Simulation and Research of Light Path Optical Wave Field of Optical Voltage Sensor Based on Pockels Effect

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Abstract. This paper introduces the development status of optical voltage sensor based on Pockels effect at home and abroad. A research scheme of optical voltage sensor with optical path reciprocity is proposed and its reciprocity mechanism is expounded. Comsol Multiphysics, a multi-physical field coupling simulation software, is used to simulate the fluctuation of the transmission of incident polarized light in the electro-optic crystal, thus realizing the three-dimensional fluctuation simulation of the light wave field, which provides a new research idea and theoretical reference for analyzing and designing the optical path component unit of the optical voltage sensor.

1. Introduction

In 1893, German physicist Pockels discovered that some isotropic transparent materials showed optical anisotropy under the action of electric field, and the refractive index of the materials changed due to the change of applied electric field, thus an optical AC voltage transformer based on Pockels effect appeared [1, 2]. The basic measurement principles of optical voltage transformers include Pockels effect, inverse piezoelectric effect and Kerr effect [3, 5]. Among them, the optical voltage transformer based on Pockels effect is relatively simple in structure, has high sensitivity and is a linear measurement, so it is most widely used. The research on optical AC voltage transformer at home and abroad has been relatively mature [6, 7]. For example, 525kV combined optical voltage sensor developed by Alstom Company of France was put into trial operation in Orlando substation in the United States in 1995. In 2011, the optical voltage transformer based on the Pockels effect developed by Nanrui Aerospace Co., Ltd. was put into operation in Jiangsu 500kV Changshu South Substation [8, 9]. However, the development of optical DC voltage sensors at home and abroad is still at the theoretical research stage, and there is no engineering application due to the polarization phenomenon of electro-optic crystal, threshold limitation of optical components, insufficient reciprocity of optical fiber optical path, and application market limitation.

2. Research Scheme of Optical Voltage Sensor Based on Pockels Effect

This paper presents a research scheme of optical DC voltage sensor based on Pockels effect and Sagnac optical interference principle for ship integrated power system. Through "non-intervention" measurement of electric field, the measured voltage information is converted into phase difference information in the field sensitive optical path, then weak signal is collected on the low voltage side...
through precise optical interference correlation detection, and precise measurement of electric field is realized by combining system double closed loop control technology.

The measurement scheme consists of five parts: electric field sensitive light path, light path component, demodulation circuit, interface circuit and power supply circuit. Its composition diagram is shown in Figure 1 below. The electric field sensitive light path is located on the electric field measurement side. The light path component, demodulation circuit, interface circuit and power supply circuit are installed in the electrical unit and then assembled in the nearby power distribution cabinet.

**Figure 1.** Schematic diagram of research scheme

The functions of each component are as follows:

A) Electric field sensitive light path: this part of the light path induces the magnitude of the electric field to be measured and sensitize to the phase difference information of polarized light;

B) Optical path component: the optical path component realizes the generation of optical signals and optical interference processing;

C) Demodulation circuit: the demodulation circuit realizes optical signal modulation, demodulation processing of optical phase interference information and interface communication;

D) Interface circuit: the interface circuit realizes mutual conversion of optical information and electrical information, and realizes external optical communication through communication optical fibers;

E) Power supply circuit: the power supply circuit realizes secondary power supply conversion.

This article mainly discusses the structural unit of the light path assembly as follows.

2.1. **Structure of Light Path Components**

The structure of the optical path component of the optical voltage sensor based on Pockels is shown in Figure 2 below. It is mainly composed of SLD light source, coupler A, coupler B (polarization beam splitter), Y waveguide, 45°rotator, collimator, LiNbO3 crystal and reflector.
The light emitted by the SLD light source is divided into two parts by coupler A, and part of the light enters Y waveguide. In Y waveguide, the light is divided into two linearly polarized light beams. After passing through the physical fusion points of 0° and 90° respectively, the two linearly polarized light beams have the same propagation direction and perpendicular polarization directions, thus realizing the transmission of the two linearly polarized light beams along the fast and slow axes of the optical fiber respectively in the optical fiber optical path and entering coupler B, and then the two linearly polarized light beams are combined into the same optical path for transmission. After passing through the delay coil, 45° rotator, collimator, and finally into the light sensitive circuit, when there is voltage around the electro-optic crystal, the two linearly polarized lights in the light sensitive circuit generate phase difference. After being reflected back at the reflector, the phase difference generated by the two linearly polarized lights doubles. The two lights containing phase difference information interfere at the Y waveguide, converting the phase information into light intensity information, and measuring the light intensity through the photo detector. The final interference signal is expressed as:

