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Output Voltage Characteristics of HVDC Electric Field Mill Sensor for Different Speed Variables of Rotating Electrode

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Abstract – This paper explains the effects of the weak signal of a rotating-type electric field mill sensor fabricated for measuring the intensity of the electric field generated by high-voltage direct current (HVDC) power transmission lines. The fabricated field mill consists of two isolated electrode vanes, a motor driver, and a ground part. The sensor plate is exposed to and shielded from the electric field by means of a rotary shutter consisting of a motor-driven mechanically complementary rotor/stator pair. When the uncharged sensor plate is exposed to an electric field, it becomes charged. The rotating electrode consists of several conductive vanes and is connected to the ground part, so that it is shielded. Determining the appropriate design variables such as the speed of the vane, its shape, and the distance between the two electrodes, is essential for ensuring optimal performance. By varying the speed, the weak signal characteristics which is used to signal processing and calibration experiment are quite different. Each weak signal pattern was analyzed along with the output voltage characteristics, in order to be able to determine the intensity of the electric field generated by HVDC power transmission lines with accuracy.

Keywords: Field mill, HVDC, Rotating electrode, Power transmission line, Signal processing

1. Introduction

In recent times, with the increasing localization of power conversion equipment, the economics of direct current (DC) transmission lines and the characteristics of power system operations have come to play an important part. It is expected that high-voltage direct current (HVDC) power lines will be developed and constructed in the near future. However, because techniques for electric field strength measurement and electric field analysis are still in the rudimentary state in South Korea, commercialized measurement equipment needs to be imported from abroad [1]. Therefore, in order to develop new methods for measuring the electric field strength, such as the technology for sensing the ion flow related to HVDC and the linkage of the electric flux lines, prior basic investigations are necessary. In South Korea, high-voltage AC and electric field strength measurement techniques have seen significant developments. However, those for HVDC measurements remain in the research stage. In order to study HVDC systems, the Korea Electric Power Research Institute (KEPCO) has developed a field test site for ±500 kV DC transmission lines as well as an ion flow analysis program. Similarly, Japan has a 168-km-long 250 kV DC line that extends from Hokkaido to Honshu while USA operates DC lines of ±600 to ±1200 kV. Further, Russia developed a ±400 kV DC line as early as 1962.

High voltage is used for the transmission of electric power, in order to reduce the energy loss because of the resistance of the cables. For a given amount of power, a voltage twice high will deliver the same power at half the current. The power heat loss of the wires is proportional to the square of the current for a conductor of a given size but does not depend on the voltage. The power loss during transmission can also be reduced by increasing the conductor size; however, larger conductors are more expensive and heavier [2-4].

An electric field mill is a specialized device used for measuring the intensity of the electrical field in the atmosphere near thunderstorm clouds. Field mills are used for determining the launch criteria for orbit-bound rockets, in order to avoid lightning strikes, and were also used with the now-retired Space Shuttle. In addition, they are also used in outdoor laboratories for lightning protection equipment, in order to determine favorable experimental conditions [5-7].

In this study, a rotating-type electric field mill was developed for measuring the strength of DC electric fields, and its output characteristics were analyzed by interpreting the weak signal using a sensor.

2. Implementation

2.1 Mechanism for obtaining alternative signal

Fig. 1 shows a schematic of the rotating-type electric field mill developed for measuring the strength of DC

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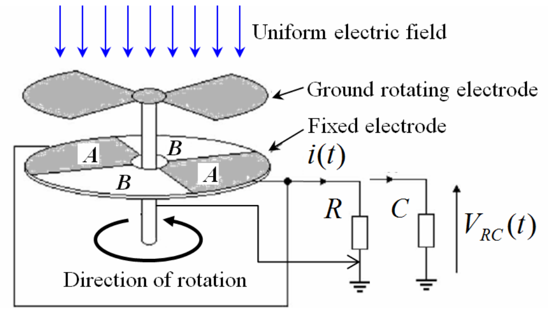


