Design and testing of a high-precision generating voltmeter for metal-enclosed megavolt level DC voltage source

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Rev. Sci. Instrum. 95, 045008 (2024)
https://doi.org/10.1063/5.0190171
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Cite as: Rev. Sci. Instrum. 95, 045008 (2024); doi: 10.1063/5.0190171
Submitted: 4 December 2023 • Accepted: 9 April 2024 • Published Online: 26 April 2024

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ABSTRACT
An extremely stable megavolt (MV) level DC voltage source is the key foundation for many scientific instruments, and the need for accurate measurement and long-term real-time monitoring of its output voltage is increasingly urgent. The utilization of conventional resistive voltage dividers for measurements introduces leakage currents, resulting in considerable measurement errors. The non-contact generating voltmeter (GVM) sensor based on electric field measurement has a simple structure and a low cost, making it expected to be an effective solution. Currently, most research on GVM sensors focuses on the measurement of weak electric fields at kV/m levels with significant interference. In this paper, an improved high-precision non-contact GVM sensor was designed. A DC voltage test platform was built, and the effects of the sampling resistor and motor rotation speed on the measurement results were discussed. The relative combined uncertainty of the improved GVM sensor reached 0.042%, which satisfied the urgent need for MV level DC voltage source measurement. The improved GVM sensor can provide an effective reference for measuring the output voltage of a metal-enclosed MV level DC voltage source or the potential of a suspended electrode.

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I. INTRODUCTION
A high stable DC source is widely used in mass spectrometry, accelerators, and other fields, acting as a key infrastructure for scientific research. As the core component of the high-voltage accelerating mass spectrometer, the extremely stable megavolt (MV) level DC voltage source is expected to have an extremely stable output voltage, which is supposed to be measured accurately and monitored in real time for a long time. However, when the traditional voltage divider is used to measure the output voltage of the MV level DC source, it is inevitable to introduce a large leakage current, which will cause certain distortion and attenuation of the measured signal and bring about a large measurement error. The non-contact DC voltage measurement method based on electric field measurement is expected to solve the problem of accurately measuring the output voltage of a DC source.

The measurement techniques of non-contact DC electric field measurement include electrical measurement,6–11 optical measurement,12–17 and MEMS technology.18–24 The electro-optic crystals of optical sensors are difficult to manufacture and expensive. Whether natural or artificially synthesized, electro-optic crystals inevitably contain certain impurities, and the process error also affects the refractive index. Although MEMS sensors have the advantages of small size, light weight, low power consumption, and high integration, they are expected to produce precise vibration, which increases the difficulty of the process. The generating voltmeter (GVM) sensor, or “field mill,” which belongs to electrical measurement, has the advantages of a simple structure, low cost, and easy implementation and may become the preferred solution for accurate measurement and long-term real-time monitoring of the output voltage of the MV level DC voltage source. The developed AC/DC electric field mill had good performance and effectively monitored...
the real-time distribution of the mixed electric field under the transmission lines. The effects of space charge on the accuracy of the mixed electric field measured by a rotating-vane-style electric field meter were obtained. The sources of measurement error of the field mill used in the study of regional atmospheric electric fields and lightning hazard warnings were analyzed, and the methods of reducing the error and correcting the relevant data were proposed. The normalization of the characteristic curve of the field mill sensor and the two-channel denoising differential measurement method were proposed to improve the anti-interference ability of the sensor and the two-channel denoising differential measurement were proposed to improve the anti-interference ability and measurement accuracy. At present, the research on GVM sensors is mostly limited to measuring the electric field under high-voltage transmission lines or atmospheric quasi-static electric fields for applications. Most of them study the measurement of a weak electric field of kV/m, while the output voltage measurement of the MV-level DC source is based on the measurement of a strong electric field. An MV-level DC voltage source with an uncertainty of ≤0.01% is urgently needed, and an extremely stable GVM for measuring its output voltage acts as an important component. The high-voltage output end of the DC source is about 30 cm away from the GVM sensor, and a strong, slightly uneven electric field is generated between them. The whole system is encapsulated in a metal cavity filled with SF₆ gas at a pressure between 0.7 and 1.2 MPa. The shielding electrode of the traditional GVM rotates at high speed, which easily distorts the electric field and may cause gas insulation breakdown in the metal-enclosed DC voltage source. Moreover, the rotor of the traditional GVM is a hollow fan-shaped metal disk, and its high-speed rotation in a high-pressure metal cavity makes the rotor suffer a large resistance and is prone to large noise interference. Therefore, an improved, extremely stable GVM for MV level metal-enclosed DC voltage sources is urgently needed.

