Model, Design and Testing of Field Mill Sensors for Measuring Electric Fields under High-Voltage Direct Current Power Lines

Yong Cui, Haiwen Yuan, Xiao Song, member IEEE, Luxing Zhao, Yumeng Liu, and Liwei Lin

Abstract—High voltage direct current (HVDC) transmission lines have been implemented in many countries, including Australia, Brazil, China and Sweden and the safety concerns as the result of the high electromagnetic-radiation underneath the HVDC lines have garnered increased public attentions. Here, we report on the model, design and testing of field-mill electric field sensors to measure the electric field at the ground level under the HVDC transmission lines. This study utilized a finite element analysis method to establish numerical simulation results based on the electrical and mechanical parameters to achieve optimal designs with experimental calibrations. Afterwards, these sensors were successfully tested and utilized at the national high-voltage test base.

Index Terms—Electric field sensors, field mill, high-voltage direct-current (HVDC) transmission, finite element analysis.

I. INTRODUCTION

Compared with a high-voltage alternating current (HVAC) transmission system, the high-voltage direct current (HVDC) scheme is a better choice for long-distance bulk power transmission to send vast amounts of electricity over a very long distance with less power losses and environmental impact [1]. Several ± 800 kV and ± 1000 kV HVDC transmission systems are now in commercial operation in some countries [2]. According to the planning of some grid cooperation, about thirty HVDC transmission projects will be constructed by 2020 in the world.

With the large-scale implementations of HVDC transmission lines, the environmental impacts due to electromagnetic waves have become a focus of public attention in the following technical parameters: electric field, ion current density, space charge density, radio interference, audible noise, etc. [3]-[11].

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In contrast to the HVAC transmission lines, the electric field under HVDC lines is greatly enhanced when a corona discharge occurs and an accurate and efficient measurement method is needed to assure the system follows the electromagnetic environmental standard. Many techniques have been proposed to measure this electric field, including microelectromechanical systems [12]-[14], optics [15]-[17], and field-induced charges [18]-[20]. Specifically, two types of the field-induced charges sensor are widely used under the HVDC transmission lines: the vibrating electrode field meter and the rotating-vane-style electric field meter or “field mill”. The field mill sensor employs an earthed rotor to periodically modulate the DC electric field by alternately exposing and covering the sensor electrode to the external electric field. For example, the field mill sensors have been used at the Hydro-Québec’s research institute (IREQ) and NASA’s Jet Propulsion Laboratory (JPL), while the vibrating electrode field meters have been used by the Bonneville Power Administration (BPA) [21]-[23]. In general, the field mill is less affected by the poor weather situations and normally operated at the ground plane to measure an electric field at the ground level. Besides the applications in the power systems, filed mill sensors have also been widely used in measuring atmospheric quasi-static electric fields for applications such as lightning hazard warning [24], radioactive pollution detection [25], earthquake prediction [26] and electrostatic nature of volcanic plumes [31].

The structure of the field mill has many types in the sensing plate, sensing area, height, etc. For example, Batemen [21], Fort [27] and Tant [28] have used two open sensing plates and Chubb [19] and Maruvada [30] have employed four and six open sensing plates, respectively, while Mendez [31], Kaplan [32] and Bai [33] have the design of eight; Soula [34] has the design of ten; and Zou [3] has the design of sixteen open sensing plates. None of these previous reports have provided detailed analyses such as the effect of the gap distance between the rotating and sensing electrodes which is adjustable by the fabrication and assembly processes. In this work, a numerical model for the field mill sensor has been developed and the simulation results have been used for device optimizations. Compared with the approach of analytical solutions, the numerical results have achieved better agreements with experimental measurements.
II. MEASUREMENT PRINCIPLE

The electrical flux $\Phi$ of a closed surface $S$ is equal to the ratio of the enclosed charge $\sum q$ and the vacuum dielectric constant $\varepsilon_0$ under the electric field, $E$ as [27]:

$$\Phi = \int E \cdot dS = \frac{\sum q}{\varepsilon_0} \tag{1}$$

The general structure of an electric field mill is shown in Fig.1 and is composed of a grounded electrode (rotor), a sensing electrode (stator) and a motor with a constant speed. The sensing electrode is exposed to and screened periodically from the electric field such that the charge $Q(t)$ induced on the sensing electrode varies in time to induce an alternating current to flow to the ground [28], [29].

