Research on Calibration System of Low Frequency Electric Field Measuring Instrument

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Abstract. In order to calibrate various types of low frequency electric field measuring instruments, this paper constructs a calibration system by using the voltage amplifier. This system uses a function signal generator to output voltage signal, which is amplified by a voltage amplifier and loaded onto the plate to generate an electric field. The intensity of electric field is achieved by adjusting the distance between the two electric plates and the output multiple of the amplifier. The electric field generated by the system ranges from 30Hz to 100kHz in frequency and the field intensity ranges from 1V/m to 3kV/m. The system established in this paper is easy to operate and use, which greatly reduces the difficulty of generating continuous low-frequency electric fields in conventional calibration systems. The experimental results show that the feasibility, stability and reliability of the proposed system are superior to the traditional high-voltage source and TEM (Transverse Electric and Magnetic Field) chamber method.

1. Introduction

With the development of modern cities, the demand for power grids is increasing. Power transmission and transformation construction of power grids, especially high-voltage power transmission and transformation projects, has been rapid developed. The locations of high-voltage overhead lines and substations are also getting closer to residential areas, schools and commercial areas [1-3]. These high-level voltage substations and related power projects provide urban with electric energy and meet the daily needs of people. At the same time, electromagnetic environment in the vicinity becomes more and more complicated. The electromagnetic radiation only affect the work of other surrounding electrical equipment, but also endanger the health and safety of the operation and maintenance staff and surrounding residents [4, 5]. Therefore, the environmental monitoring department needs to carry out environmental monitoring on high-voltage lines, substations and other venues. The performance of the low-frequency electric field measuring instruments used in environmental monitoring is different, which results in different field intensity values. Therefore, improving the accurate and reliable performance of the low-frequency electric field measuring instrument is significant to ensure the safety of living environment.

At present, there are two main methods for calibrating low-frequency electric field measuring instruments in the world: TEM cell method and parallel plates method. The TEM cell method uses TEM cell as the main device to generate field intensity, which can be calculated according to the theory. The usable frequency is related to the design of the TEM cell. Generally, the larger the cell size, the lower the usable frequency (the higher the height of the spacer), and it is difficult to generate
a large electric field in the case of good matching. The parallel plates method can generate a large electric field, and almost all of them are loaded by transformers. The parallel plates method mainly realizes the calibration of the frequency from 50 Hz to 1 kHz, which cannot meet the calibration requirements of the conventional low frequency electromagnetic field measuring instrument in the market. There are few organizations for calibrating the low-frequency electric field measuring instruments in China. The electric field is calibrated according to the relevant national standards or industry standards. There is no verification procedure or calibration specification for the verification or calibration of the low frequency electric field measuring instruments. Based on the research on the calibration principle of low-frequency electric field measuring instruments, a system of low-frequency electric field measuring instrument calibration is developed, which can realize the calibration of various low-frequency electric field measuring instruments with frequency from 30Hz to 100 kHz and electric field intensity from 1V/m to 3kV/m.

2. Calibration principle

Calibration of low frequency electric field measuring instruments requires establishment of a standard electric field. At present, there are two common methods to establish a standard electric field: the standard antenna method and the standard field intensity method [6, 7]. The standard antenna method requires a large site, which is easy to leak and is affected by external environmental disturbances. The standard field intensity method commonly uses the TEM cell method. The TEM cell has good uniformity and high safety, but the tapered transition input connectors at both ends cannot withstand high voltages, and its minimum frequency is 9 kHz, which means it cannot realize the electric field calibration below 9 kHz. This paper mainly uses standard field intensity method which generates low-frequency electric fields with the parallel plates method [8]. The parallel electric plates method uses two parallel plates as an electric field generating device, and directly loads the voltage output from the function signal generator onto the parallel plates, thereby generates the required electric field intensity. The electric field intensity is calculated as follows:

\[ E = \frac{U}{d} \]  

The larger the parallel plates, the more uniform the electric field. In theory, when the electric plates are infinite, the generated central electric field can be regarded as uniform, and the influence of the edge of the electric plates on the central field intensity can be neglected. When large electric plates are adopted, the capacitance between the two electric plates will get large, at this point, there will be big capacitive impedance. Ordinary signal sources cannot directly drive large plates, so the signal must be amplified to produce a high-intensity electric field. The size of the plates and the voltage difference between them are also key parameters to ensure uniform electric field intensity [9]. When calibrating, the size of the field intensity probe can be neglected, compared to the size of the electric plates. The test probe can be regarded as a mass point and placed in a uniform electric field generated by the electric plates to ignore the influence of the probe inserted into the electric field.