Fig. 1. Concept of rotating-electrode-type electric field mill

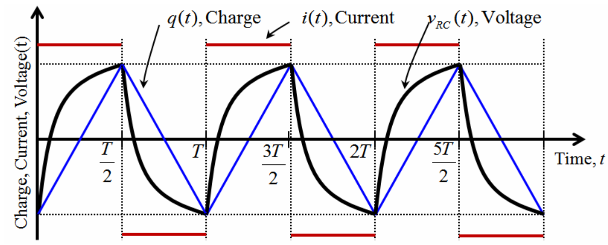


Fig. 2. Relationship between charge, current, and voltage in case of parallel connection between resistor and capacitor

electric fields. When the rotating electrode rotates evenly in a uniform electric field, the charge that accumulates in the fixed electrode can be calculated by Gauss's law, as shown in (1).

$$q = \int_A \int_t \varepsilon_0 \, \mathbf{E} \cdot d\mathbf{A} = \varepsilon_0 \, EA \qquad (1)$$

where ε_0 is the permittivity of air, **E** is the electric field intensity, and **A** is the surface area of the fixed electrode. The temporal variation in the charge gives the current, and the instantaneous voltage induced across impedance can be determined as shown in (2). Z is the magnitude of the impedance due to the parallel connection of the resistor and capacitor.

$$v(t) = Z\frac{dq(t)}{dt} = \frac{\varepsilon_0 \, EA\omega}{2} Z \cos \omega t \qquad (2)$$

The maximum instantaneous voltage can be calculated from (3) and (4).

$$v_{\max} = \frac{\varepsilon_0 \, E \, A \, \omega \, R}{2}, \ \text{if } (\omega RC)^2 << 1 \qquad (3)$$

$$v_{\max} = \frac{\varepsilon_0 \, E \, A}{2C}, \ \text{if } (\omega RC)^2 >> 1 \qquad (4)$$

If the impedance value is too large, the electric field strength will not be a function of the frequency. Therefore, the electric field intensity can be calculated from the output voltage. In this study, a capacitor of 100 nF and a resistance of 10 MΩ were used. Fig. 2 shows the relationships between the charge, current, and voltage for the case where the resistor and capacitor are connected in parallel.

2.2 Field mill sensor unit

Fig. 3 shows the shapes and dimensions of the fixed and ground electrodes designed in this study. The rotating electrode is directly connected to the ground while the fixed electrode is connected to the ground through a load. Each electrode has six vanes, which were manufactured

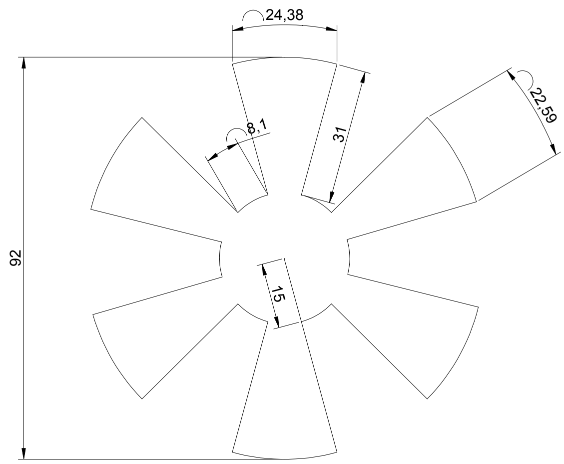
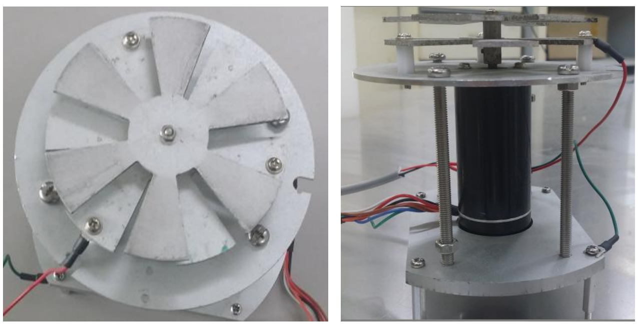


Fig. 3. Dimensions of rotating and fixed electrodes with 6 vanes (unit: *mm*)



(a) (b)

Fig. 4. (a) Top view and (b) side view of fabricated electric field mill

using a single conductor, in order to ensure they are equi-potential.

