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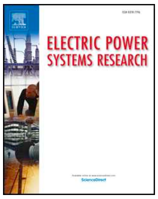

Measuring AC/DC hybrid electric field using an integrated optical electric field sensor

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ABSTRACT

Measuring the AC and DC hybrid electric field is significant for the electromagnetic environment evaluation and for the design of AC/DC hybrid transmission lines. In this paper, a measuring method for both DC and AC electric field measurement by the integrated optical electric field sensor was proposed. The DC electric field can be measured by rotating the sensor by a servomotor which modulates the DC signals into AC signals. A measuring system was implemented and calibrated. A field measurement under an AC/DC hybrid transmission line in Jeju Island, Korea was carried out, and the measured data of the electric field under different DC operating modes were obtained. The results obtained by the proposed method were in reasonably good agreement with a commercial AC probe and the computed DC electric field.

1. Introduction

Due to the increasing demand for power consumption and the scarcity of the power transmission line corridor area, hybrid lines, in which the corridor is shared by different power transmission lines, draw attentions in recent years [1]. We hereafter call the lines that a transmission tower is shared by both alternating current (AC) and direct current (DC) conductors, hybrid AC/DC lines.

To design and construct hybrid lines, the electric field below the lines is one of the most important factors because it is strictly restricted by the regulation [2]. On the other hand, the electric field under a hybrid AC/DC line cannot simply be regarded as a superposition of the electric field determined by the AC and DC lines, respectively, because the ion flow distribution under the DC lines will also be affected by the AC electric field, especially considering complex surroundings [1,3].

Different sensors have been used in the power system to measure the electric field [4–7], among which capacitive probes are widely adopted. However, there was not many literatures on the electric field measurement of the hybrid lines due to the lack of an effective method to measure both the AC and DC electric field by one sensor. Generally, a probe can only measure either an AC or DC electric field.

The field mill is mainly developed for the DC electric field measurement [8–10]. It consists of two coaxial discs called the shielding rotor and sensing plate, respectively. The shielding rotor is placed above the sensing plate and grounded directly, and the sensing plate is connected to the ground through a resistor. During the working process, the shielding rotor continuously rotates with a shaft, and the sensing plate is then alternately exposed to and shield from the DC electric field. Therefore, the DC field is modulated into an alternating one which induces alternating charges on the metallic plates. The charges generate an alternating current flowing from the sensing plate to the ground, which can be measured through the resistor; then the electric field is calculated from the measured current. Nevertheless, the metallic components in a field mill distort the field distribution locally, and limit the measuring accuracy. Moreover, the shielding rotor and sensing plate must be connected to the earth, which make the measurement configuration inconvenient in some applications.

To remove the large metal components in a field mill, the micro-machined electric field mills (MEFMs) were investigated [11–13]. Based on the micro-fabrication techniques, most MEFMs also employ a moving shutter to alternately expose and shield the sensing electrodes, and are able to measure the AC and DC electric field [11,12]. Many of MEFMs are aimed at applications of AC electric field or low field strength [12,13]. To measure the electric field of a high voltage DC transmission line, charged ions may accumulate at the surface of the MEFM chips. Owing to the small size of the shutter and chip, small amount of charges may generate a large electric field between the sensing electrodes, therefore the electric field distortion led by the charge needs to be solved.

Compared to the existing methods in the hybrid electric field measurement, the optical electric field sensor may be a competitor for its little distortion, good insulation, broad bandwidth, and fast response

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[7,14,15,18]. Considering the distinction of structures, those sensors can be divided into bulk optical sensors or integrated optical sensors. The bulk optical sensor has a configuration of common path interferometer, and has been used to measure the quasi-static electric field and space charge field [16,17]. The integrated optical electric field sensor (IOES) with a light waveguide fabricated on the substrate has been studied by many groups [6,7,14]. Typically, the operating bandwidth of the sensors is between several Hz and several hundred megahertz or even higher, and the dynamic range is from 0.1 kV/m to 1 MV/m. These characteristics are dependent on the electrode structures that are implemented on the waveguide, and can therefore be optimized by designing better electrode structures [28,29]. The sensors have been used for many applications, e.g., triggered or natural lightning observations [24,25,26], transient voltage measurements [27], air gap discharge research [30]. However, when the above mentioned optical sensor is exposed to a DC electric field, the sensor fails in measuring the electric field directly.

Inspired by the principle of field mills and taking advantage of optical sensors, we propose a new method to measure the hybrid electric field by one sensor [19]. By rotating the sensor using a servomotor, both AC and DC electric field can be measured using one sensor simultaneously. Both calibration experiments and a field measuring under a hybrid AC/DC transmission line in Jeju Island, Korea, were carried out, which demonstrate the effectiveness of the method. The measuring results offer a reference for the design of hybrid lines.