In this paper, the electric field distribution on the sensing electrode and the influence of the edge effect of the vane openings on the measurement results were discussed with COMSOL simulation software. According to the simulation results, an improved GVM sensor was designed. An experimental platform was built to study the effects of key factors on the measurement results and to verify the feasibility of the output voltage measurement of a DC source based on the improved GVM sensor. Finally, the measurement uncertainty evaluation of the improved GVM sensor was carried out.

II. MEASUREMENT PRINCIPLE

The principle of measuring DC high voltage with the help of a GVM sensor is illustrated in Fig. 1. The GVM sensor is placed in the uniform electric field generated by the DC voltage. When the sensing electrode rotates at high speed, the area of the sensing electrode exposed to the electric field changes periodically, which causes the induced charges on the sensing electrode to vary in time to induce an alternating current. The induced current is converted into an amplified voltage after flowing through an external impedance, which is directly proportional to the DC voltage to be measured.

Gauss’s law states that the electrical flux $\phi$ out of a closed surface is equal to the charge enclosed ($\Sigma q_i$) divided by the permittivity of vacuum $\varepsilon_0$.

$$\phi = \oint E \cdot dS = \frac{1}{\varepsilon_0} \Sigma q_i$$  \hspace{1cm} (1)
where $S$ is the maximum exposed area of the sensing electrode, $U_{DC}$ is the DC voltage to be measured, and $H$ is the distance between the GVM sensor and the high voltage electrode.

The relationship between the DC voltage to be measured ($U_{DC}$) and the amplitude of the output voltage ($U_R$) can be theoretically expressed as follows:

$$U_{DC} = \frac{HT_2}{2\varepsilon_0 S} \times \frac{U_R}{R}, \quad (5)$$

where $R$ is the external sampling resistor.

### III. NUMERICAL SIMULATION

#### A. Effect of distance between sensing electrode and shielding electrode

As shown in Fig. 4, the electric field simulation model of the GVM sensor was established. Both the high-voltage electrode and the ground electrode were metal discs with a radius of 30 cm and a thickness of 1 cm. There was a uniform electric field of 10 kV/cm between the high voltage electrode and the ground electrode. The diameters of the shielding electrode and the sensing electrode were 90 and 64 mm, respectively. The distance between the sensing electrode and the shielding electrode, with a thickness of 1 mm, was adjustable. There were eight fan-shaped vane openings on the shielding electrode and the sensing electrode. As shown in Figs. 5(a)–5(c), the area of the sensing electrode exposed to the electric field varied at different rotation angles. Ensure that the upper surface of the shielding electrode is flush with the upper surface of the ground electrode during measurement.

Figure 6 shows that the electric field distribution on the sensing electrode with different angles staggered from the shielding electrode when the distance ($d$) between the sensing electrode and the shielding electrode is 2 mm. The simulation results indicated that when the sensing electrode was fully overlapped by the shielding electrode, the stagger angles between the sensing electrode and the shielding electrode were $0^\circ$, but there was still a weak electric field at the edge of the sensing electrode. When the sensing electrode was fully exposed, the stagger angles between the sensing electrode and the shielding electrode were $22.5^\circ$, and the electric field at the middle position on the sensing electrode was stronger than that at the edge, which indicated the vane openings of the shielding electrode had a certain weakening effect on the electric field on the sensing electrode; that was called the edge effect.