If the electric field is constant and uniform, the induced charges on the sensing electrode with an area of $S(t)$ is given by:

$$Q(t) = \sum q = \varepsilon_0 E S(t) \tag{2}$$

The induced current is expressed as:

$$i(t) = \frac{dQ(t)}{dt} = \varepsilon_0 E \frac{dS(t)}{dt} \tag{3}$$

The magnitude of the electric field $E$ is related to the induced current $i(t)$.

![Fig. 1. Structure view of the field mill.](image)

![Fig. 2. The shape of the electrode (top view).](image)

Fig. 2 shows the rotor design with $n$ vanes such that the angle of each vane is $\pi/n$. $R$ and $r$ are external and internal radius of the vane, respectively. If the grounded electrode rotates by an angle of $2\pi/n$, the effective area of the rotor will change as:

$$S(t) = \begin{cases} \frac{1}{2} \varepsilon_0 \omega (R^2 - r^2) & 0 \leq t < \frac{T}{2} \\ \left(\frac{\pi}{2} - \frac{1}{2} \varepsilon_0 \omega (R^2 - r^2)\right)E & \frac{T}{2} \leq t < T \end{cases} \tag{4}$$

Where the period $T$ equals $2\pi/\omega$; and $\omega$ is the rotation speed of the motor. The induced current $i(t)$ can be derived by Eq. (4) as:

$$i(t) = \begin{cases} \frac{1}{2} \varepsilon_0 \omega (R^2 - r^2)E & 0 \leq t < \frac{T}{2} \\ \frac{1}{2} \varepsilon_0 \omega (R^2 - r^2)E & \frac{T}{2} \leq t < T \end{cases} \tag{5}$$

The current causes a voltage $V_{RC}(t)$ across the active RC circuit and the electric field can be detected by measuring the voltage $V_{RC}(t)$.

III. NUMERICAL SIMULATION BASED ON FINITE-ELEMENT METHODS

The analytic model of a field mill sensor is based on the uniform distribution of an electric field between the two parallel plates with fan-shaped openings. However, the incident electric field at the electrode edge can produce distortions to result in uneven distribution. A numerical simulation model for a field mill sensor is developed in this work to account for the edge and other effects.

A. Numerical calculation of sensor charge and current

The FEM software ANSYS (Version 15.0) is employed to build and solve the numerical model of field mill sensor. The sensor shown in Fig. 3 has 8 open sensing electrodes and grounded rotors where the internal and external diameters of the opening vanes are 10 mm and 30 mm, respectively. The distance between the sensing electrode and grounded rotor is 3 mm.

A cubic space model (500×500×500 mm³) with the uniform electric field was used. It is assumed that air is the medium with a relative dielectric constant of 1, conductivity of 0. The voltage load is applied in the analysis by specifying a constant value to the bottom of cubic air, sensor shell body and sensor grounded rotor as 0 V. The voltage applied to the top of the model is set to 5000 V to make the incident electric field intensity 10 kV/m.

![Fig. 3. The numerical simulation model of the proposed field mill sensor. (a) Model of the field mill sensor. (b) Electric-field distribution](image)

The simulation starts with $t_0 = 0$ when the sensing electrode is completely covered by the incident electric field. At time $t_1$, the shield has a turning angle of $\pi/n$:

$$T = 2 \times (t_1 - t_0)$$
The quantity of the electrical charges on the sensing electrode can be calculated accordingly. Fig. 4. Electric field distributions above the sensing electrode.

The electric field distributions above the sensing electrode for a certain time are simulated in Fig. 4 based on the model in Fig. 3. As the rotation angle increases, the effective area of the sensing electrode that is exposed to an incident electric field also increases. A curve reflecting the quantity of induced electric charge and rotation angle is obtained in Fig. 5.

![Quantitative relationship of the induced electric charge and rotation angle](image)

Fig. 5. Quantitative relationship of the induced electric charge and rotation angle.

It is observed that the induced electric charge varied non-linearly with respect to time with slow increases initially and fast increases afterwards before slowing down again. The maximum rate of increase is reached when the grounded rotor turns to the half angle (\(\pi/2n\)) position. The induced current is calculated as:

\[
i(t) = \frac{dQ}{dt} = \frac{\Delta Q}{\Delta t}
\]

(8)

Induced current \(I_1(t)\) with respect to time is shown in Fig. 6.

![Induced current with time](image)

Fig. 6. Induced current with time.

It is found that the induced current waveform by numerical simulation is close to a sinusoidal wave, while the induced current waveform obtained by the analytic model is a square wave. The two wave forms differ because the analytic model does not include the edge effects.