The electrodes were made of a light aluminum material having high corrosion resistance and processability. The electrodes were placed in a housing, in order to protect them from foreign substances and rain. Fig. 4 shows the top and side views of the fabricated electric field mill.

2.3 Signal processing unit

When the charge trapped at the fixed electrode is transferred to the ground, a weak alternating signal is generated. Because the electric field should be constant, the alternating signal is amplified, filtered, differentiated, and integrated. In order to analyze the weak signal from the and the corresponding printed circuit board (PCB) was

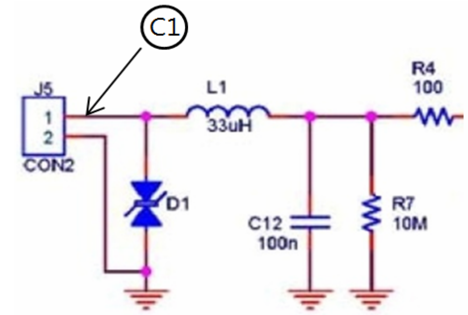


Fig. 5. Circuit of resistor and capacitor connected in parallel to fixed electrode of electric field mill

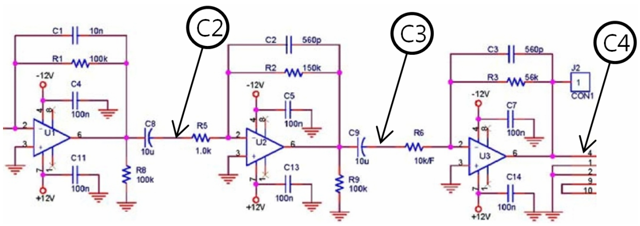


Fig. 6. Circuit for processing of alternating signal (amplifier and differentiator) and terminals for checking signal.

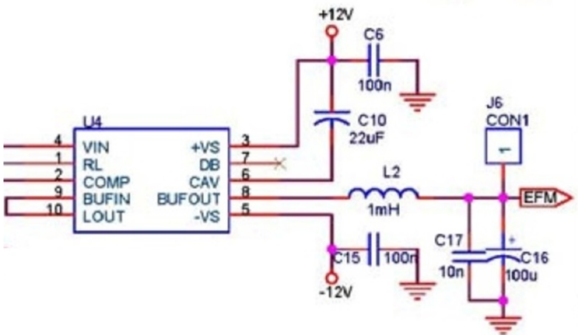


Fig. 7. Circuit for converting alternating signal into rms DC value

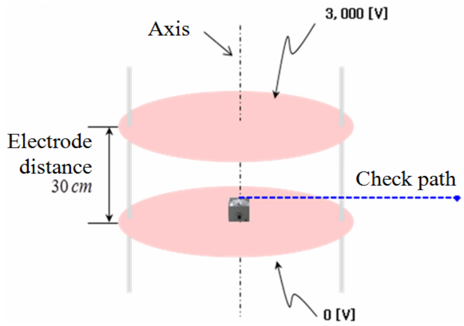
Fig. 8. PCB fabricated for signal processing

fabricated. Fig. 5 shows the circuit design for the parallel connection of the resistor and capacitor. Thus, as stated above, the weak alternating signal was amplified, filtered, differentiated, and integrated and was eventually measured in the form of a DC voltage. Fig. 6 shows the integrator circuit used for amplifying the weak alternating signal. The effective value of the amplified alternating signal was obtained using the circuit shown in Fig. 7, while the PCB fabricated for signal processing is shown in Fig. 8.

