Research and Design of Rotary Optical Electric Field Sensor

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Abstract. In order to solve the problem that traditional optical electric field sensors are susceptible to temperature, charge drift and other internal and external factors in the measurement of DC electric field and ultra-low frequency electric field, an optical electric field sensor with rotating structure is proposed. The mathematical model of the output signal of the sensor is theoretically analyzed and deduced, and the structural design scheme of the sensor is given, and the experimental verification is carried out. The simulation analysis and experimental verification results show that the rotating optical electric field sensor has good linearity, and can improve the measurement accuracy and stability of the sensor when measuring DC electric field and ultra-low frequency electric field.

1. Introduction

With the development of electric power production, the voltage level and transmission capacity of power system have been greatly improved. Electric field measurement has been widely used in condition monitoring of power transmission and transformation equipment, reasonable selection of electrical equipment, high voltage test and corona discharge research, electromagnetic environment analysis of high voltage system, etc. [1] [2]. The requirement for accuracy of measurement equipment is also increasing. Traditional electric field sensors cannot meet the requirements of modern power grid construction because of the reasons of sensing mechanism, so it is urgent to develop new electric field sensors. Optical electric field sensor based on optical fiber sensing technology has many advantages, such as small size, light weight, good insulation performance, strong anti-interference ability, large dynamic range of measurement, good frequency characteristics, fast response speed, direct connection of output digital quantity with computer, etc. It can overcome the inherent defects of traditional sensor, so it is practical in power system. Inter-measurement has broad application prospect [3-5].

At present, the working principle of the optical electric field sensor developed at home and abroad mainly includes Pockels effect, Kerr effect and inverse piezoelectric effect, among which the sensor based on Pockels effect has been widely studied [3]. Reference [6] proposes a reflective dual-optical-path sensor based on BTO crystal, which improves the linearity of power frequency voltage measurement and the transient voltage resolution. In reference [7], a sensor with dual transverse modulation structure is developed, which improves the measurement range and sensitivity of the sensor. In reference [8], a sensor using crystal splitting to measure electro-optic phase delay directly and linearly is designed, which improves the temperature characteristics of the system.
The above-mentioned research on optical electric field sensor mainly focuses on improving measurement accuracy and long-term operation stability, focusing on the selection of crystal materials, sensor structure design, measurement method research, temperature stability analysis and signal processing method improvement, etc. [3][9], but most of the methods are only applicable to AC electric field. Measurement. Based on the basic principle of optical electric field sensor with Pockels effect, a new type of sensor, rotary optical electric field sensor, is designed in this paper. The influence of charge drift and space charge in measurement of DC electric field and ultra-low frequency electric field is eliminated by rotating structure of sensor head. The input DC electric field signal is modulated to AC signal output, which reduces the interference of input light intensity fluctuation and temperature drift, so as to improve the measurement accuracy and stability of sensor. The practicality of the device in the power system lays the foundation.

2. Principle

2.1. Basic Principle of Rotary Optical Electric Field Sensor

The optical system configuration for a ROVS is shown in Fig. 1. After the light from the light source is collimated by the optical fiber collimator, it is changed into linear polarized light through the polarizer, and then into circularly polarized light through the $\frac{\lambda}{4}$ wave plate. The circularly polarized light can be regarded as the superposition of two linearly polarized light beams perpendicular to each other along the eigenaxis of the crystal. When they pass through an ideal electro-optic crystal, the refractive index of the two linearly polarized light beams and the phase difference delta produced when they propagate in the crystal are related to the applied electric field. Because the wave plate will delay the propagating polarized light by 90°, the phase difference of the linearly polarized light emitted from the crystal will change by a total of $\delta + 90°$. Because the phase difference delta is so small that it is difficult to measure directly, the polarized interferometry is used to convert the measured phase into the measured light intensity, and then the photoelectric detector is used to collect the signal and input it to the signal processing device.