The quantity of the electric charge at \(t_0\) is defined as \(Q_0\), and at \(t_1\) is defined as \(Q_1\). Within a half cycle of the induced current change (T/2), the average value of induced current \(I_{ave}\) is:

\[
I_{ave} = \frac{1}{12} \sum_{k=1}^{12} I_k(t) = \frac{Q_1 - Q_0}{12*\pi/(12n\omega)} = \frac{n\omega(Q_1 - Q_0)}{\pi}
\]

(9)

The maximum quantity of induced electric charges can be obtained when the sensing electrode is completely exposed to the electric field as: \(Q_1 = \epsilon_0 \pi E (R^2 - r^2)/2\). If the sensing electrode is completely covered, the electric field intensity on its surface is zero and the induced quantity of electric charge \(Q_0\) is also 0. However, the edge effect can result in the field intensity on an uncovered sensing electrode to be smaller than that of the incident field intensity. Furthermore, when the sensing electrode is completely covered, some electric field remains such that the actual electric charge is not zero. These effects lead to the average induced current obtained from the numerical stimulation smaller than that obtained from the analytic model.

B. Optimal design for vane quantity

The induced current is formed by the periodic change of the effective area of a sensing electrode within the incident electric field. The faster the area changes, the larger the amplitude of the induced current. When the motor speed is a constant, angular frequency of an induced current signal is \(n\omega\). According to the analytic model (Eq. (5)), large vane number will result in large induced current. Therefore, to improve the sensitivity (the differential of the output voltage signal to incident electric field, \(\Delta V/\Delta E\) with a fixed electrode area, more electrode openings are desirable. Fig. 7 shows model results with 2, 6, and up to 16 openings. The results indicate that the electric field intensity on the sensing electrode decreases and the impact of the edge effect increases as the number of electrode openings increases.

![Electric field distribution with 2, 6, 10 and 16 vane opening designs](image)

Fig. 7. Electric field distribution with 2, 6, 10 and 16 vane opening designs.

The quantity of electric charges \(Q_1\) and \(Q_0\) on the sensing
electrode were calculated for various numbers of openings. The change of induced electric charge is defined as \( \Delta Q = Q_i - Q_0 \), and the average value \( I_{ave} \) of the induced current is calculated by Eq. (9) with results shown in Fig. 8.

![Table](image)

<table>
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<th>Gap (mm)</th>
<th>Induced Charge (pC)</th>
<th>Induced Current (nA)</th>
<th>Electric Field (KV/m)</th>
<th>Output (V)</th>
</tr>
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<td>Q_1</td>
<td>0kV/m</td>
<td>0</td>
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<tr>
<td>3</td>
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<tr>
<td>6</td>
<td>Q_0</td>
<td>Q_1</td>
<td>8kV/m</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 8. (a) Induced electric charge versus number of vane openings. (b) Induced current versus number of vane openings.

Fig. 8(a) shows that the induced electric charge \( Q_1 \) and \( \Delta Q \) decreases as the number of vane increases. Fig. 8(b) shows that the maximum induced current is obtained when the number of opening electrodes reaches six. This occurs because the edge effect impacts the electric field distributions on the sensing electrode. The increase in the number of openings results in the increase of the edge effect, which decreases the electric field intensity on the uncovered sensing electrode and decreases the quantity of induced electric charge. Therefore, the sensitivity of the sensors will not necessarily increase with increased number of openings.

C. Preliminary design on the gap distance between the sensing electrode and rotor

The analytic model won’t be able to examine the effects of the gap distance between the sensing electrode and rotor (d) for the electric field mill sensor. The numerical simulation is employed to quantitatively analyze the effect of the gap on the induced current. Subsequently, the vane opening number is fixed to eight, and the gap is varied from 2.0 to 6.0 mm. The average value \( I_{ave} \) and induced current under various gaps are calculated as shown in Fig. 9.

Fig. 9(a) shows that as the gap distance increases, the induced electric charge \( Q_1 \) decreases, and the change quantity of induced electric charge \( \Delta Q \) decreases. Fig. 9(b) shows that the average induced current decreases as the gap distance increases. The electric filed distributions between the rotor and sensing electrode is shown in Fig. 9(c) with different gap distances. This supports that the edge effect of an electric field is affected by the gap distance. As such, the gap should be as small as possible to improve the sensitivity. In practice, placing sensing electrodes close to the rotor can cause collisions and increase the difficulty in the assembly process. Two sensors with the gaps of 3.6 mm and 4.7 mm have been fabricated and tested. The differences in sensitivity between the testing and numerical simulation results are 8.5% and 7.1% respectively as shown in Fig. 9(d).