There were eight fan-shaped vane openings on the shielding electrode or the sensing electrode. The sensing electrode was fully covered by the shielding electrode for the first time at $t = 0$, when the stagger angles between the sensing electrode and the shielding electrode were $0^\circ$. When the sensing electrode was rotated to the position where it was fully exposed to the electric field for the
first time, the stagger angles between the sensing electrode and the shielding electrode were $22.5^\circ$, and $t$ was $T_2/2$. The sensing electrode continued to rotate and was gradually covered by the shielding electrode. When the sensing electrode was fully covered by the shielding electrode for the second time at $t = T_2$, the stagger angles were $45^\circ$. Figure 7 shows the induced charge on the surface of the sensing electrode vs stagger angles with different distances ($d$) between the shielding electrode and the sensing electrode in $T_2$. The symbol in front of the induced charge only represents the polarity of the charge. The simulation results showed that with the increasing stagger angles between the shielding electrode and the sensing electrode in $T_2/2$, the induced charge on the sensing electrode increased slowly, then increased rapidly, and finally increased slowly, which may be attributed to the edge effect of vane openings. Although the area of the sensing electrodes with stagger angles of $0^\circ$ was fully covered, the electric field on the sensing electrode could not be fully covered, and there was still a weak electric field at the edge, as shown in Fig. 6(a). Although the area of the sensing electrodes with stagger angles of $22.5^\circ$ was fully exposed, the electric field on the sensing electrode was weakened, as shown in Fig. 6(c). With a shorter distance ($d$) between the sensing electrode and the shielding electrode, the electric field on the sensing electrode became stronger, and the induced charge increased.

The induced charge on the sensing electrodes with the stagger angles of $\theta_{t1}$ and $\theta_{t0}$ were $Q_{t1}$ and $Q_{t0}$, respectively. The average induced current ($I_{av}$) generated by the sensing electrode was calculated by

$$I_{av} = \frac{\Delta Q}{\Delta t} = \frac{|Q_{t1} - Q_{t0}|}{\theta_{t1} - \theta_{t0}} \times \frac{360^\circ}{T_1}. \quad (6)$$

When the rotation period ($T_1$) of the motor was constant, the stagger angles between the shielding electrode and the sensing electrode were proportional to the time. Therefore, the change rate of the induced charge was proportional to the average induced current. Figure 8 shows the change rate of induced charge vs stagger angles between the shielding electrode and the sensing electrode in $T_2$, which also indicates that the induced current varied in $T_2$. The simulation results showed that when the distance between the sensing electrode and the shielding electrode was 2 or 3 mm, the induced current waveforms obtained by the numerical simulation were close to a sinusoidal wave, while the waveform was close to a square when the distance was 1 mm. With a decrease in the distance between the sensing electrode and the shielding electrode, the weakening effect of the shielding electrode on the electric field on the sensing elec-
trode weakened, and the induced current waveform changed from a sinusoidal wave to a square wave. At the same time, the amplitude of the induced current increased, which improved the sensitivity of the sensor to some extent. However, the output signal waveforms closing to a square wave were not conducive to subsequent signal processing, and a margin of assembly was required. Therefore, the distance between the sensing electrode and the shielding electrode was set at 2 mm, which could obtain a suitable output waveform and high measurement sensitivity.

B. Effect of the number of vane openings

Figure 9 shows the electric field distribution on the surface of fully exposed sensing electrodes with different numbers of vane openings when \(d\) is 2 mm. It was found that when the number of vane openings varies from 4 to 12, the electric field on the fully exposed sensing electrode is gradually weakened. With the increase in the number of fan-shaped vane openings, although the total area of the sensing electrode exposed to the electric field remained unchanged, the area of each fan-shaped vane decreased. The shielding electrode with a smaller area of vane opening had a stronger shielding effect, and the electric field on the fully exposed sensing electrode got weaker.