![Fig 1. Optical system configuration for a ROVS](image)

When the DC electric field applied on the crystal rotates around the optical axis, the fast and slow axis of the crystal will rotate accordingly, and the refractive index and phase delay will change accordingly, so that the output of the sensor will change periodically with the rotation angle. The rotating structure can modulate the output of the sensor into an AC signal related to the rotating frequency of the DC electric field by introducing a rotating angle. Compared with the traditional sensor, it can reduce the influence of external disturbances such as light source fluctuation on the output of the sensor in the process of measuring the DC electric field and improve the stability of the sensor.

In addition, for the traditional optical sensor, when the crystal is under the action of DC electric field and ultra-low frequency electric field, the free carriers drift along the electric field line in the crystal, and the accumulated charge will generate an electric field opposite to the electric field to be measured inside the crystal, which will eventually lead to the unstable output signal of the sensor; if the measured electric field exists in the space. The free charge also accumulates on the surface of the
crystal, which affects the electric field distribution in the crystal [10][11]. The rotating structure can effectively eliminate the influence of charge drift and space charge on the sensor and improve the measurement accuracy.

2.2. Electro-optic Effect of Crystals in Rotating Optical Electric Field Sensors

Without electric field, BGO crystals are identical. The principal axis coordinate system (X, Y, Z) of BGO crystals is established. The photometric volume equation can be expressed as follows:

\[ \beta_0 (X^2 + Y^2 + Z^2) = 1 \]  

(1)

In the formula, \( \beta_0 = 1/(n_0^2) \) is the inverse dielectric tensor. \( n_0 \) is the basic refractive index of crystal. Under the action of external electric field, the crystal becomes anisotropic, the refractive index ellipsoid changes from a sphere to a triaxial ellipsoid, and its principal axis direction no longer coincides with the original coordinate axis [12]. In order to obtain the intrinsic polarization state and refractive index easily, a new coordinate system (\( \alpha, \beta, \gamma \)) is constructed. The transformation relationship between the coordinate system and the principal axis coordinate system (X, Y, Z) of crystal is shown in Fig. 2 (a).

![Fig 2. The relationship between different axis](image)

Through coordinate transformation, the equation of the photometer in the new coordinate system (\( \alpha, \beta, \gamma \)) is obtained as follows:

\[ \frac{\alpha^2}{(n_0^2)} + \left[ \frac{1}{(n_0^2)} + \gamma_{41}E_\alpha \right] \beta^2 + \left[ \frac{1}{(n_0^2)} - \gamma_{41}E_\alpha \right] \gamma^2 + 2\gamma_{41}E_\beta \alpha \beta - 2\gamma_{41}E_\gamma \alpha \gamma = 1 \]

(2)

In the formula, \( \gamma_{41} \) is the electro-optic effect coefficient, and \( E_\alpha, E_\beta, E_\gamma \) are the components of the electric field along the direction of \( \alpha, \beta, \gamma \) respectively.

If the direction of the applied electric field \( E \) rotates in the plane \( \alpha \Omega \beta \) and the angle between the applied electric field \( E \) and the \( \alpha \) axis is \( \theta \), then there are \( E\alpha = E\cos \theta \) and \( E\beta = E\sin \theta \). If the light direction is along the \( \gamma \) axis, the vibration direction of the eigenpolarized light lies in the \( \alpha \Omega \beta \) plane, and its elliptic equation is as follows:

\[ a\alpha^2 + b\beta^2 + 2c\alpha\beta = 1 \]

(3)
In the formula, \( a = \frac{1}{n_0^2} \), \( b = \frac{1}{n_0^2} + \gamma_{41} E_\alpha \), \( c = \gamma_{41} E_\beta \).