IV. PROTOTYPE FABRICATION

Based on the analyses, the prototype system is designed to have eight vane openings with the internal and external diameters of the vanes as 10 and 30 mm, respectively. The gap is set as 3 mm and the radius of the sensor shell body is set as 40 mm. The sensor height is 90 mm and the shell body is made of aluminum with nickel plating to avoid the accumulation of ion flow under a HVDC transmission line. Fig. 10 shows the general structure and field mill prototype.

![Diagram](image)

Fig. 10. The schematic (left) and fabricated prototype field mill sensor (right).

The DC motor is enclosed in the upper part of the field mill sensor and connected together with the earthed rotor through the motor shaft. The sensor electrode is periodically exposed to the DC field by the earthed rotor and the speed of the motor is measured by a photoelectric sensor as the feedback signal to control the speed of the motor as well as being the synchronous control signal for phase sensitive detection. A printed circuit board is placed in the lower part of the field mill sensor to avoid noise. A high-performance microcontroller is used to acquire
real-time speed signals and compare this it a given value to achieve a constant rotation speed for the DC motor. The signal conditioning circuitry is composed of a charge amplifier, a band pass filter that provides phase-sensitive detection, and a low pass filter to convert field-induced charge to voltage. A schematic illustration and image of the signal conditioning part are illustrated in Fig. 11.

The majority of the current field mill sensors are not waterproof and a special mechanical structure is designed in this project for the waterproofing function. Specifically, the upper part of the sensor is comprised of the sensing electrode, the grounded rotor, DC motor, and a photoelectric sensor. Drainage holes are designed on the top side of the upper part of the sensor to allow the drainage of rainwater. The printed circuit board is installed in the lower internal part and a rubber gasket is mounted between the upper and lower part to prevent the water entry.

The electric field sensor is connected with a customized wireless node which can acquire and process the analog signals from the electric field sensors and send the digital sensing data to the remote sink node which is connected with a PC located at the measurement room. The wireless communication unit embedded in the wireless node is the 2.4 GHz Xbee Pro Radio Frequency (RF) module based on the IEEE 802.15.4 protocol from Digi™ (Minnetonka, MN, USA). The mesh networking protocol is applied in the wireless sensor network to address the complex operating conditions with a long wireless transmitting distance (>100 meters) under power transmission lines.

V. EXPERIMENTAL RESULTS
A. Comparison with Numerical Simulation Results
The induced current versus time results by the numerical simulations (blue dashed line), the analytic method (yellow solid line) and the measurements (red line) are shown in Fig. 12. The measurement results are collected from the output of prototype field mill sensor with the motor running at 3000 rpm. It is found that the results from the numerical method are in close agreement with the experimental results.

![Fig. 11. Schematic illustration (top) and an optical photo (bottom) of the signal conditioning parts for the field mill.](image1)

![Fig. 12. Comparisons between the analytic method (yellow solid line), numerical method (blue dashed line), and measurement results (red line).](image2)

![Fig. 13. Setup used for the calibration system of a field mill.](image3)

![Fig. 14. Calibration results for 4 field mill sensors.](image4)

B. Sensor calibration
A calibration apparatus (Fig. 13) is setup according to the IEEE 1227™-1990 (R2010) standard composed of two 1 × 1 m² aluminum plates and the distance between the top plate and bottom plate is 0.5 m. The power supply provides an adjustable DC voltage from −50 kV to +50 kV to the plates to generate a uniform field of known magnitude and direction and the field
mill sensors are placed at the center of the bottom plate.

Four electric field sensors were calibrated with results shown in Fig. 14. It is observed that this calibration system can generate a standard electric field of $-60 \text{kV/m}$ to $+60 \text{kV/m}$, and the linearity of the electric field strength of the sensors are better than 1%. The sensitivity of the four calibrated sensors were different and details are also shown in Fig. 14. The differences are mainly caused by the variations in the mechanical structure introduced during the fabrication and assembly processes. The accuracy of the prototype electric field sensor is 2.4%, which is better than the commercial field mill sensor [35].