2. Measuring method

2.1. The measuring system based on IOES

The sensors used to measure the electric field are integrated optical electric field sensors based on the Pockels effect, whose structure is shown in Fig. 1 [21,22]. Note the direction of x, y and z axis in Fig. 1 is based on the crystal orientation of the $LiNbO_3$ crystal. A waveguide to transfer the light is fabricated on the $LiNbO_3$ wafer by the Ti-diffusion process. Two modes of light, namely, the transverse electric (TE)-like mode polarized in the y-direction and the transverse magnetic (TM)-like mode polarized in the x-direction, can propagate in the waveguide. Because of the Pockels effect, when an electric field applied on the sensor along the y-direction, the refractive index changes linearly to the electric field [22,23]:

$$\begin{aligned} n_1' &= n_0 + \frac{1}{2} n_0^3 \gamma_{22} E_2 \\ n_2' &= n_0 - \frac{1}{2} n_0^3 \gamma_{22} E_2 \end{aligned} \tag{1}$$

where n_1' represents the refractive index for TM-like mode and n_2' represents that for the TE-like mode. n_0 is the ordinary refractive index without the external electric field, γ_{22} is the electro-optic coefficient, and E_2 is the applied electric field along the y-direction. After the two modes of light in orthogonal polarized directions propagate a distance through the waveguide, a phase difference related to the applied electric field occurs [22,23]:

$$\varphi(E) = \frac{2\pi}{\lambda}\Delta n \cdot L = \frac{2\pi}{\lambda} n_0^3 \gamma_{22} E_2 L \tag{2}$$

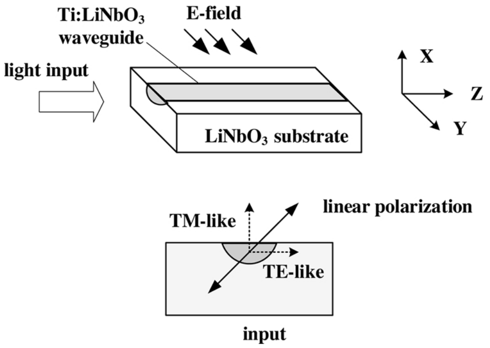

Fig. 1. Schematic diagram of the sensor (Note the direction of x, y and z axis is based on the crystal orientation of the $LiNbO_3$ crystal).

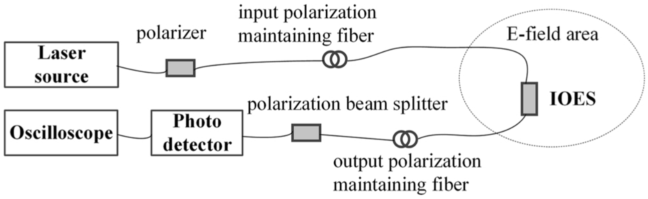

Fig. 2. Configuration of the measuring system (the IOES is an in-house product; all others are public commercial products, and are integrated together by the authors).

where λ is the wavelength of light and L is the effective length of the waveguide. Therefore, the electric field signal can be obtained by measuring the phase difference.

To use the IOES to measure the electric field, a measuring system shown in Fig. 2 is set up. Light emitted from a laser is polarized by a polarizer and enters the waveguide with a polarization angle of 45°. Thus, the light splits into two modes with the same intensity. When they leave the waveguide, the angle between the axis of $LiNbO_3$ crystal and polarization maintaining fiber is 45°. Interference of the two modes of light happens on the fast and slow axis of the fiber, respectively. The light intensity can be expressed as [23]:

$$\begin{aligned} P_1 &= \frac{P_{in}}{2}(1 + \cos(\varphi(E) + \varphi_0)) \\ P_2 &= \frac{P_{in}}{2}(1 - \cos(\varphi(E) + \varphi_0)) \end{aligned} \tag{3}$$

where φ(E) is already defined in Eq. (2) and φ_0 is the optical bias due to the natural birefringence. Subsequently, a polarization beam splitter is used to separate the light by the axis and one path is connected to the photodetector, the light intensity which can represent the electric field signal is converted into a voltage signal and can be captured by an oscilloscope. Combining Eqs. (2) and (3), the final response can be expressed as [22,23]:

$$V_{out} = A \cdot [1 + b\cos(kE + \varphi_0)] \tag{4}$$

where A reflects the photo-electric conversion coefficient and the transmission loss; b represents the extinction ratio; k reflects the sensitivity. When the applied field is much smaller than the half-wave electric field, and φ_0 is designed to be $\pi/2$, Eq. (4) reduces to a linear function according to Taylor's expansion (i.e., $\sin(x) \approx x$ when x is near zero):

$$V_{out} = A(1 + bkE) \tag{5}$$

2.2. Principle for DC electric field measurement

In a DC electric field, the electric field that the sensor detects has relation with the electric conductivity of the $LiNbO_3$ crystal and the package of the sensor. Although the $LiNbO_3$ is almost a kind of insulting material, the electric conductivity of the package of the sensor is much larger than that of air. So the voltage distributed on the sensor (as well as the electric field) decays for DC signals.

An experiment was carried out to qualitatively show this fact. A DC voltage was applied on parallel plate electrodes to provide a uniform electric field, and the sensor was placed between the electrodes to detect the DC electric field. As shown in Fig. 3, when the applied electric field (the red curve) jumps to 400 V/m, the sensor's output (the blue curve) follows and jumps to 178 mV, but when the electric field is kept constant (which can be considered as a DC electric field condition), the

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