The quantity of the electric charge on the fully covered sensing electrode was defined as \(Q_0\), and the quantity on the fully exposed sensing electrode was defined as \(Q_1\). Within the half period of the induced current (\(T_2/2\)), the variation of the induced charge was defined as \(\Delta Q\). It can be seen from Fig. 10 that the induced charges \(Q_1\) and \(\Delta Q\) decreased as the number of vane openings increased. With a constant motor rotation speed, the signal period of the induced current (\(T_2\)) decreased as the number of vane openings increased. The average induced current (\(I_{av}\)) was proportional to the change rate (\(\Delta Q/\Delta \theta\)) of induced charge on the sensing electrode in \(T_2/2\). Figure 11 shows the average change rate of induced charge on the sensing electrode vs the number of vane openings with different distances (\(d\)) between the shielding electrode and the sensing electrode in \(T_2/2\). It could be seen that there was a maximum of \(\Delta Q/\Delta \theta\) with different \(d\) as the number of vane openings increased, and the number of vane openings corresponding to the maximum value of \(\Delta Q/\Delta \theta\) increased with the decrease in \(d\). The increase in the number of vane openings resulted in the enhanced edge effect, which weakened the electric field on the exposed sensing electrode and brought about a few induced charges. Therefore, as the number of vane openings increased, the change rate of induced charge increased first on account of the dominantly decreasing signal period (\(T_2\)) and then decreased because of the dominantly strong shielding effect. With the decrease in \(d\), the number of vane openings corresponding to

![Graph](image-url)
the maximum value of the change rate of induced charge got larger, and the edge effect gradually got weaker.

In summary, the distance between the sensing electrode and the shielding electrode was initially set at 2 mm, and the number of fan-shaped blades on the electrodes was initially set at 8, which could obtain a better output signal waveform and measurement sensitivity while ensuring a suitable mechanical assembly distance.

IV. PROTOTYPE FABRICATION

A. Design of the GVM sensor

The traditional GVM sensor, where the rotor over the stator acts as a shielding electrode, is not suitable for the measuring output voltage of the MV level DC voltage source. The reason is that once the rotor vibrates to a large extent due to mechanical reasons, the rotating shielding electrode is more likely to distort the electric field, resulting in gas insulation breakdown in the metal-enclosed DC voltage source. The improved structure and object of the GVM sensor are shown in Fig. 12. The stator was used as the grounded shielding electrode, while the rotor, acting as the sensing electrode, was insulated from the motor shaft, which effectively blocked interference signals from the motor shaft. The induced current was drawn out through two copper brushes with good electrical conductivity and converted into a voltage signal through an external sampling resistor. A thin printed circuit board (PCB) plate where there were eight conductive sectors covered with copper material replaced a metal disk with hollow sectors as the sensing electrode. The structure of this sensing electrode can help to decrease the environmental resistance that the high-speed rotating sensing electrode suffers, decrease the fluidity of the medium gas, and improve the stability of the output signal. Combining the above simulation results with the consideration of the possible vibration of the rotor, it was more appropriate to adopt the sensing electrode with eight vane openings that were 2 mm away from the shielding electrode.

The rotor was driven by a brushless DC motor with built-in pulse width modulation (PWM) speed regulation. Table I shows the results of the speed stability evaluation of the selected brushless motor at no load. Seven motor rotation cycles were read continuously when the motor speed was around 4438 rpm. The relative standard deviation of the motor rotation cycle was 0.02%, which indicated that the selected DC brushless motor has better rotational stability at high-speed rotation and could meet the requirements of the GVM sensor application.

B. Testing platform

The testing platform for measuring DC voltage is shown in Fig. 13. The improved GVM sensor was placed in a closed cavity filled with SF₆ at 0.4 MPa. In order to avoid the effect of fluctuations in the sensor output signal caused by the DC voltage itself, a high stability DC voltage source of model 2290-10 was used to
apply the voltage, and the output voltage uncertainty of this DC voltage source was 0.01%. The signal period ($T_2$) of the output voltage was 4 ms, and the DC electric field to be measured was 15.38 kV/cm.