3. System Components

As shown in Fig. 1, the calibration system is composed of a function generator, a voltage amplifier, a digital multimeter and electric plates. The function generator outputs the low frequency signal, which is then inputted to the voltage amplifier for amplification, and the amplified signal is loaded onto the electric plates. The voltage of the loaded plates is monitored by the digital multimeter.
The most important points of the calibration system design are:

1) The driving capability and stability of the voltage amplifier is one of the keys to the success of the system. According to the design requirements of the plate capacitor, the voltage amplifier must be able to drive large capacitor.

2) The size and uniformity of the plates is also the key point to generating a uniform electric field. Therefore, in the system operation, on one hand, drive capability of the amplifier should be considered, on the other hand, the impedance matching of the voltage amplifier needs to be taken into account.

3.1. Design of Voltage Amplifier

In order to generate high electric field intensity, high voltage must be loaded onto the plates. The Capacitor composed of two electric plates has a large capacitance value. Capacitance shows a gradual decline with frequency increasing, but the loss also increases as frequency increases. In order to generate a large voltage, the output power needs to be larger and larger, which conventional signal generators cannot achieve. So an amplifier with large output power must be selected. At present, voltage amplifiers in the market have large output voltage, nevertheless frequency cannot meet the requirements. So as to meet the frequency requirements, the output voltage cannot get large enough. Meanwhile, if the large capacitor is driven, the frequency can be adjusted in normal range at the sacrifice of frequency.

In order to solve the above contradictions, a voltage amplifier is designed in this paper. Firstly, the operational amplifier is used to form an amplifying unit. The voltage amplifying stage and power amplifier are used to combine and cascade the circuit structure, which increases the charging and discharging capacity of the amplifier to the load, thereby enabling output power amplification. The coupling between the operational amplifier and the power amplifier seriously affects the performance of each amplifier, especially the gain. Therefore, the coupling between the input and the output of the amplifier must be properly designed to effectively reduce the loss of overall gain due to cascade of the two units [10].

Stability of the voltage amplifier is ensured by improving stability of the capacitive load of the op amp via the voltage feedback network [11]. The amplifier circuit in this system connects a voltage feedback resistor between the op amp output and the load capacitor to solve the stability problem. When the amplifier drives a capacitive load, the interaction between the output capacitor and the capacitive load adds a pole to the amplifier's response, resulting in the phase shift [12]. So a resistor is connected in series with the amplifier output for purpose of voltage feedback, thus ensuring isolation of feedback point from capacitive load for better stability.

3.2. Design of Electric Plates

Material of electric plates must be considered in the first place. Conductive material with high conductivity and not easily deformed is selected. Secondly, the electric plates should meet the requirements of IEC61786-2013. The size of the electric plates is 1.5m×1.5m. The electric field generated by the large and well electric conducted plates can effectively reduce the influence of probe on central electric field [13, 14]. However, when the size of the electric plates get large, voltage applied to electric plates is probably to cause voltage difference (referred to as a voltage difference) from the connection point to the periphery of each electric plate. Voltage difference of the electric
plates changes the electric field. The intensity of central and surrounding electric fields is different, which leads the electric field to be unstable and uneven.

