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Fiber-optic Electric Field Sensor Based on Electrostriction Effect

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Abstract. This paper presents a new method for measuring AC field strength, with application of electrostriction effect of electrostrictive ceramics and technology of fiber Bragg grating. We use electrostriction effect to design the fiber-optic electric field sensor. This device turns the strain of electrostriction material influenced by electric field into the strain of fiber Bragg grating, then wavelength of feedback changes. We can get the strain of electrostriction material through the comparison between initial wavelength and wavelength of feedback, then measurement of electric field strength can be achieved by detecting the strain of electrostriction material. Experiments indicate that fiber-optic electric field sensor based on electrostriction effect is of effective value for measuring electric field strength, and the response of measuring system to AC electric field is linear. We apply an effective method for the research of measuring electric field strength.

Introduction

Measurement of high voltage & strong electric field is always a key research area in high- voltage measurement, one is frequency field measurements, such as electromagnetic fields near the transmission lines or ground, electric field measurement in the surface of insulator, voltage loop, switch and other high voltage equipment; the other is transient field measurement, such as pulsed power technology, lightning or gap discharge, substation switching processes etc [1]. Ever since a long time ago, when the piezoelectric phenomenon of some crystalloid came to light, researchers have focused on the research and application of piezoelctric function of piezoelectric material. Designing a kind of fiber-optic electric field sensor which exchange energy through piezoelectric material to detect electric field strength is of effective value [2]. Sensor technology has been one of mainstays of modern information technology [3, 4]. Fiber Bragg grating sensor has become the perfect choice in electric power industry, because of its ability to be transmited through long distance with low loss, owing to its character of prevention to interference of electromagnetic field. Fiber Bragg grating sensor has a wide prospect. Fiber Bragg grating sensor has numerous advantages, such as prevention to interference of electromagnetic field, small size(the net size of standard optical fibre is 125um), light weight, high tolerance of temperature(the maximum working temperature can reach 400 to 600 centidegree), long transmmission distance, rustproof ability, high sensitivity, easily changed shape. In electric power industry, the change of electric field strength turns to changement of voltage, which leads to a shape change of PZT. The shape change can be easily obtained by means of wavelength drift of fiber Bragg grating sticked on the piezoelectric ceramics, then the electric field strength can be measured. This is a method with low cost; moreover, complicated electric isolation is not needed.

This paper describes a new kind of measuring method, with application of electrostrictive ceramics, which can meet the need for measuring high electric field strength in elctric power system of high voltage, such as measurement of electric field strength of area near ultra high voltage transmmission line, research of character of all kinds of air gap under impulse voltage [4]. Experiments indicate that this system has high sensitivity and resolution.

The measurement system

As shown in Fig. 1, measurement system consists of the following components: electric field probe, optical fiber, fiber Bragg grating demodulator.

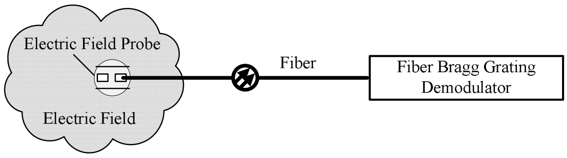

Fig. 1.The measurement syetem

Electric field probe receives and outputs laser, the laser is then transmitted to the fiber Bragg grating demodulator with optical fiber. Comparing the initial wavelength with the feedback wavelength under the electric field, the fiber Bragg grating demodulator would get the strain of electrostrictive ceramic. The electric field strengh can be measured according to the electrostrictive ceramic strain.

Design and working principle of electric field probe

Schematic of the probe is shown in Fig. 2.

The metal spherical shell is divided into two parts in average, the middle of the two hemispheres installed a flat body, on the flat body fixed a signal amplification, conversion circuit and a rectangular electrostrictive ceramics, electrostrictive ceramics including specifications for the 8 mm×8 mm×20 mm. The two metal hemispheres are placed in the electric field, two metal cables are soldered to the upper and lower inner shell surface respectively, the metal line at the other end receives the circuit board, then the electric signal of the electric field can load on the circuit. This signal is amplified, transformed, filtered by the circuit. And then the circuit produces DC voltage. Positive and negative leads of electrostrictive ceramics attach to DC voltage produced by circuit. Bragg grating glues to the side of electrostrictive ceramics direction, that is the elongation of the direction of shortening. Upper and lower surface of the ceramic is electrode surface. Positive and negative leads of electrostrictive ceramics extract from both sides. Optical fiber extracts from the upper and lower ball cracks and comes to fiber Bragg grating demodulator.

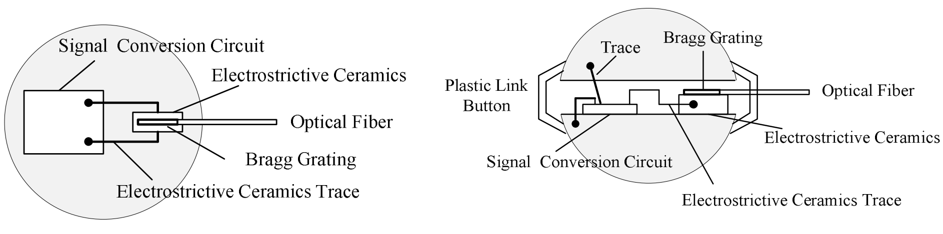

Fig. 2. (a) Top view inner electric field probe; (b) Cutaway view of electric field probe

Transducer is one of the core components of the sensor [5], so selecting the appropriate transducer material is important. Electrostriction is the fundamental electromechanical coupling in all materials—everything is electrostrictive [6]. Elastic strain in the material results from distortion of the bond lengths, electron distribution functions, or electric dipoles with an applied electric stress. Electrostriction is a phenomenon that the stress and strain are proportional to the square of electric field. Some polyurethane elastomers and perovskite-type ceramics can produce large deformation under applied electric fields. In engineering these electrostrictive materials are used as transducers and actuators. So their strength and electric field distribution should be considered [7].Schematic diagram of PLZT piezoelectric of stacked piles is show in Fig. 4 [8].

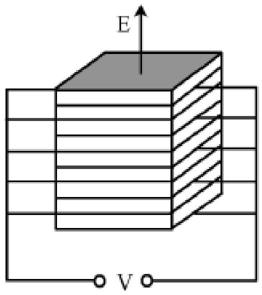

Fig. 3. Schematic diagram of PLZT piezoelectric of stacked piles

The fundamental requirements of electrostrictive materials for transducer applications are as follows:

a) Large field-induced polarization for obtaining large induced piezoelectric coefticients.

b) High dielectric constant for enabling a good electrical impedance matching to the system electronics, especially for small element size of phased arrays.

c) Low electrical loss tangent to reduce the amount of heat generated on transmit and improve signal-to-noise ratio on receive.

d) Wide operating temperature range.

e) Fast polarization switching speed (turn ON/OFF time), and zero remanent polarization when E-field is removed for achieving the complete OFF state on elevation aperture control [9].

Electrostriction material experiments used is developed by China Electronic Science and Technology Corporation 26th Research Institute called WTYD0808020 type material. PLZT, PMN, PZN ferroelectric ceramics are the most used electrostrictive materials [10-12]. The material of rectangular block is encapsulated of epoxy by PLZT thin multi-layer stack , the volume of 8mm×8mm×20mm. The material has the feature of short response time, withstanding the maximum blocking force large, electric field perpendicular to the direction of displacement and the displacement of high output. And its displacement hysteresis loop is long and narrow which contains a very small area [13]. In the operating voltage range of 0V-200 V, the voltage - displacement curve diagram is shown in Fig. 4. In a small low voltage, the loop line introduced by hysteresis effect changes little. According to the type curve of PLZT material [13-15], its hysteresis within the voltage range of 0V-10 V is not obvious. Displacement and electric field strength form a well quadratic curve [16].

Provide a functional relationship between the induced dielectric displacement and the applied electric field that can be used to define electrostriction. An electrostrictive ceramic excited by an E-field given by $E = E_{dc} + E_\omega \cos \omega t + E_\Omega \cos \Omega t$,where E_ω is amplitude of the carrier , E_Ω is amplitude of the low frequency field and Edc is the dc bias, produces strains (using e = ME2),

$$e_\omega = (2ME_{dc}E_\omega)\cos \omega t \tag{1}$$

$$e_{\omega\pm\Omega} = ME_\omega E_\Omega \cos(\omega t \pm \Omega) \tag{2}$$

Along with strains edc, e_Ω and higher harmonics [4].The strain of dielectric materials under the electric field and the applied electric field strength is as follows:

$$e = dE + ME^2 \tag{3}$$

In the formula, e is strain, d is piezoelectric coefficient, M is electrostrictive coefficient (m2/V2) (M may change with the external environment situation such as temperature); E is electric field strength (V/m) [13]. Electrostriction and piezoelectricity are both electromechanical properties that can be linked via thermodynamic formalism [17]. In ferroelectric ceramics, electrostrictive coefficient is much larger than the piezoelectric coefficient, the later plays a leading role [16]. To this kind of ferroelectric ceramics, the deformation in the electric field is followed by the formula: e≈ME2. The magnitude of electrostriction can be improved by: increasing the drive field or increasing the M coefficient. Materials with large values of dielectric displacement have much larger values of useful electrostrictive strain [17]. The low hysteresis and high strain achievable with unipolar excitation of electrostrictors is advantageous. In addition, because the electrostrictive spontaneous does not exist polarization, making such material even at high operating frequencies can still showed no or very small hysteresis losses [13].

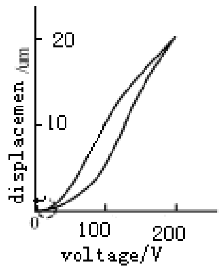

Fig. 4. Voltage - displacement curve of electrostriction material

From the electrostrictive ceramics characteristic simulation, Fig. 6 and Fig. 7 show that the strain of electrostrictive ceramics directly placed in the electric field is small.

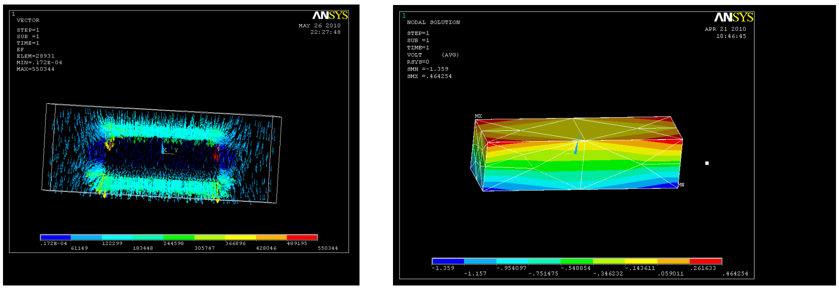

Fig. 5. (a) Power line distribution around electrostrictive ceramics in electric field; (b) Potential distribution of electrostrictive ceramics in electric field

When electrostrictive material is placed between two metal circular plates which simulate a uniform electric field environment, because the electrostrictive material dielectric constant is so large and induced potential difference of the upper and lower electrode surface is too small, if the material placed directly in the field, the material deformation is small. But telescopic effect is obvious when directly add voltage source on the material. Fig. 5 shows the relationship between voltage and strain to the electrostrictive material if directly adding voltage source on that. When the voltage is very low, the material deformation is still very apparent. Therefore, this paper adopts the method of voltage signal load to realize the impact of strain on the material.

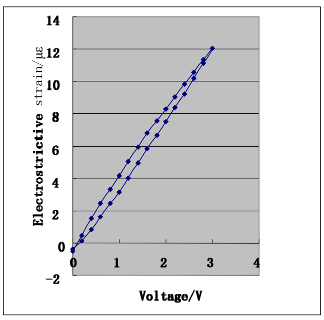

Fig. 6. Relations between the load voltage of electrostrictive material and stretching strain

When the electric field to be tested acting on the metal spherical shell, the metal spherical shell will induce the consistent electric signals as the electric field strength. With the processing of circuit amplification, conversion, filtering, the induced signals transform to the DC voltage signals. Apply the DC voltage to the electrostrictive material on the positive and negative terminal; electrostriction material will be deformed according to the size of DC voltage signals. The Bragg grating linked to the electrostriction material is deformed too. The feedback wavelength to fiber Bragg grating demodulation changes too. Fiber Bragg grating demodulator compares wavelength back from the electric field with the initial state to calculate the strain of Bragg grating or electrostriction material. Micro-strain relations with the wavelength as:

$$e = (ID - \lambda_0) * 1000 / 1.2 \tag{4}$$

In the formula, e is strain, ID is feedback wavelength for the tested electric field, λ0 is the initial state wavelength, and 1.2 is the conversion factor between wavelength and micro-strain with unit pm/με. The strain and the two ends voltage of the material are square relationship. Through the modulation of the circuit, the electric field strength and the output of the direct voltage of the circuit is in the square relationship too. And then we can see that the strain of the material and the electric field strength are in the linear relationship.

Through the detection of micro-strain, electric field strength can be achieved. Enable the measurement of the electric field.

Experimental results and analysis

Use the system shown in Fig. 1.

With two smooth circular metal plate's analog external electric field, electric field strength ranges $0kV/m \sim 200kV/m$. Outputing system response according to the electric field strength is as the curve shown in Fig. 8. Two kinds of test method type that AC field amplitude increases and decreases respectively, the results are of linear line. It shows that the system response according to the external electric field has good linearity. And the system output increases with the AC field amplitude increasing, decreases with the decreasing, indicating the electrostrictive ceramics hysteresis effect is not obvious, the impact to the experiment is negligible. Repeating experiments is to compare the experimental results. Observation of Fig. 8, from three lines of the overlapping situation, overlapping, which indicates good repeatability measurement system, the experimental results is high reliability.

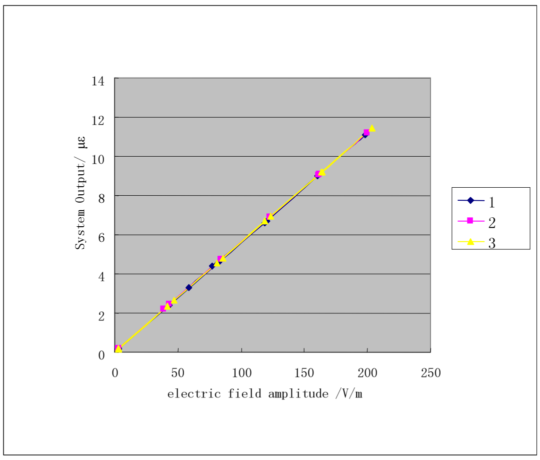

Fig. 7. The relationship between electric field amplitude and the system output

Conclusion

This paper is about a new fiber-optic electric field sensor design. The system has good stability, high sensitivity, good linearity etc. This paper shows the theoretical analysis and process implementation. Experimental results show that the system has good performance. It can meet the measurement of electric power system.

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