The shielding electrode of the GVM sensor was grounded reliably and parallel to the high-voltage electrode. When an extremely stable DC voltage was applied to the high-voltage electrode, there was a slightly uneven DC electric field between the high voltage electrode and the shielding electrode. When the sensor was working, the induced current generated by the sensing electrode was converted into an amplified voltage signal through an external sampling resistor ($R$). After that, the voltage signal entered the signal processing circuit through a voltage follower that consisted of an operational amplifier with a low bias current, high input impedance, and low output impedance, which reduced the impact of peripheral circuits on the external sampling resistor. The output voltage waveform was displayed with the help of a data acquisition card (DAQ) and a personal computer (PC).

The output voltage waveform of a GVM sensor with equivalent sampling resistors ($R$) of 100k is shown in Fig. 14. It could be found that the amplitude of the output voltage was extremely stable, and the waveform of the output voltage was close to a sine wave, not a square wave, which was attributable to the edge effect of the fan-shaped vane openings.

V. EXPERIMENTAL RESULTS

A. Effect of external sampling resistor

When the signal period ($T_2$) of the output voltage was 4 ms, the output characteristic fitted curves of the GVM sensor with different equivalent sampling resistors are shown in Fig. 15. When the DC electric field strength varied from 3 to 16 kV/cm, the output voltage amplitude increased linearly. Figure 16 shows the measurement sensitivity of the improved GVM sensor with different equivalent sampling resistors. It was found that the output voltage amplitude increases linearly with an increase in the external sampling resistor.
B. Effect of motor rotation speed

The ratio of the motor rotation period \( (T_1) \) to the signal period \( (T_2) \) of the output voltage of the GVM sensor is the constant \( N \), which is the number of vane openings of the sensing electrode. Therefore, the motor rotation period can be characterized by the signal period of the output voltage. When the equivalent sampling resistor was 1 M\( \Omega \), Fig. 17 shows the output characteristic fitted curves of the GVM sensor with signal periods \( (T_2) \) of output voltage of 3.3, 4.1, 6.1, 8.2, and 8.85 ms. It was found that the output voltage amplitude increases linearly with the increase in the electric field to be measured, and the linearity of the output characteristic curve of the GVM sensor under different motor rotation speeds is excellent. Figure 18 shows the measurement sensitivity of the GVM sensor under different motor rotation speeds as shown in Eq. (5).

\[
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\text{doi: 10.1063/5.0190171}
\]

![Figure 17](image1.png)

**FIG. 17.** Output characteristic of a GVM sensor with different signal periods \( (T_2) \) of output voltage.

![Figure 18](image2.png)

**FIG. 18.** Measurement sensitivity of a GVM sensor with different signal periods \( (T_2) \) of output voltage.

VI. MEASUREMENT UNCERTAINTY EVALUATION

A. Uncertainty evaluation model

The measurement uncertainty was evaluated according to the guide to the uncertainty in measurement (GUM) method in this paper, referring to the JFF 1059.1-2012 specification. The measurement uncertainty is generally composed of several components, and each component is characterized by the estimated value of the standard deviation of its probability distribution, which is called the standard uncertainty. The method of obtaining the experimental standard deviation from a series of measured values \( x_i \) of \( X \) is called type A assessment, and the standard uncertainty \( u_A(\bar{X}) \) is given as

\[
s(\bar{x}_n) = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2},
\]

\[
u_A(\bar{x}) = \frac{s(x_i)}{\sqrt{n}},
\]

where a series of measured values \( x_i \) are obtained by taking \( n \) independent observations of the measured \( X \), \( s(x_i) \) is the experimental standard deviation of the individual measurement value \( x_i \), and \( \bar{x} \) is an average value of a series of measured values \( x_i \).

The method of estimating the standard deviation based on the prior probability distribution estimated from the relevant information is called type B assessment, and the standard uncertainty \( u_B \) is calculated as

\[
u_B = \frac{a}{k},
\]

where \( a \) is the half-width of the interval of possible values of the measured variable, and \( k \) is the confidence coefficient obtained from probability theory.