C. Relationship between sensor sensitivity and the electrode/rotor gap

![Fig. 15. Relationship between sensor sensitivity and the gap between the sensing electrode and rotor. (a) 65 fabricated field mill sensors to be calibrated; (b) Quantile-quantile plot of the slope ratio versus the standard normal quantile for the tested sensors. If data were perfectly Gaussian, they would match the solid red line. (c) Histogram bar chart of the slope ratio for the sensors. (d) Linear regression analysis result for the relationship between the slope ratio and gap distance.](image)

Sixty-five fabricated field mill sensors as shown in Fig. 15(a) were fabricated and characterized. The distribution of the slope ratio which is defined as one divided by sensitivity is compared to the Gaussian distribution in a quantile-quantile plot in Fig. 15(b) with good matches. The mean value of the slope ratio is 55.46 with the standard variance of 6.68 within the range of $(42.35, 68.56)$ with a probability of 95% as shown in Fig. 15 (c). Using the regression analysis method with the gap as the independent variable and the slope ratio as dependent variable, the correlation coefficient ($R = 0.818$) can be obtained, which indicates a strong linear correlation between the two variables. Fig. 15(d) shows that as the gap increases from 2.5 mm to 3.5 mm, the slope ratio of the sensor increases from 43 to 66 with the rate of change of 53%. According to the numerical simulation model in Fig. 9 (b), when the gap increases from 2.5 mm to 3.5 mm, the sensor induced current decreases from 26.5 nA to 18 nA and the rate of change is 47.2%, which agrees relatively well with experiments.

D. HVDC electric field measurement

To validate the proposed field mill sensors, 4 bundles of 100m-long experimental double transmission lines with 40 cm in spacing, were erected with the model number of LJG-95/20. The minimum distance to the ground plane is 7 meters and the separation distance between the positive pole and the negative pole is 6 meters. The electric field under the test lines was measured at 17 different points by the field mill sensors as shown in Fig. 16. The origin of the measurement coordinate was set at the central ground position of the positive pole and negative pole. The field mill sensors were arranged along a direction perpendicular to the transmission lines with a distance from the origin at $-12 \text{m}$, $-10 \text{m}$, $-8 \text{m}$, $-7 \text{m}$, $-6 \text{m}$, $-5 \text{m}$, $-4 \text{m}$, $-3 \text{m}$, $0 \text{m}$, $3 \text{m}$, $4 \text{m}$, $5 \text{m}$, $6 \text{m}$, $7 \text{m}$, $8 \text{m}$, $10 \text{m}$, and $12 \text{m}$. The voltage applied to the positive pole was 220 kV and the corresponding voltage applied to the negative pole was $-220 \text{kV}$ respectively. Meteorological conditions are also an important element that influences measurement results. The measurement results were collected on a clear day with wind speeds lower than 1.2 m/s and temperature of $19^\circ \text{C}$~$25^\circ \text{C}$ and relative humidity of 47%~73%. Fig. 17 shows one set of the measured values (240 minutes) and calculation results using FTM (flux tracing method) [36].

![Fig. 16. Electric field measurements at the HVDC test base.](image)

![Fig. 17. Results of the ground-level electric field for the bipolar ±220 kV test line.](image)

It is found that experimental data on the ground-level electric field profile show reasonable agreement with calculations for a 220 kV bipolar DC test line configuration. Furthermore, the complexity of corona effects on conductor surface as well as
ambient atmospheric variables (transversal wind, relative humidity etc.) [6], [37] all have influences on the electric field profile. The position of the peak electric field under the test line, which may be at between 2-5 meters (or negative 2-5 meters) away from the central ground location of the line will depend on various conditions to be fixed.

The comparison test between the commercial sensor EFM-100 [38] and the prototype electric field sensor for the bipolar ±350 kV test line was conducted. The statistical analysis was carried out on the long-term test data with the mean value, μ, and the standard deviation, σ, of the ground-level electric field as shown in Fig. 18. Both sensors have nearly the same results. However, the prototype sensor is small in size and is specially designed for the ground-level electric field under HVDC power transmission lines with low power consumption, water-proof function, and the wireless communication capability.

![Graph showing comparison between proposed field mill sensor and commercial electric field sensor](image)

**Fig. 18.** Comparison between proposed field mill sensor and a commercial electric field sensor for the bipolar ±350 kV test line.

VI. CONCLUSION

This paper has developed a numerical model for the field mill sensor based on the finite element method for optimal parameters. Compared with the traditional analytic model used for the field mill sensor, the numerical model matches better with the measurements results. The optimum quantity of vane and gap between the rotor and sensing electrode have been obtained based on the prototype design parameters. The field mill sensor was designed, calibrated and successfully tested at the national high-voltage test base.

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REFERENCES AND FOOTNOTES


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