Formula (3) shows that the rotation of the electrodes will change the direction of the electric field applied to the crystal, resulting in the rotation of the principal axis of the ellipse around the coordinate origin. The long and short half-axis lengths of the ellipse are the refractive index of the intrinsically polarized light, respectively. Therefore, the coordinate system \((\alpha, \beta, \gamma)\) is changed into \((\alpha', \beta', \gamma')\) by the coordinate transformation shown in Fig. 2 (b), so that the elliptic equation represented by equation (3) is transformed into a standard form in order to obtain the refractive index. Since \(\gamma_{41}\) is very small, the approximate calculation [13]:

\[
a + b >> c, a + b \approx 2/n^2
\]  

(4)

The refractive index of the obtained crystal is:

\[
n_{1,2} = \frac{2}{\sqrt{a+b}} \left[ 1 \pm \sqrt{(a-b)^2 + 4c^2} \right] / 2(a+b)
\]  

(5)

The angle between axis \(\alpha'\) and \(\alpha\) is \(\varphi\):

\[
\tan \varphi = \frac{b-a + \sqrt{(b-a)^2 + 4c^2}}{2c}
\]  

(6)

If the length of the direction of light passing through the crystal is \(l\) and the wavelength is \(\lambda\), the phase difference of the emitted beam is \(\delta\):

\[
\delta = \frac{2\pi}{\lambda} l(n_1-n_2)
\]  

(7)

2.3. Mathematical Model of Rotary Optical Electric Field Sensor

As can be seen from reference [14] [15], the Jones matrix of crystal in rotary optical electric field sensor is

\[
J_c = \cos \frac{\delta}{2} \begin{bmatrix}
1 - i \tan \frac{\delta}{2} \cos 2\varphi & -i \tan \frac{\delta}{2} \sin 2\varphi \\
-i \tan \frac{\delta}{2} \sin 2\varphi & 1 + i \tan \frac{\delta}{2} \cos 2\varphi
\end{bmatrix}
\]  

(8)

The Jones matrix of polarizer, \(\lambda/4\) wave plate and polarizer is combined, and the intensity of light emitted from polarizer is obtained as follows:

\[
I_o = \frac{I}{2} (1 + \sin 2\varphi \cdot \sin \delta)
\]  

(9)

It can be seen from the formula that the rotating optical electric field sensor can modulate the DC signal to AC signal. The modulation \(S\) can be obtained by separating AC and DC components through signal processing program [16].
Formula (10) shows that the modulation has a sinusoidal relationship with the rotation angle, but has nothing to do with the input light intensity.

For the traditional optical electric field sensor, when measuring DC electric field or ultra-low frequency electric field, the output light intensity of the sensor is as follows:

$$I_o/I_i = \frac{1}{2} \left[ 1 + \left(\frac{2\pi}{\lambda}\right) n^3_0 \gamma_{41} E \right]$$

(11)

According to formula (11), the output light intensity of the traditional sensor is proportional to the input light intensity, and the output signal is greatly affected by the input light intensity and other external interference factors. Compared with the traditional sensors, the rotating optical electric field sensor uses a rotating structure, which makes the output waveform change from DC to sinusoidal waveform, and is less affected by interference factors, thus improving the stability of the sensor. The modulation can be obtained by signal processing program, which can effectively eliminate DC current. The influence of input light intensity fluctuation on sensor output in the process of field or ultra-low frequency electric field measurement can improve the accuracy of electric field measurement.

3. Experimental verification and performance analysis

3.1. Experimental Platform of Rotary Optical Electric Field Sensor

The experimental platform is built according to the schematic diagram of the experimental device of the rotary optical electric field sensor shown in Figure 3.

**Fig 3.** Experimental structure of rotary optical electric field sensor

In the experiment, acrylic cylinder is used as the rotating part. Bearings are mounted on both sides of the acrylic cylinder and fixed on the bearing seat so that it can rotate freely around the central axis. Two rectangular iron sheets are symmetrically arranged on the inner wall of the cylinder as electrodes. One end of the wire is connected to the electrode, and the other end is drawn to the DC power supply through the conductive sliding ring. Manually rotating acrylic cylinder or using DC speed regulator to drive cylinder through belt can form uniform electric field rotating 360° around the rotating axis. The BGO crystal is fixed on the pillar and extended into the cylinder, so that the crystal is located in the middle of the bipolar plate. The polarizer, wave plate and polarizer are placed according to figure 3.