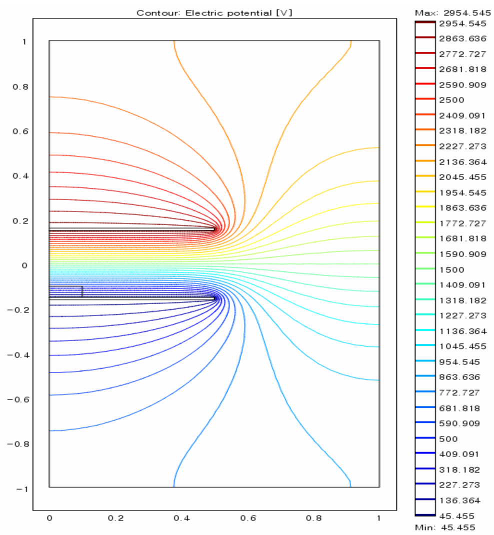
3. Experiment

In order to calibrate and verify the feasibility of the electric field mill, parallel electrodes were fabricated, and the sensor was tested experimentally. The plate electrodes were axisymmetric, so that a uniform electric field was produced between the plates.

The effective size of the plate electrodes was calculated based on an electromagnetic field analysis. For a diameter of 0.1 m of the rotating electrode of the electric field mill,



(a)



(b)

Fig. 9. (a) Axisymmetric model used for electric field analysis and (b) equip-potential lines of parallel-plate electrode

the minimum equi-potential field area of the flat electrodes would have to be thrice the diameter of the rotating electrode, in order to be ensure results regardless of the position or movement of the electrodes. Therefore, radius corresponding to the equi-potential field area of the flat electrode was set at 0.3 m.

A 3D axisymmetric electrostatic model was used to simulate the field mill and verify the obtained results. The basic equations used for the finite element analysis were as follows:

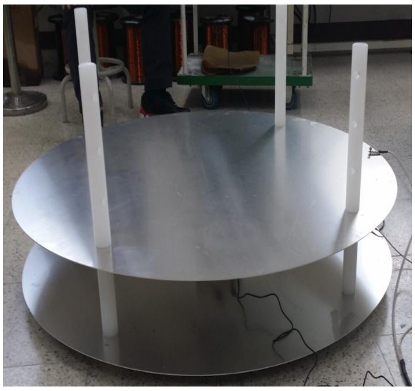
$$\mathbf{E} = E_r\mathbf{a_r} + E_z\mathbf{a_z} \ , \ \ \partial V / \partial\varphi = 0 \tag{5}$$

$$\nabla^2 V = -\rho_v / \varepsilon_0 \tag{6}$$

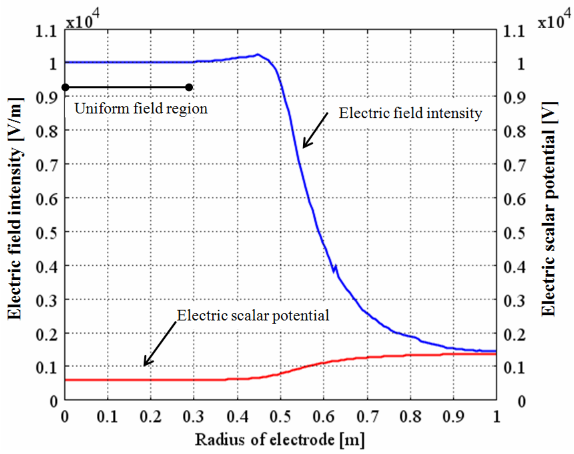
where E_r is the radial component and E_z is the axial direction component of the electric field.

Fig. 9 shows the distribution of the equi-potential line and the electric field intensity as determined by the electro-magnetic analysis. It was found that a uniform electric field was formed in the central area while a non uniform electric field was found at the edges. This was because the electric flux lines were concentrated locally at the edges owing to the fringing effect.