The system adopts stainless steel metal plates. Considering the large area of the electric plates, if the amplifier output is connected to the electric plates, the contact point is far away from other areas of the electric plates, which is easy to cause voltage difference. Therefore, a copper net with good conductivity is used to wrap one side of the electric plates, and the contact point of the electric plates is amplified by the copper net, so that the number of contact points between the output signal core ports and the plates increases. Contact area increase effectively improved the voltage on the plate surface, so that the voltage difference of the plates was managed within 1%. Putting two ends of the multimeter on two arbitrarily selected points of the plates, the visible voltage is almost zero, which satisfies the requirements of voltage difference of electric plates in IEC61786-2013, thus ensuring the uniformity of the electric field generated between the plates.

4. System Verification

In order to verify whether the system meets the electric field intensity generated by the frequency of 30 Hz~100 kHz, the EHP-50F probe produced by Narda Company of Germany is used for the test. The calculated center field intensity is compared with that detected by the EHP-50F probe showed on its display. The calibration test physical diagram is shown in Fig. 2.
The calibration results are shown in Table 1.

Table 1. EHP-50F Test results.

| Frequency (Hz) | Voltage (V) | Distance (m) | Field Intensity (V/m) | Display Value (V/m) |
|----------------|-------------|--------------|-----------------------|---------------------|
| 30             | 40          | 0.8          | 50                    | 50.51               |
| 40             | 40          | 0.8          | 50                    | 49.82               |
| 60             | 40          | 0.8          | 50                    | 49.58               |
| 80             | 40          | 0.8          | 50                    | 50.32               |
| 100            | 40          | 0.8          | 50                    | 50.08               |
| 200            | 40          | 0.8          | 50                    | 49.40               |
| 400            | 40          | 0.8          | 50                    | 49.56               |
| 600            | 40          | 0.8          | 50                    | 49.56               |
| 800            | 40          | 0.8          | 50                    | 49.60               |
| 1000           | 40          | 0.8          | 50                    | 49.72               |
| 2000           | 40          | 0.8          | 50                    | 49.18               |
| 4000           | 40          | 0.8          | 50                    | 49.31               |
| 6000           | 40          | 0.8          | 50                    | 49.38               |
| 8000           | 40          | 0.8          | 50                    | 49.44               |
| 10000          | 40          | 0.8          | 50                    | 49.49               |
| 15000          | 40          | 0.8          | 50                    | 49.50               |
| 20000          | 40          | 0.8          | 50                    | 49.50               |
| 40000          | 40          | 0.8          | 50                    | 49.58               |
| 60000          | 40          | 0.8          | 50                    | 49.59               |
| 80000          | 40          | 0.8          | 50                    | 49.46               |
| 100000         | 40          | 0.8          | 50                    | 49.27               |

In the work frequency band, system test of the traced low-frequency field intensity was carried out. First, distance between the two plates was set to 80cm, the low-frequency electromagnetic field intensity meter HI-3604 was placed in the center of two plate, the frequency range of function generator was set from 30Hz to 100 kHz, and the magnification of the amplifier was chosen maximum. The function output was adjusted and the voltage on the plates was gradually changed, the AC voltage value on the digital multimeter 34401A was sequentially recorded together with the corresponding electric field intensity. System measurements are as follows in Table 2.

Table 2. System measurements.

| Frequency (Hz) | Voltage (V) | Distance (m) | Field Intensity (V/m) | Display Value (V/m) |
|----------------|-------------|--------------|-----------------------|---------------------|
| 50             | 80          | 0.8          | 100                   | 105.9               |
| 50             | 160         | 0.8          | 200                   | 216                 |
| 50             | 240         | 0.8          | 300                   | 322                 |
| 50             | 320         | 0.8          | 400                   | 427                 |
| 50             | 400         | 0.8          | 500                   | 532                 |
| 50             | 480         | 0.8          | 600                   | 636                 |
| 50             | 560         | 0.8          | 700                   | 743                 |
| 50             | 640         | 0.8          | 800                   | 848                 |
| 50             | 720         | 0.8          | 900                   | 953                 |
| 50             | 803         | 0.8          | 1004                  | 1063                |
| 50             | 884         | 0.8          | 1105                  | 1170                |
Traceability results are as follows in Table 3.

| Frequency (Hz) | Nominal value (kV/m) | Display Value (kV/m) |
|---------------|----------------------|----------------------|
| 50            | 0.100                | 0.1074               |
| 50            | 0.200                | 0.218                |
| 50            | 0.400                | 0.427                |
| 50            | 1.000                | 1.056                |
| 50            | 2.000                | 2.17                 |
| 50            | 3.000                | 3.22                 |

According to Table 2, it can be concluded that the field intensity generated by the voltage applied to the plate at the frequency of 50 Hz is consistent with that shown in the HI-3604 traceability report. According to the traceability data in Table 3, field intensity displayed by HI-3604 is almost consistent with the calculation results according to Table 2, and the consistency of the system can be verified.