The measured variable \( Y \) is determined by the other variables \( X_1, X_2, \ldots, X_N \) by means of a linear measurement function \( f \). According to the uncertainty propagation law, the standard uncertainty \( u_Y(y) \) of the estimated value \( y \) of the measured variable \( Y \) is expressed as

\[
\begin{align*}
u_Y(y) &= \sqrt{\sum_{i=1}^{N} \left( \frac{\partial f}{\partial Y} \right)^2 u(x_i)^2 + 2 \sum_{i=1}^{N} \sum_{j=i+1}^{N} \frac{\partial f}{\partial X_i} \frac{\partial f}{\partial X_j} r(x_i,x_j) u(x_i) u(x_j)},
\end{align*}
\]

where \( \frac{\partial f}{\partial X} \) is the partial derivative of the output variable with respect to the input variable \( x_i \), \( u(x_i) \) is the standard uncertainty of \( x_i \), and \( r(x_i,x_j) \) is the correlation coefficient between \( x_i \) and \( x_j \).

When there is no correlation between the input variables, the correlation coefficient is 0. The standard uncertainty \( u_Y(y) \) of the estimated value \( y \) of the measured variable \( Y \) can be written as

\[
u_Y(y) = \sqrt{\sum_{i=1}^{N} \left( \frac{\partial f}{\partial Y} \right)^2 u(x_i)^2}.
\]

The actual waveform of output voltage \( (U_R) \) is not a square wave, and the electric field strength of the surface of the sensing electrode under the shielding electrode may be lower than the electric field strength to be measured. Therefore, the actual voltage divider
ratio of the GVM is not equal to the calculated one. However, the ratio of the actual voltage divider ratio to the calculated ratio of GVM under the same measurement conditions is a constant K. Therefore, the uncertainty evaluation model of \( U_{DC} \) is given by

\[
U_{DC} = K \times \frac{HT_2}{2\varepsilon \delta} \times \frac{U_b}{R}.
\]  

(12)

The key inputs include the sampling resistor \((R)\), the output signal period \((T_2)\), and the reading of the output voltage amplitude \((U_b)\), which may bring some uncertainty to the DC voltage to be measured. Since there is no correlation between the sampling resistor \((R)\), output signal period \((T_2)\), and reading of the output voltage amplitude \((U_b)\) in the GVM measurement model, the standard uncertainty of \( U_{DC} \) can be derived from the expression in \((10)–(12)\) as

\[
u(U_{DC}) = \sqrt{(k_R \times u_R)^2 + (k_{T_2} \times u_{T_2})^2 + (k_{U_b} \times u_{U_b})^2},
\]

(13)

where \(k_R\), \(k_{T_2}\), and \(k_{U_b}\) are the sensitivity coefficients corresponding to the sampling resistor \((R)\), the output signal period \((T_2)\), and the voltage output amplitude \((U_b)\), respectively.

### B. Sensitivity coefficients corresponding to key influencing factors

Localized linear processing is performed in \((12)\). By using the partial derivative, the sensitivity coefficient reflecting the influence of each input variable on the measurement result can be derived from \((12)\) as

\[
\begin{align*}
  k(T_2) &= \frac{\partial U_{DC}}{\partial T_2} = \frac{KHT_2}{2\varepsilon \delta}, \\
  k(U_b) &= \frac{\partial U_{DC}}{\partial U_b} = \frac{KHU_b}{2\varepsilon \delta}, \\
  k(R) &= \frac{\partial U_{DC}}{\partial R} = -\frac{KHU_b T_2}{2\varepsilon \delta}. 
\end{align*}
\]

(14)

In order to compare the influence of each input variable on the measurement result, the sensitivity coefficient needs to be normalized. If the uncertainty of \(x_i\) and \(U_{DC}\) are expressed as relative percentages, the sensitivity coefficient is the ratio of the relative change of the output to the relative change of the input. The sensitivity coefficient \((k^*)\), as shown in

\[
k^* = \frac{\nu(U_{DC})}{\nu(x_i)} = \frac{k_x(u(x), u_{x_i})}{u(x)}.
\]

(15)

According to Eqs. \((14)\) and \((15)\), \(T_2\), \(U_b\), and \(R\) had the same degree of influence on the uncertainty of the measurement result, and the absolute value of \(k^*\) was 1. However, the effects of \(T_2\), \(U_b\), and \(R\) on the measurement results were complementary. When \(T_2\) and \(U_b\) increased, the measurement results were slightly enlarged, while the measurement results decreased when the value of \(R\) increased.