As shown in Fig. 10, when a voltage of 3000 V was applied to the flat electrodes with a radius of 0.5 m and interelectrode distance of 0.3 m, an equi-potential area was formed in the area corresponding to a radius 0.3 m from the center. The model yielded an equi-potential area with a diameter of 0.6 m and therefore was considered suitable for experimental validation. If the electrode distance were to be larger than that of the present electrodes, an even



(a)



(b)

Fig. 10. (a) Fabricated parallel electrodes used for verification and (b) electric scalar potential and electric field intensity along check path between the two electrodes

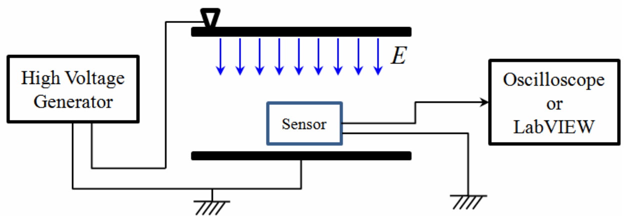
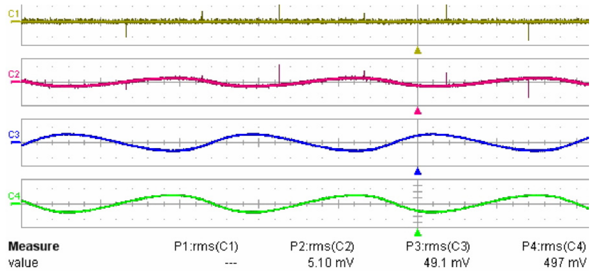
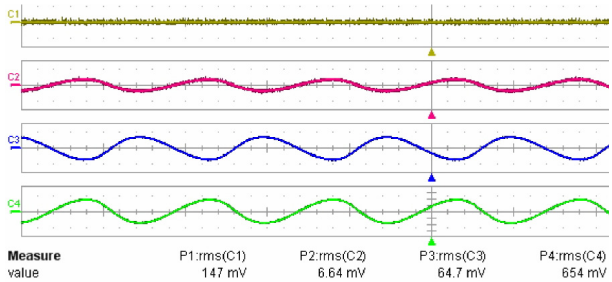


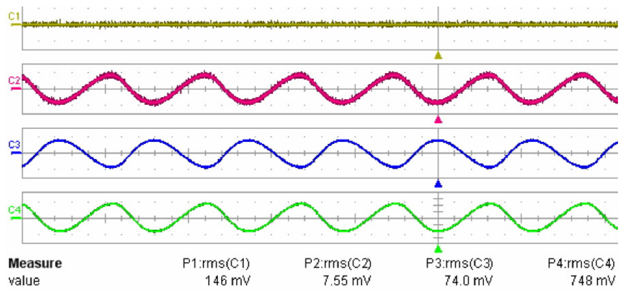
Fig. 11. Setup used for characterization of electric field mill



(a) Speed: 850 rpm



(b) Speed: 1300 rpm



(c) Speed: 1750 rpm

Fig. 12. Waveforms corresponding to each signal processing step for different rotational speeds of rotating electrode

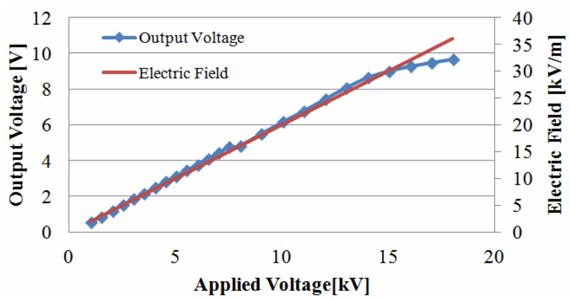
larger equip-potential area would form, owing to a stronger fringing effect. The distance between the plate electrodes, which were made of aluminum, was maintained by an insulating epoxy supporter.

Fig. 11 shows a diagram of the setup used for characterizing the electric field mill while evaluating the plate electrodes. The output voltage characteristics were measured using an oscilloscope based on the changes in the high voltage; the changes were in the range of tens of kilovolts, owing to the use of high-voltage equipment. Furthermore, the output characteristics were tested for various distances between the plate electrodes and rotational speeds of the electric field mill.

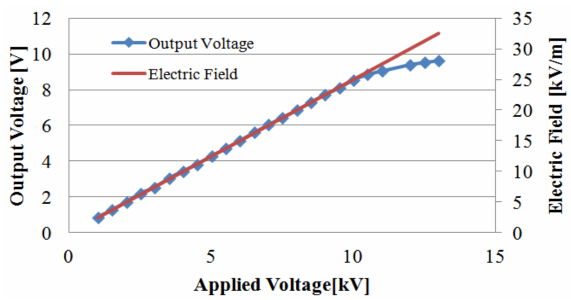
4. Results

Figs. 5 and 6 show the signal processing performed after the measurement of the voltage at terminals C1, C2, C3, and C4, while Fig. 12 shows the output characteristics at each terminal for different speeds of the rotating electrode. It can be seen that the initial weak signal changes to a sine wave.

Finally, the output characteristics of the field mill were investigated by converting the sine wave into the effective rms DC value. Fig. 13 shows the intensity of the electric field and the output voltage for different electrode distances. The output voltage is linear for a field strength of 25 kV/m. Therefore, the value of the electric field could be deduced from the output voltage. Fig. 14 shows the output voltage characteristics for different interelectrode distances for the electrodes used for verification. Finally, Fig. 15 shows the output DC voltage for different speeds of the rotating electrode.



(a) Distance: 0.5 m



(b) Distance: 0.4 m

Fig. 13. Output DC voltage characteristics of electric field mill and electric field intensity

5. Conclusion

This work describes the results of an analysis of the output voltage characteristics of an electric field mill sensor fabricated for measuring the intensity of the electric field generated by HVDC transmission lines. The fabricated field mill contained a signal processing unit, and the feasibility of the device was confirmed using test electrodes. The output voltage exhibited linear characteristics. Further,

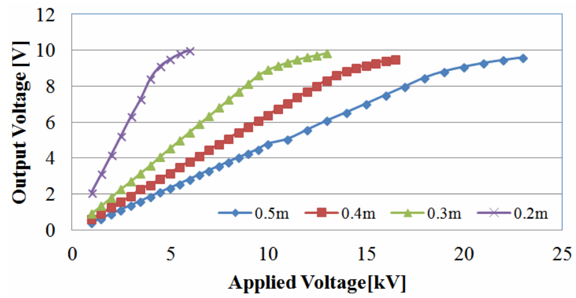
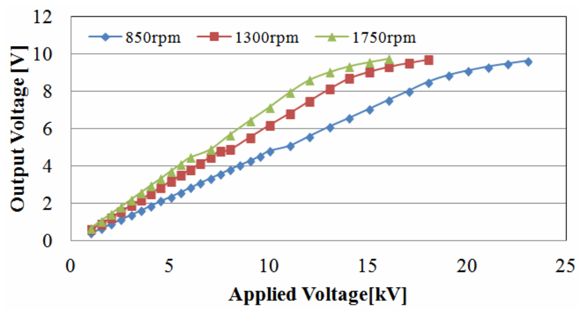
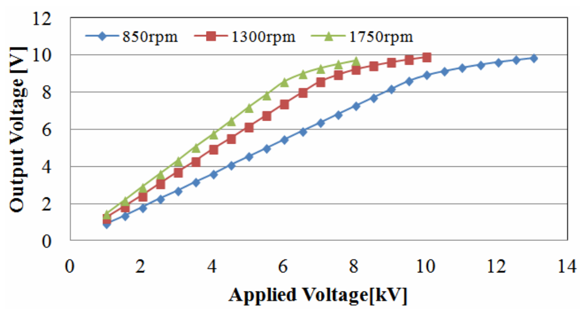


Fig. 14. Output DC voltage characteristics of electric field mill for different distances between electrodes used for validation (speed: 850 rpm)



(a) Distance: 0.5 m



(b) Distance: 0.3 m

Fig. 15. Output DC voltage for different speeds of the rotating electrode

the obtained results were reasonable, indicating that the device would be suitable for measuring HVDC electric fields. However, further studies are needed to accurately calibrate the mill and determine the proportionality constant for the output voltage and electric field intensity.

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