5. Analysis of instruments measurement uncertainty

According to the composition of instruments and the field intensity calculation formula 1, the instruments measurement uncertainty is consisted of the following aspects:

5.1. Error caused by edge effects

Since the electric field generated by Equation 1 is an electrostatic field, the influence on the center field intensity can be neglected only when the parallel plates are infinite. As frequency increases, the voltage between the parallel plates varies in different positions, and the power lines at the edge of the plates are not perpendicular to them with direction gradually radiating outward. According to IEC61786-1-2013, the influence of the edge on the central field intensity is shown in Fig. 3 below.

![Figure 3](image-url)  
Figure 3. Influence of the distance between the edge and center on electric field intensity

As shown in the above Fig. 3, if distance between the edge and is greater than or equal to 0.6 m, the influence on the central field intensity can be neglected. In this paper, 1.5m x 1.5m electric plates were used and the center is at the 0.75m position when calibrating, so the influence of distance between edge and plate on the field intensity measurement instruments can be neglected.
5.2. Error caused by the function signal generator

The function generator 33250A is adopted. According to the 33250A specification, the maximum allowable error of the amplification factor when outputting the maximum gain at 1 kHz is ±1%, then the half width \( a = 1\% \), which is considered to be evenly distributed within the interval, including the factor \( k = \sqrt{3} \), then error caused by the function signal generator is:

\[
\frac{1\%}{\sqrt{3}} = 0.58\%
\]

5.3. Error caused by voltage amplifier

According to the traceability certificate of the voltage amplifier, the maximum allowable error of the amplification factor when outputting the maximum gain at 1 kHz is ±5%, then the half width \( a = 5\% \), which is considered to be evenly distributed within the interval, including the factor \( k = \sqrt{3} \), then error caused by voltage amplifier is:

\[
\frac{5\%}{\sqrt{3}} = 2.89\%
\]

5.4. Error caused by digital multimeter

According to the technical indicators of the digital multimeter 34401A, when the measurement frequency is 1 kHz and the voltage is 100 V, the maximum allowable error of the digital multimeter is: ±0.68%, then the half width \( a = 0.68\% \), which is considered to be evenly distributed within the interval, including the factor \( k = \sqrt{3} \), then error caused by digital multimeter is:

\[
\frac{0.68\%}{\sqrt{3}} = 0.39\%.
\]

In summary, since the sources of errors are not relevant, the standard uncertainty of the calibration instruments is:

\[
u_c = \sqrt{u_i^2 + u_z^2 + u_j^2} = 2.973\%
\]

The extended uncertainty is:

\[
U = k \times u_c = 2 \times 2.973\% = 5.95\%
\]

The extended uncertainty in logarithm is:

\[
U = 20 \log(1 + 0.0595) = 0.50\text{dB} \ (k = 2)
\]

6. Conclusion

It can be seen from the system verification results that the low frequency electric field measuring instrument calibration system can generate a stable and uniform field intensity and meet the calibration requirements. By means of measuring the voltage difference of the electric plates, it can be concluded that the electric field distribution is uniform and the central field intensity is stable in the frequency range from 30 Hz to 100 kHz. When carrying out instrument calibration, the distance between the plates can be adjusted, and the probe can be regarded as a mass point, whose influence on the electric field is negligible [15]. At the same time, the system also verifies that the influence of edge effect on central field intensity is slight if the plates are large enough. In further research edge effect and on-plate voltage will be minimized, and the impact of each uncertainty component on the system will be comprehensively evaluated.
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