In this experiment, Thorlabs laser diode with tail fiber is used as the light source, the model is LP852-SF30, and the central wavelength is 846.3 nm. BGO crystal with size of 5 mm × 5 mm × 10 mm is selected as the sensing material, in which the direction of light transmission is 10 mm, and the distance
between the two electrodes is set to 50mm. During the experiment, the theoretical value of electric field is 8×10^4 V/m when a 4kV DC voltage is applied to one plate and the other plate is grounded.

3.2. Manual Rotating Pole Plate Method

When measuring electric field by manual rotating plate method, the dial should be fixed at one end of the acrylic cylinder and calibrated in the direction shown in Fig. 1. Then the cylinder should be rotated to measure and record the rotating angle and the output voltage of the corresponding sensor at intervals of 10 degrees. The relationship between the output voltage of the sensor and the rotation angle of the electrode can be obtained by rotating the plate one week as shown in Fig. 4.

![Fig 4. Relationship between output and rotary angle of sensor](image)

From Fig. 4, it can be seen that the output voltage of the sensor contains DC and AC components in the process of changing the electric field direction around the optical axis by manually rotating the electrode plate. The obtained modulation is sinusoidal with the rotation angle of the electric field, which is consistent with the theoretical analysis.

3.3. Mechanical transmission mode

When DC speed regulator drives acrylic cylinder to rotate by conveying belt, the output signal frequency of the sensor is proportional to the rotation frequency of the motor. When the rotation speed of the plate is 10r/s, the output of the sensor is shown in Figure 5.

![Fig 5. Output waveform of sensor](image)

As can be seen from the figure above, the output voltage waveform of the sensor includes DC component, AC component and noise. The noise is filtered by the extended Kalman filter method, and the results are processed by the principle shown in formula (10). The waveforms of DC and AC components can be obtained as shown in Figure 6.
From Fig. 6, it can be seen that the DC component of the output voltage is 0.5, the AC component is about 0.03, and the frequency is 10 Hz. The theoretical analysis and simulation results shown in Fig. 7 are basically consistent. The experimental platform meets the requirements and provides a basis for the development of the final product of the rotary optical electric field sensor.

3.4. Linearity Test

By changing the applied voltage on the electrode plate and measuring it by mechanical transmission, the magnitude of the output AC component of the sensor under different applied electric fields is obtained in turn, as shown in Fig. 7.

From Fig. 7, it can be seen that the amplitude of AC component measured by the sensor has a good linear relationship with the applied voltage of the polar plate, and can be used to measure the electric field. However, the actual measurement results are slightly deviated from the standard values, which indicates that the accuracy of the experimental system may be affected by factors such as the deviation of rotation angle, vibration and so on. The experimental platform can be used to measure DC electric field.

4. Conclusion

The general mathematical model of rotary optical electric field sensor is deduced theoretically. The advantages of rotary optical electric field sensor in measuring DC electric field and ultra-low frequency electric field are obtained. The charge drift and space charge can be effectively eliminated by using rotary structure. At the same time, the input DC voltage signal can be modulated into AC to reduce the light source. The influence of fluctuation, temperature drift and other disturbances on the sensor can improve the measurement accuracy and stability of the sensor.

The simulation analysis and experimental results show that when the electric field direction rotates around the optical axis, the fast and slow axis of the crystal rotates along with it, and the phase delay and the output of the sensor vary periodically with the rotation angle of the electrode. The rotating
optical electric field sensor has good linearity in measuring the electric field. The experimental platform lays a foundation for the subsequent physical design of rotary optical electric field sensor.

In this paper, the rotating electric field is used to make the electric field direction rotate relative to the sensor unit to verify the feasibility of the rotating optical electric field sensor. But in practical measurement, it is difficult to ensure the reliable rotation of electric field, so the method of rotating electro-optic crystal is needed. The idea is as follows: the polarizer, λ/4 wave plate, BGO crystal and polarizer are integrated into the insulated sensor head housing, and the uninterrupted transmission of light between the rotating sensor head and the stationary light source and photoelectric detector is realized through the optical fiber sliding ring. Bearings are installed on both sides of the sensor head and fixed on the bearing seat, and then micro-electronics is used. The machine drives the sensor head to rotate. The object of rotary optical electric field sensor needs further study.

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