### C. Uncertainty components and combined uncertainty

The DC electrode field measured was 15.38 kV/cm. The external equivalent sampling resistor was 5 MΩ. The waveform of the output voltage \((U_b)\) is shown in Fig. 19. An uncertainty assessment of \(U_{DC}\) based on this measurement result was carried out.

The signal period was affected by the motor speed and the number of vane openings. When the number of vane openings was fixed, the signal period was inversely proportional to the motor speed, so the uncertainty of the signal period could directly represent the uncertainty of the motor speed, and the influence of the motor speed on the measurement results could be assessed. Five series of measurement waveforms were recorded, and each recorded waveform contained 17 consecutive output signal waveforms. The average values \([T_2(i)]\) and relative uncertainties \([\nu(T_2)]\) of the signal period \(T_2\) of five series of output signal waveforms are shown in Table 2, and the relative uncertainty \([\nu(T_2)]\) of five average values \(T_2\) was calculated to be 0.009% according to \((7)\) and \((8)\).

There was also uncertainty in the amplitude of \(U_b\) when reading the voltage amplitude. Five series of measurement waveforms were recorded, and each recorded waveform contained 17 consecutive output signal waveforms. For the uncertainty assessment, a highly stable DC source with an uncertainty of 0.01% was selected. Fluctuations in the DC source were directly reflected in the amplitude of the output signal, so the uncertainty of the output signal already included the uncertainty of the DC source.

### TABLE II. Relative uncertainty of \(T_2\). Average value: 8.0696 and relative uncertainty \(\nu(T_2)\): 0.009%.

<table>
<thead>
<tr>
<th>(i)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_2(i)) (ms)</td>
<td>8.0671</td>
<td>8.0702</td>
<td>8.0690</td>
<td>8.0709</td>
<td>8.0707</td>
</tr>
<tr>
<td>(\nu(i)) (%)</td>
<td>0.066</td>
<td>0.044</td>
<td>0.053</td>
<td>0.048</td>
<td>0.048</td>
</tr>
</tbody>
</table>

###TABLE III. Relative uncertainty of \(U_b\). Average value: 6.4494 and relative uncertainty \(\nu(U_b)\): 0.018%.

<table>
<thead>
<tr>
<th>(i)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U_b(i)) (V)</td>
<td>6.4528</td>
<td>6.4473</td>
<td>6.4517</td>
<td>6.4476</td>
<td>6.4475</td>
</tr>
<tr>
<td>(\nu(i)) (%)</td>
<td>0.072</td>
<td>0.057</td>
<td>0.053</td>
<td>0.063</td>
<td>0.074</td>
</tr>
</tbody>
</table>
(Table IV).

According to type A assessment, the average values \([U_R(i)]\) and relative uncertainties \([u(i)]\) of the signal amplitude \((U_R)\) of five series of output signal waveforms are shown in Table III, and the relative uncertainty \([u_i(U_R)]\) of five average values \((U_R)\) was calculated to be 0.018% according to (7) and (8).

When the sampling resistor worked for a long period of time, fluctuations in resistance value would occur due to the temperature drift or changes in DC voltage. A precision resistor with a low temperature coefficient of 5 ppm/°C was adopted as a sampling resistor. If only the temperature drift of the sampling resistor was considered and the ambient temperature variation range was assumed to be 10–40°C, the relative uncertainty of \(R\) was 0.004% according to the B type assessment. When the measured values were uniformly/rectangularly distributed in the interval, the confidence factor \(k\) is \(\sqrt{3}\) by checking the table,

\[
u(R) = 0.0005% \times \frac{(40 - 10)/2}{\sqrt{3}} = 0.004\%.
\] (16)