\[ I_d = I_0 (1 + \cos 2\delta) \]  

Where: \( \delta \) is the phase difference between the two beams caused by Pockels effect; \( I_0 \) is the intensity of incident light; \( I_d \) is the interference light intensity received by the detector. Demodulating the phase signal in the above formula can obtain the measured voltage intensity.

### 2.2. Optical Path Reciprocity Mechanism

In order to conveniently describe the mechanism of optical path reciprocity, we temporarily call the light beam propagating along the fast axis in the optical fiber path (1) and the light beam propagating along the slow axis (2). The two beams of light are emitted through the Y waveguide. After the two beams of light pass through the physical fusion points of 0° and 90° in the forward direction respectively, the two beams (1) and (2) propagate perpendicular to each other in the optical fiber path. After passing through the 45° rotator, the two beams of light rotate 45° in the same direction (clockwise in the incident direction) respectively. When reaching the reflector, the phase of the two beams changes 180°. When returning, the two beams of light passing through the 45° rotator will rotate 45° in the counterclockwise direction (as viewed in the incident light direction). That is, the original (1) light propagating along the fast axis changes to propagate along the slow axis when returning, and the original (2) light propagating along the slow axis propagates along the fast axis when returning, thus realizing the exchange of the two beam modes during the propagation process. The change of polarization modes of the two beams of light is shown in Figure 3 below. In this way, various parasitic effects generated when the two beams of light
propagate in the optical path can be eliminated, so that the phase difference of the two beams of light can be accurately measured (the phase difference of the two beams of light only includes the phase difference value caused by the refractive index difference of the two beams of light in the light sensitive circuit). Finally two beams of light return to Y waveguide and interfere [10,11].

![Figure 3. Polarization mode of two polarized light in light path part](image)

3. Three-dimensional simulation of light wave field using Comsol Multiphysic

Light has wave-particle duality. Geometrical optics studies the imaging and propagation of light only by its corpuscular property. Light itself is an electromagnetic wave. The optical discipline that describes the propagation of light through Maxwell equations is called wave optics. When the geometric size reaches 1000 times of the wavelength, the light fluctuation is not obvious, and the geometric size of the optical voltage sensor has far exceeded this value [12]. In the field of wave optics, previous work is basically based on geometric optics, or directly deducing Jones matrix of each optical component to carry out mathematical modeling and simulation. In this paper, electric field is used to define incident light in Maxwell equations by Comsol Multiphysics, thus the transmission and polarization state of incident light wave in optical fiber path are expressed by transmission and polarization of electric field. The abstract light wave transmission process is visualized by using the three-dimensional wave simulation of the light wave field.

In Comsol Multiphysics, firstly, three-dimensional steady-state electrostatic physical field is selected, and the control equation used for charge conservation is:

\[ E = -\nabla \phi \]  \hspace{1cm} (2)

\[ \nabla \bullet (\varepsilon_0\varepsilon_r \mathbf{E}) = \rho \] \hspace{1cm} (3)

\[ D = \varepsilon_0\varepsilon_r \mathbf{E} \] \hspace{1cm} (4)

Among them, \( E \) is electric field intensity vector, \( V \) is electrostatic potential, \( \rho \) is space free charge density, \( D \) is electric displacement vector, \( \varepsilon_0 \) is vacuum dielectric coefficient and \( \varepsilon_r \) is relative dielectric constant of materials.

The geometric model established in Comsol consists of two parts: LiNbO3 crystal and copper metal electrode plate. Figure 4. is a physical model of electro-optic crystal after grid division, where in the width, depth and height of LiNbO3 crystal are 5mm, 10mm and 4 mm respectively: The thickness of the metal electrode plate is 0.5mm, the upper electrode plate is loaded with voltage \( U=10KV \), and the
lower electrode plate is grounded, \( U_0 = 0 \). Figure 5. is the overall and YZ cross-sectional distribution of the electric field vector inside the simulated crystal. The size and direction of the red arrows in the figure respectively indicate the size and direction of the electric field. As can be seen from the figure, the electric field inside the crystal has uniform electric potential distribution, equal size and downward direction. The simulated electric field distribution is ideal for simulating Pockels effect [13].

**Figure 4.** Three-dimensional geometric model

**Figure 5.** Electric field vector distribution of whole and YZ section

In the above macro physical model, cuboid microelements with width, depth and height of 0.4\( \mu \)m, 0.4\( \mu \)m and 1\( \mu \)m respectively are taken, and their geometric models are shown in the following figure 6. A beam of linearly polarized light is incident from the surface port in the negative Y-axis direction of the model. The polarization direction of the light is along the Z-axis and the propagation direction is along the negative Y-axis direction. The electric field is used to define the incident light wave, and the expression is as follows:

\[
E_0 = \exp(-i \cdot emw.ko \cdot n_\text{glass} \cdot y)
\]  

Wherein, \( emw.ko \) is the wave vector of electromagnetic wave in air and \( n_\text{glass} \) is that refractive index of electro-optic crystal material.
In the setting of boundary conditions, the two surfaces of the electro-optic material parallel to the vibration direction of the electric field, that is, the two surfaces parallel to the coordinate plane YOZ, are set as Perfect Magnetic Conductor (PMC) with the equation:

\[ \mathbf{n} \times \mathbf{H} = \mathbf{0}; \]  

(6)

The two surfaces of the electro-optic material perpendicular to the vibration direction of the electric field, that is, the two surfaces parallel to the coordinate surface XOY, are set as Perfect Electric Conductor (PEC) with the equation:

\[ \mathbf{n} \times \mathbf{E} = \mathbf{0}; \]  

(7)

Figure 7 shows the distribution of electric field and magnetic field of incident ray polarized light, Figure 8 shows the time-average power flow of incident light wave, indicating the propagation direction of light, and Figure 9 shows the distribution of polarization state of incident light wave in crystal. According to Figure 7, 8 and 9, the incident photoelectric field, magnetic field and light propagation direction are perpendicular to each other and are TEM waves, which are consistent with the initial setting conditions and satisfy Maxwell equation. Through the theoretical analysis of wave optics, Comsol is used to realize the three-dimensional simulation of light wave field for polarization state of incident light wave, which provides the basis and modeling idea for coupling simulation of multiple physical fields such as electric field, temperature field, vibration, etc [12].

Figure 6. Microelement geometric model

Figure 7. Distribution of electric field and magnetic field of incident light wave
Figure 8. Average power flow of incident light wave

Figure 9. Distribution of polarization state of incident light wave in crystal

4. Conclusion

(1) This paper puts forward a research scheme of optical voltage sensor with optical path reciprocity. It mainly studies the optical path component structure unit including electric field sensitive optical path unit located at high voltage side and optical path component structure unit located at low voltage side, and expounds the optical path reciprocity mechanism of optical path component unit, which provides theoretical basis and reference for the design of optical path component unit of optical voltage sensor.

(2) Comsol Multiphysics is used to innovatively realize the three-dimensional wave simulation of light wave field. Accurate calculation and research of multi-physical field distribution of optical path unit is the premise to accurately analyze various performance influencing factors, perfect its design, improvement and structure, and improve its performance. Using multi-physical field simulation, various internal design factors including structure and size as well as various external environmental factors including temperature and vibration can be simulated and calculated to accurately grasp various characteristic indexes of the sensing unit. Using Comsol Multiphysics to simulate the optical voltage sensor can greatly shorten the development and manufacturing cycle and reduce the development cost, which has certain positive significance for promoting the practical process of the optical DC voltage sensor.
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