced. And it analyzed the measurement principle of the parallel capacitive sensing unit. The structure parameters of the electric field sensing unit with equipotential ring were been designed by simulation, which reduced the influence of edge effect on the performance of the sensing unit. According to the measurement standard of power frequency electric field, the designed sensing units were tested under uniform electric field. And the influence of the sampling capacitances on the static characteristics of the sensing unit was been analyzed. The sensing unit with the best performance had a linearity of 1.6025% and a sensitivity of 248 mV/(kV/m). Its sensing unit had the characteristics of small volume, low production cost and it was easy to integrate and have mass production.

1. Introduction
In the power system, whether it is the detection of the operating state of the equipment of the power system or the provision of the near-electricity warning for the workers in the electric power operation, the measurement of the electric field is indispensable. At present, the measurement methods of the power frequency electric field are mainly divided into two categories: optical electric field measurement and electric principle measurement method [1-11]. The optical electric field sensor has the advantages of fast response and high safety [2,3], but the crystal material required for the sensing unit is special. The sensor of electrical principle measures the electric field of space according to the induced current or induced voltage between the two plates according to the characteristics of the induced charge generated by the metal plate in the electric field. The measuring unit has a spherical shape, a parallel capacitance type, a box type, an antenna type, a cylindrical type, and so on [4-8]. Due to the complicated processing technology of the spherical electric field sensing unit, the processing is difficult. In practice, the electric field sensing units such as polygons and parallel plates are used more easily because of the simple fabrication. According to the literature [9-11], the measurement error of the sensing unit of the parallel capacitance structure and the spherical structure is between 1% and 2%. Therefore, the author designed and tested a power frequency electric field sensing unit that reduces the edge effect and with high linearity of the plate capacitance.

2. Sensor unit measurement principle
It is known from Gauss's theorem that there is an induced charge on the metal plate in the electric field $E$, and the in-plane density of the induced charge is $\sigma$, $\varepsilon$ is the dielectric constant of the medium.
between the plates. The change in the measured electric field strength changes the amount of induced charge, which it can be expressed as:

\[ Q(t) = \int \sigma ds = \varepsilon E(t) S \]  

(1)

In equation (1), \( Q(t) \) is the amount of induced charge of the plate. \( E(t) \) is the measured electric field intensity. \( S \) is the effective area of the sensing plate [9-11].

The structural principle of the sensing unit is shown in Figure 1. The upper and lower plates are respectively connected to the two ends of the sampling capacitance \( C_s \), and the voltage signal \( U(t) \) generated by the induced charge of the plate on the sampling capacitance \( C_s \) is used as an output signal. Its relationship shows:

\[ U(t) = \frac{kQ(t)}{C_x + C_s} \]  

(2)

\( C_x \) is the inherent capacitance of the sensing unit, \( k \) is the correction factor, and its value is related to the structure of the sensing unit. Substituting equation (1) into equation (2) is:

\[ U(t) = \frac{keE(t)S}{C_x + C_s} \]  

(3)

The electric field strength of the measurement position can be obtained by measuring the voltage \( U(t) \) of the sampling capacitance \( C_s \) [12-15]. Equation (3) establishes the relationship between the output voltage of the sensing unit and the detected electric field strength. The information of the electric field strength can be obtained by processing and calculating the output voltage signal of the sensing unit.

3. Sensor unit structure and parameter design

The design of the electric field sensing unit structure is shown in Figure 2, which is composed of an upper plate, a lower plate and an equipotential ring. Due to the edge capacitance between the parallel plate capacitors, it is difficult to ensure the stability of the capacitor edge charge accumulation under the interference of the external electric field. The capacitance cannot be kept stable, which will bring errors to the measurement of the sensor, making the output of the sensor unstable, the sensitivity is lowered, and the output characteristic nonlinearity. Therefore, in order to reduce the influence of the edge effect when designing the electric field sensing unit, the structure of the equipotential ring is adopted to eliminate the edge effect between the two plates. This structure enables the electric field lines at the edge of the upper plate to be straight. The electric fields of the upper and lower plates are substantially uniform. The divergent fringing electric field occurs on the periphery of the equipotential ring. Therefore, the electric field between the two electrodes of the sensing unit is not affected, so as to ensure the accuracy of the sensor measurement.
The electric field sensing unit is fabricated by using a printed circuit board, and a pair of round copper disks are used as parallel plates, and the intermediate insulating material is epoxy resin. Such a simple manufacturing process not only has low cost but also can ensure good consistency and stability of each unit. According to the power frequency electric field measurement standard (GBT12720-91), the influence of the structural parameters of the electric field induction unit on the electric field strength is analyzed by COMSOL simulation software. Simulating the radius \( r \) and spacing \( d \) of the induction plate of the electric field sensing unit in the power frequency electric field \( E \). Obtaining the electric field strength \( E'_{\text{max}} \) on the induction plate compared with the original electric field strength \( E \). The degree of influence of the structural parameters on the original electric field strength is characterized by the distortion coefficient \( \gamma = (E'_{\text{max}} - E) / E \). The simulation results are shown in Table 1 and Table 2.