The measurement value of \(U_{DC}\) was mainly affected by \(T_2\), \(U_R\), and \(R\). After comprehensive analysis, the combined uncertainty of \(U_{DC}\) was 0.021%, as shown in Table IV. The relative extended uncertainty is the half-width of the inclusion interval of the measurement values. In general, the relative extended uncertainty is obtained by multiplying the relative combined standard uncertainty by the inclusion factor as follows:

\[
U = ku_i.
\] (17)

The measurement result \(Y\) could be expressed as follows:

\[
y = y \pm U.
\] (18)

\(y\) is the estimated value of the measured value \(Y\); the possible values of \(y\) fall in the interval \([y - U, y + U]\) with a high inclusion probability. The probability of this depends on the value of the inclusion factor. In this paper, the probability distribution characterized by \(u_i(y)\) was approximately normal. If \(k = 2\), the inclusion probability of the interval defined by \(U = 2u_i\) was about 95%. If \(k = 3\), the inclusion probability of the interval defined by \(U = 3u_i\) was about 99%. In usual measurements, \(k = 2\) is generally taken. Therefore, the relative expanded uncertainty was 0.042% at a confidence level of 95% (Table IV).

### Table IV. Relative uncertainty of \(U_{DC}\).

<table>
<thead>
<tr>
<th>(T_2)</th>
<th>(U_R)</th>
<th>(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative uncertainty (%)</td>
<td>0.009</td>
<td>0.018</td>
</tr>
<tr>
<td>(k^*)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Relative combined uncertainty</td>
<td>(\sqrt{(0.009%)^2 + (0.018%)^2 + (-1 \times 0.004%)^2} = 0.021%)</td>
<td></td>
</tr>
<tr>
<td>Relative expanded uncertainty</td>
<td>0.042%</td>
<td></td>
</tr>
</tbody>
</table>

VII. CONCLUSION

In this paper, a three-dimensional finite element simulation model of the GVM sensor was established, the effects of the key influencing factors on the output characteristics of the GVM sensor were studied experimentally, and measurement uncertainty was discussed in detail. It was verified that it was feasible for the improved GVM sensor to measure MV level DC voltage. The main conclusions were as follows:

1. The simulation results indicated that the induced current waveform changed from a sinusoidal wave to a square wave with a decrease in the distance (\(d\)) between the sensing electrode and shielding electrode on account of the edge effect of the shielding electrode with many vane openings. With the increase in the number of vane openings, the induced current increased first and then decreased. With the decrease in \(d\), the number of vane openings corresponding to the maximum value of the change rate of the induced charge got larger.

2. The experimental results suggested that the output voltage waveform of the designed GVM sensor was close to a sine wave, and the output voltage amplitude increased linearly with the increase in the applied DC electric field. The measurement sensitivity increased linearly with the increase in the sampling resistor, and there was an inversely proportional function relationship between the measurement sensitivity and the signal periods.

3. The uncertainty of the measured value of the voltage to be measured was mainly affected by the uncertainty of the signal period \((T_2)\), signal amplitude \((U_R)\), and sampling resistor \((R)\). The sensitivity coefficients reflecting the influence of \(T_2\), \(U_R\), and \(R\) on the uncertainty of measured value \((U_{DC})\) were 1, 1, and -1, respectively. The combined relative uncertainty of the measured value \((U_{DC})\) was calculated to be 0.021%, and the expanded uncertainty of the measured value \((U_{DC})\) was 0.042% at 95% confidence probability, which met the uncertainty requirement for the MV level metal-enclosed DC voltage source.

ACKNOWLEDGMENTS

This work was supported by the State Grid Corporation of China (Grant No. 5500-202355793A-3-8-KJ).
AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Xiaoang Li: Formal analysis (equal); Methodology (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal).
Shuxiao Wang: Data curation (equal); Investigation (equal); Software (equal); Writing – original draft (equal).
Xiaoxiao Lv: Investigation (equal); Software (equal).
Zhipeng Zhang: Investigation (equal); Project administration (equal).
Yikai Shao: Investigation (equal).
Zhibing Li: Project administration (equal); Resources (equal); Supervision (equal).
Qiaogen Zhang: Resources (equal); Supervision (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES