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基于全偏振态检测的悬挂式光纤电压传感器

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摘 要:针对现有光纤电压传感器结构复杂、调整难度大、温度稳定性差、光功率损耗大及电压引入不便等问题,提出一种基于全偏振态检测且无需起偏器与检偏器的光纤电压传感器.传感器只含有自聚焦透镜、$Bi_4Ge_3O_{12}$晶体以及全反射镜等 3 个主要元件,器件少,结构简单,对准较容易.介绍了全偏振态检测系统光路,采用分振幅法检测偏振态,具有快速响应、算法简单等优点.计算得出了偏振态、离线电场与被测电压之间的公式.进行了悬挂式高压试验,试验中的传感器上无电极,也无需接地,不但省去了昂贵的绝缘子,而且增大了传感器的量程.试验结果表明,在室温条件下 0～10 kV 工频交流电压范围内,该传感器具有良好的线性关系,证明了该结构的可行性.

关键词:光纤传感器;光纤电压传感器;Pockels 效应;全偏振态检测;悬挂式
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Suspended Optical Fiber Voltage Sensor Based on All Polarization State Detection

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Abstract: Aiming at some problems of existing optical fiber voltage sensors, such as complex structure, adjustment difficulties, poor temperature stability, optical power loss and voltage introduced inconvenience, a new structure of suspended optical fiber voltage sensor based on all polarization state detection without polarizer and analyzer was proposed. The sensor only contained three main elements that are a self-focusing lens, a $Bi_4Ge_3O_{12}$ crystal and a total reflection mirror. For the fewer devices, the structrue is simple and it is easy to align. All polarization state detection system was described. It uses division-of-amplitude method and has fast response and simple algorithm. Formulas about polarization state, electric field and the measured voltage were calculated. Experiment of measuring the high voltage by suspending the sensor was demonstrated. The sensor in the experiment has no electrode and without ground, which eliminates the need for expensive insulators and increases the range of the sensor. The experiment results show that the sensor has a good linearity at room temperature in the range of 0～10 kV AC voltage at power-frequency, which proves the feasibility of the structure.

Key words: Optical fiber sensor; Optical fiber voltage sensor; Pockels effect; All polarization state detection; Suspended sensor
OCIS Codes: 060.2370; 130.6010; 120.1880; 120.2130

0 Introduction

With continue increment of measurement and protection requirements, optical fiber voltage sensor is getting more and more applications in the ultra-high voltage power transmission system[1-2]. By now, optical

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fiber voltage sensor is mainly based on Pockels electro-optic effect, converse piezoelectric effect, electro-optical Kerr effect, the linear electro-optic effect in thermally poled fiber, etc[3-7], among which the Pockels electro-optic effect in the BGO ($Bi_4Ge_3O_{12}$) crystal is most widely used. In 2012, Feng Pan proposed an optical AC voltage sensor utilizing two bulk BGO crystals which showed good linearity and accuracy[8]. In 2013, Akiko Kumada proposed a new optical high-voltage measuring system using a Pockels crystal in a longitudinal modulation arrangement which could measure high voltage up to ±450 kV [9]. Hui Li proposed a closed-loop detection system for optical voltage sensors based on Pockels effect, and the accuracy of the sensor is within 0.2% [10]. But there are still some important technical issues which affect its further application: 1) The structure of the sensor is complex, its adjustment and assembling is difficult, and its temperature stability is poor. The current sensor consists of six elements, such as a front self-focusing lens, a polarizer, a 1/4 wave plate, a BGO crystal, an analyzer and a back self-focusing lens. A fine and careful adjustment must be done for aligning the optical path, including axial distance, pitch angle and horizontal deflection angle of the six optical elements. It is unable to place many multi-dimensional tuning frames to adjust them because the elements are small and the space is limited. After adjusting, the optical adhesive must be used to fix and bond the sensor. Because of many elements and adhesive surfaces, the stability of the adhesive may decrease, and then the sensor is susceptible to temperature and other environmental factors, which adding additional instability. 2) A polarizer and an analyzer will introduce 3dB loss, and the variation of input polarization state will introduce the fluctuation of the optical power. The optical axis of the polarizer must also be strictly aligned with the analyzer, otherwise it will introduce errors. 3) In most cases, the 110 kV or higher test voltage is directly or through the capacitive voltage divider applied to the BGO crystal electrodes, and the isolation is very difficult. The capacitive voltage divider is expensive, bulky, and needs large area. It also has flashover and other issues, not easy to apply.

To solve the above problems, we abandon the polarizer - analyzer sensing solutions, and propose a novel scheme of fiber sensor based on all polarization state detection to simplify its structure. The proposed fiber sensor is directly suspended closely from the power transmission line.

1 Structure of Sensor System

The structure of the suspended optical fiber voltage transducer based on all polarization state detection was shown in Fig. 1. The light from the Laser Diode (LD), which power is 15 mW, goes through the Polarization Controller (PC) and the optical circulator, and then goes into the sensor. The test voltage on the power transmission line is produced by a test transformer, which output voltage can be adjusted by the regulator [11-12]. Under the test electric field, the polarization state of light pass through the crystal will be rotated due to the Pockels electro-optic effect. And then rotated light returns to the optical circulator, and enters the all polarization state detection unit. After the contrasting and calculating the output polarization states, the voltage value can be measured.

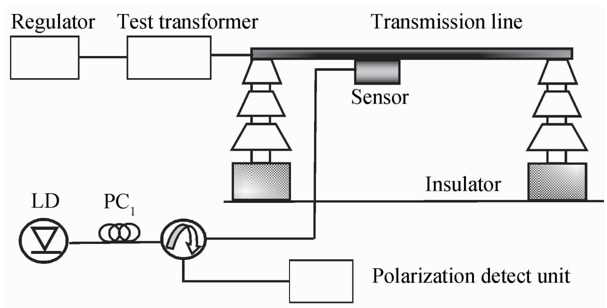

Fig. 1 The structure of suspended optical fiber voltage sensor based on all polarization detection system

1.1 Structure of sensor

The sensor gives up the polarizer, the wave plate and the polarization analyzer, as shown in Fig. 2. It only contains three main elements, which are a self-focusing lens, a BGO crystal and a total reflection mirror. This simple structure of sensor makes it easy to be aligned. For the proposed sensor, there are only two adhesive surfaces to be stuck along the light transmission direction and the difficulty of fixing is reduced. The sensor is the reflective structure, comparing with the transmission structure, the length of electro-optic effect of the sensor increases one times, and its half-wave voltage is $U_\pi = 67.989\ 5$ kV.

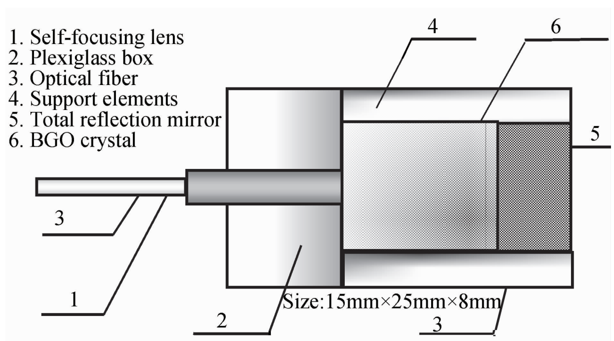

Fig. 2 Schematic diagram of the sensor

Using insulation material, the sensor is suspended closely from the power transmission line, as shown in Fig. 3.

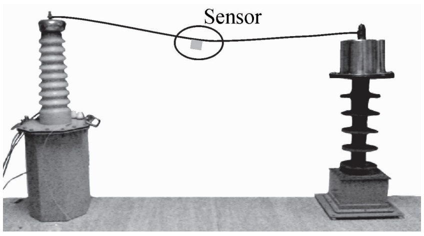

Fig. 3 Schematic diagram of the suspended sensor

1.2 All polarization state detection unit

This unit uses division-of-amplitude method to detect polarization state[13]. It has fast response and simple algorithm, as shown in Fig. 4. The detection unit is supported by +5 V and −5 V power sources.

The principle of the all polarization state detection system is based on Eq. (1). The input light is divided by a 1 × 4 coupler into four equal intensity parts. Through an attenuator, the first part goes for photoelectric conversion. After going through PCs, the second, third, and forth parts get into Polarization Beam Splitters (PBS) and divide into two beams of light whose polarization state is perpendicular to each other. Adjusting three polarization controllers, coordinates of Poincare Sphere for every part will reach the same, and then we get each optical power value of Eq. (1).

$$\begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} E_x^2 + E_y^2 \\ E_x^2 - E_y^2 \\ 2E_x E_y \cos p \\ 2E_x E_y \sin p \end{bmatrix} = \begin{bmatrix} I_x + I_y \\ I_x - I_y \\ I_{+45} - I_{-45} \\ I_R - I_L \end{bmatrix} \tag{1}$$

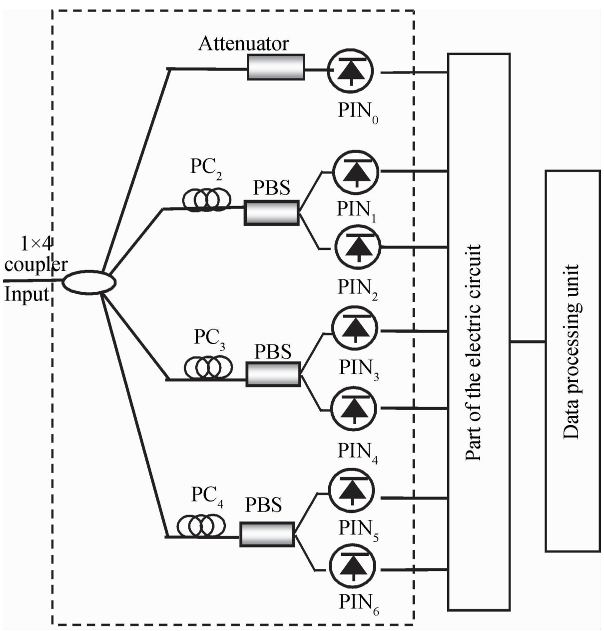

Fig. 4 Four routes all polarization detection system

The functions of the electrical circuit are photoelectric conversion and differential amplification. Since the quantities in formula Eq. (1) are differential of two light intensities except for s_0, the differential amplifier gains the difference between the optical powers directly and it can eliminate common mode noise. After calculation and normalization, we may obtain s_0, s_1, s_2, and s_3, and then obtain the polarization state of the input light. Substituting the values of s_0, s_1, s_2, and s_3 into Eq. (2) of the literature[14], we may calculate the voltage applied on the crystal.

$$U_1 = U_0 + \frac{U_\pi}{2\pi} \cdot \arcsin \frac{s_2 s_{03} - s_{02} s_3}{s_{02}^2 + s_{03}^2} \tag{2}$$

where U_0 is initial voltage at $t=0$, and it can be set to 0. $\boldsymbol{S}_0 = (s_{00}, s_{01}, s_{02}, s_{03})^T$ is Stokes vector of the initial state at $t=0$. $\boldsymbol{S}(t) = (s_0, s_1, s_2, s_3)^T(t)$ is the polarization state of the next moment.

2 Measurement of the high voltage by suspending the sensor

2.1 Calculation of high-voltage on the power transmission line

The electric field near the power transmission line is very strong and the interference of other out electric field is almost negligible, and this field intensity is linear relationship with the voltage of the transmission line. Therefore, we can measure the electric field nearby the power transmission line to measure its voltage. As long as the relative position and the ground conductivity are unchanged, the measured value will be stable. The calculation of power-frequency electric field intensity under the power transmission line is traditionally based on recommended approach of "CIGRE Section 36.01 Working Group"[15]. In the calculation process, we assume that the power transmission line is parallel to the ground and it is an infinitely long straight conductor. For power-frequency electric field, resistivity of the ground is less than 10^5 Ω·m and then the ground can be regarded as a good conductor. Under these assumptions, we can reduce the following equation

$$U(t) = \frac{x}{d} \ln \frac{2h}{R} \cdot U_1(t) \tag{3}$$

where $U(t)$ is the voltage of the transmission line to ground, x is the distance from the sensor position to the charged straight line, d is the thickness of the BGO crystal, his the height of the power transmission line to ground, R is the diameter of the power transmission line, $U_1(t)$ is the voltage across the BGO crystal.

For the suspended sensor from the power transmission line, x, d, hand R are all certification. Then we can define $C = \frac{d}{x} \ln^{-1} \frac{2h}{R}$, so formula Eq. (3) can be simplified as

$$U_1(t) = CU(t) \tag{4}$$

The value of C can be calibrated by measuring, and the value of $U_1(t)$ can be obtained by measurement and formula Eq. (2), so the voltage $U(t)$ of the power transmission line can be calculated.

2.2 Test results of sensor performance

The test results of output s_0, s_1, s_2, s_3 were shown in Fig. 5, when power voltage is within 0～10 kV at 50 Hz frequency.

According to formula Eq. (2), we can calculate the voltage effective value U_1 after obtaining the change of Stokes vector. According to Eq. (4), we make the effective value for curve fitting, as shown in Fig. 6. The actual voltage U was measured by the instrument transformer, which error less than 0.02%.

The slope of the curve is $C=0.0211$. When the test voltage is less than 3 kV, Fig. 6 shows that the actual voltage is quite different with the calculated voltage. This is due to the half-wave voltage of the BGO crystal in the sensor is large, and it causes signal-to-noise ratio decreases when the external electric field is small. In the range of 3～10 kV voltage, the error is less than ±1%, which shows that the sensor has a good linearity and demonstrates the feasibility of the system.

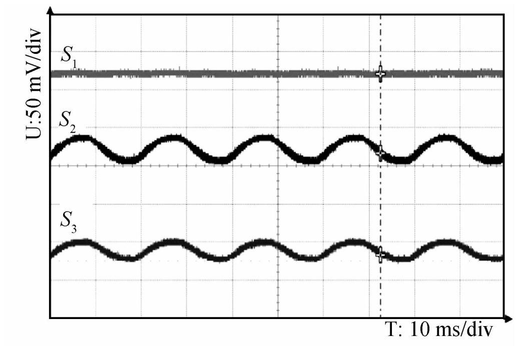

Fig. 5 Circuit output results

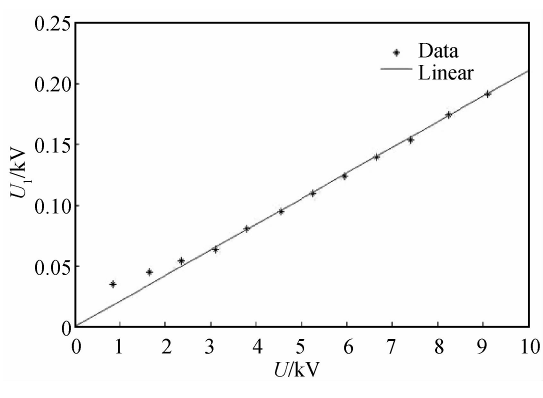

Fig. 6 Fitting curve of actual voltage U and the calculated voltage U_1

3 Conclusion

A new structure of suspended optical fiber voltage sensor is proposed based on all polarization state detection. We design and manufacture the reflective sensor, giving up the polarizer-analyzer sensing solutions. The sensor has some advantages: a few optical elements, easy to adjust and temperature stability. The four-routes all polarization state detection system is developed and rapid detection of Stokes parameters for the sensing signal is realized. We test the suspended sensor and deduce the formulas about the relationship between the detected Stokes parameters and the measured voltage. We also determine the proportional coefficient. The utilization of suspending sensor can eliminates the use of an expensive divider insulator for support sensor and it is easy to install. Test results show that the sensor has a good linearity at room temperature, in the range of 0～10 kV AC voltage at power-frequency, the scheme is feasible and has good application prospects.

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