As shown in Figure 3, the equipotential ring width \( k \) of the sensing unit with different radii is determined by the isoline of electric field strength \( E' = 0.06E + E \) on the sensing plate. This equipotential ring can rule out the effects of a 94% distorted electric field. The widths of the equipotential rings of the sensing units with different radii are obtained by simulation, and the results are shown in Table 3. The relationship is fitted by MATLAB:

\[
k = 8.35r^{-0.3584}
\]

In Table 1, the electric field distortion coefficient of the sensing unit at different radii changes little. It shows that the change of the area of the induction plate has little influence on the degree of distortion of the induced electric field strength. For portability, the sensing unit selects a smaller radius. As can be seen from Table 2, as the pitch of the sensing plates increases, the electric field distortion coefficient of the sensing unit also increases. The change in the distance of the sensing plates directly affects the degree of distortion of the induced electric field strength. Therefore, when designing the sensing plate spacing of the sensing unit, try to choose a smaller plate spacing. At the time of production, the 1.6mm thick PCB sensing unit is fabricated according to the data obtained from the simulation in Table 3 and the factory process level. The physical object is shown in Figure 4.

| Table 1. Effect of Induction Plate Radius \( r \) on Distortion Coefficient \( \gamma \) |
|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Plate Radius \( r \) (mm) | 8           | 14          | 20          | 26          | 32          | 38          | 44          |
| Distortion Coefficient \( \gamma \) | 0.875       | 0.901       | 0.922       | 0.854       | 0.816       | 0.897       | 0.917       |

| Table 2. Effect of Induction Plate Spacing \( d \) on Deviation Coefficient \( \gamma \) |
|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Plate Spacing \( d \) (mm) | 1           | 1.6         | 2.2         | 2.8         | 3.4         | 4           |
| Distortion Coefficient \( \gamma \) | 0.682       | 0.959       | 1.183       | 1.246       | 1.286       | 1.434       |

| Table 3. Relationship between the radius \( r \) of the induction plate and the width \( k \) of the equipotential ring |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Serial number | 1           | 2           | 3           | 4           | 5           | 6           | 7           |
| Plate Radius \( r \) (mm) | 8           | 10          | 12          | 14          | 16          | 18          | 20          |
| Width \( k \) (mm) | 3.9         | 3.8         | 3.4         | 3.2         | 3.05        | 2.95        | 2.9         |
4. Test of sensor unit in power frequency electric field

4.1 Influence of the inherent capacitance of the sensing unit

According to the (GBT12720-91) power frequency electric field measurement standard, build a power frequency electric field test platform. The test platform consists of three parts: voltage regulator, high-voltage experimental transformer and parallel plate device. The experimental platform is shown in Figure 5. A single-phase uniform power frequency electric field is generated between the upper layer and the lower layer of the parallel plate device, and the sensing unit without the sampling capacitance is placed at the center of the parallel plate device. Reading the peak-to-peak value of the output signal of the sensing unit through an oscilloscope. Adjust the electric field strength through a voltage regulator and record the output voltage value of the transformer. Reading the output value of the sensing unit after the voltage regulation is completed. Complete testing for all sensing units. The tentative data and fitting results of each unit are shown in Figure 5, and the test results are analyzed as shown in Table 4.

It can be seen from Figure 6 that the measured values of the sensing units have a good linear relationship. After the field strength exceeds 200 kV/m, the sensing units have not reached saturation state. And the optimal linearity of the sensing unit No. 5 It reaches 1.6025% with a large calibration coefficient. As we can know from Table 4 that as the sensing area of the sensing unit increases, the calibration coefficient of the sensing unit from 1 to 5 increases continuously, reaching a maximum of 248 mV/(kV/m), while the number 6 and 7 are decreased. The calibration coefficient of the sensing unit is degraded, and the cause is still under investigation.
4.2 Sampling capacitances effects
After the power frequency electric field test is performed on the sensing unit without the sampling capacitance. The better sensing No. 5 sensing unit is connected to different sampling capacitors for testing and analysis. The test process is the same as the power frequency electric field test. The test results are shown in Table 5.

It can be seen from Table 5 that when different sampling capacitances are connected, the sensing units have different calibration coefficients and have certain linearity. When the sampling capacitance is small, the calibration coefficient of the sensing unit is large. But the output signal is too large to perform signal processing, which is not conducive to electric field measurement. The output signal waveform is severely distorted at high field strength, and the measurement performance of the sensing unit is not good. Under the larger sampling capacitance, the calibration coefficient of the sensing unit becomes smaller, the output signal also decreases, and the distortion of the output signal waveform is also small. Therefore, based on the comprehensive analysis of the test conditions and design requirements, the actual sampling capacitance $C_s$ value is chosen to be 3.3 nF.

| Serial number | Sampling capacitances $C_s$ (nF) | Linearity | The calibration coefficient (V/kV/m) | $V_{pp}|E=200kV/m (V)$ |
|---------------|---------------------------------|-----------|------------------------------------|----------------------|
| 5-0           | 0                               | 1.6025%   | 0.248                              | 49.159               |
| 5-1           | 0.33                            | 2.2101%   | 0.087                              | 17.1703              |
| 5-2           | 0.68                            | 1.0458%   | 0.057                              | 11.6582              |
| 5-3           | 1                               | 0.8837%   | 0.054                              | 10.913               |
| 5-4           | 2.2                             | 1.8399%   | 0.042                              | 8.5471               |
| 5-5           | 3.3                             | 0.3586%   | 0.030                              | 6.149                |
| 5-6           | 4.7                             | 0.7776%   | 0.028                              | 5.6982               |

It is the peak-to-peak value of the output signal when the sensing unit is at a field strength of 200 kV/m.

5. Conclusion
In this paper, the measurement principle of the plate capacitive electric field sensing unit is studied. In order to solve the problem of edge effect, a plate capacitive alternating electric field sensing units with an equipotential ring is designed according to the modeling and simulation results of COMSOL simulation software and measurement requirements. The sensing units of designed have been tested in uniform power frequency electric field. The results show that the measured results of the designed 5th sensing unit have better linearity and high calibration coefficient in the field of 200kV/m electric field strength. Selecting the sampling capacitance of 3.3nF, the output signal is easy to be processed. It can be used as a sensing unit for a large range of electric field sensors. It is small in size, easy to integrate and has good portability.

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