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Research and Application of a Non-contact Optical Voltage Sensor for the Monitoring of Lightning and Switching Overvoltage in EHV Power Grid

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***Abstract*—In this paper, a type of sensor for the non-contact monitoring of lightning and switching overvoltage in power grid is presented. It is designed based on Pockels effect and stray-capacity coupling theory. Double-crystal structure is utilized to restrain the unwanted influence caused by natural birefringence. The transmission of the data is achieved by optical fibers which are immune to the electromagnetic interference in substation. This type of sensor is applied to an EHV transformer substation for on-line monitoring.**

Keywords-Lightning overvoltage; Pockels effect; Non-contact monitoring; Double-crystal; LiNbO$_3$

I. INTRODUCTION

Overvoltage, especially lightning overvoltage, is always one of the most serious factors damaging the operation safety of power system[1-3]. Monitoring of the voltage in substations is necessary to ensure the safe operation of power system. With the development of EHV/UHV power system, some kinds of overvoltage with unknown characteristics gradually appear. Accurate waveform data of some kinds of overvoltage when the frequency is too high cannot be acquired by traditional voltage sensors utilized in power system at present. The maintaining of the traditional voltage sensors is inconvenient because of their direct connections to the primary equipment in substation.

In this paper, a type of sensor for the non-contact monitoring of overvoltage in substation is presented. It is based on Pockels effect and stray-capacity theory. It is characterized by passive, large bandwidth, high sensitivity, and small size. The transmission of the data is achieved by optical fibers which are immune to the surrounding electromagnetic interference. The sensibility to temperature of LiNbO$_3$ crystal is effectively restrained by using a double-crystal structure. An experimental system in the laboratory is established to test the performance of the sensor. And its operation when applied to a transformer substation in EHV power grid is presented.

II. BASIC PRINCIPLE

The installation diagram of the sensor is shown in Fig. 1. The voltage sensor is installed under the transmission line or bus bar. It is composed of two parts: voltage induction unit and electric optical conversion unit.

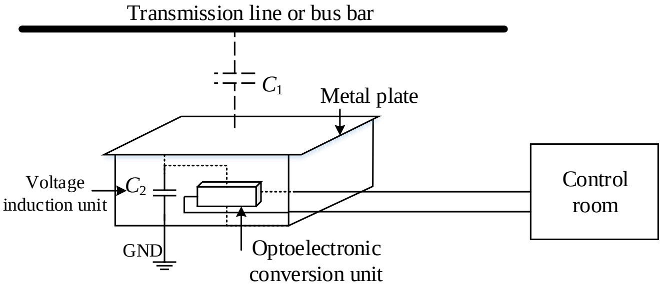

Figure 1. The installation diagram of the sensor

A. Voltage Induction Unit

The voltage induction unit is designed to be a metal plate which is under the transmission line or bus bar, in series with a capacitor and further connected to earth. The theoretical voltage division ratio of the voltage induction unit is:

$$k_1 = (C_1 + C_2) / C_1 \qquad (1)$$

where C_1 is the value of stray-capacity between the metal plate and the transmission line or bus bar, C_2 is the value of the capacitor connected to the metal plate[4].

B. Electric Optical Conversion Unit

The voltage signal is converted to optical signal by the electric optical conversion unit. As is shown in Fig. 2, the

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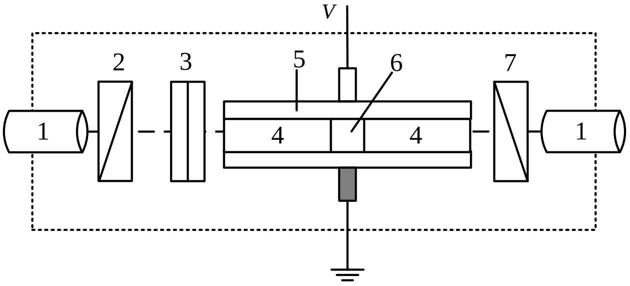
sensibility to temperature of $LiNbO_3$ crystal is effectively restrained using a double-crystal structure[5].



1: Collimator, 2: Polarizer, 3: Quarter wave-plate, 4: LiNbO3 crystal, 5: Electrodes 6: Half wave plate, 7:Analyzer

Figure 2. Structure diagram of electric optical conversion unit

The intensity of output light beam is given as:

$$I = I_0 sin^2\left[\frac{1}{2}\left(\frac{\pi}{2} + \varphi\right)\right] = \frac{I_0}{2}\left(1 + sin\varphi\right) \qquad (2)$$

$$\varphi = 2\pi\left(r_{33}n_e^3 - r_{13}n_o^3\right)VL/\lambda_0 d \qquad (3)$$

where I_0 is the intensity of input light beam, φ is the phase difference between the polarizer and analyzer, λ_0 is the wavelength of the light beam in vacuum, no is the ordinary refractive index of the $LiNbO_3$ crystal, and ne is the extraordinary refractive index of the crystal. r_{33} and r_{13} are the linear electro-optic coefficients of the crystal in different directions, and d and L are the thickness and the length of each crystal, respectively. V is the voltage applied to the crystal which is induced by the voltage induction unit. The voltage on the transmission line or bus V_{in} can be calculated by the following equation:

$$V_{in} = k_1 V = \frac{k_1 \lambda_0 d}{2\pi L\left(r_{33}n_e^3 - r_{13}n_o^3\right)} arcsin(\frac{2I}{I_o} - 1) \qquad (4)$$

III. DESIGN OF THE SENSOR

The photos of the sensor is shown in Fig. 3. The voltage induction unit is made of a metal plate (200 mm×300 mm) and a capacitor module with 3 grades for adjustment. The electric optical conversion unit and capacitor module are fixed in an insulation mold, and the metal plate is fixed on the top of the mold. The insulation mold is installed in a shielding shell made of metal material, the cover of the shield shell is made of insulating material. The optical fibers are connected with the sensor through the small hole at the bottom of the shielding shell.

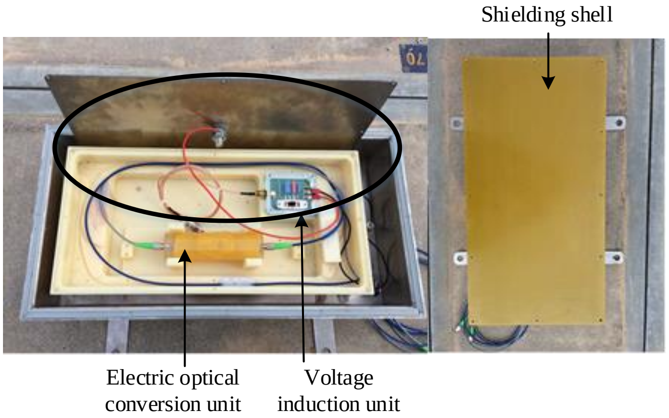


Figure 3. Photos of the sensor

For the installation of the sensor, the influence of other phases should be taken into consideration, the sensor under the phase A is taken as example to explain it, as shown in Fig.4. There exist stray capacitance C_B, C_C between the phase B/C and the metal plate which is under the phase A. The voltage of phase B and C would inevitable induced by the sensor under the phase A. The decoupling technology for this type of sensor is discussed in [4]. While, in order to simplify the decoupling process, the influence of other phases should be decreased as much as possible, in other words, the stray capacitance C_B and C_C should be reduced as much as possible.

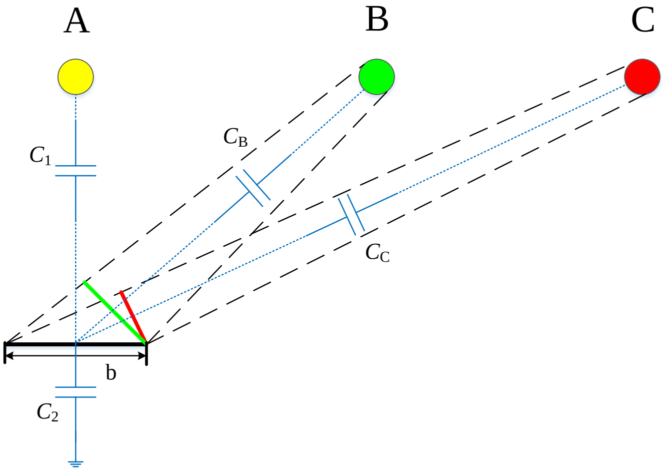


Figure 4. The influence of other phases

The value of stray capacitance is related to the size of metal plate and the linear distance between the metal plate and the transmission line[1]. As shown in Fig.5, the decrease of linear distance between the metal plate and phase A can lead to the decrease of the effective area of metal plate toward the phase B (phase C), then the C_B and C_C would be correspondingly reduced. Moreover, the decrease of linear distance between the metal plate and phase A would lead to the increase of C_1 by a large margin. The overall result is the influence of phase B and C is sharply restrained.

On the other hand, the decrease of the linear distance between the metal plate and transmission line would raise the risk threatening the security of power grid. Thus, on the basis of beyond the safe distance, the sensor should be installed close to the transmission line as far as possible.

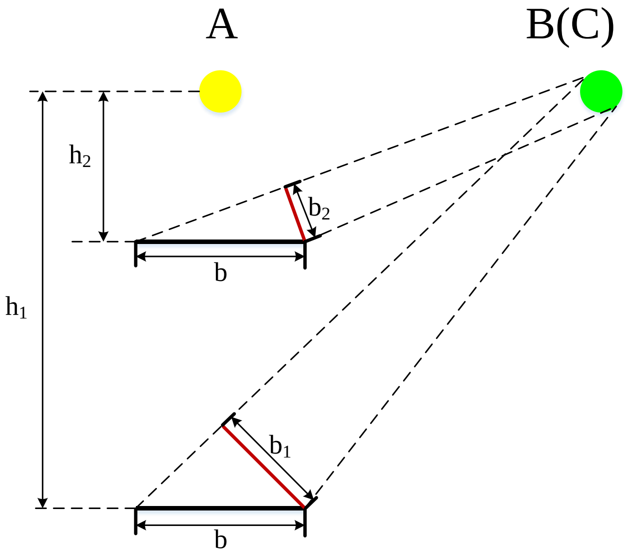


Figure 5. The status when the linear distance is decreased

IV. TESTS IN LABORATORY

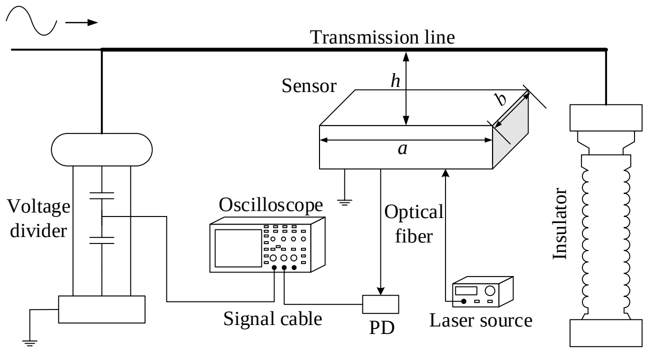


Figure 6. Test circuit of voltage measurement

A voltage measurement system is designed to test the performance of the sensor in non-contact measurement of the high voltage on a transmission line, as shown in Fig. 6. In the system, the radius of the transmission line is 0.025m, and the length of it is 4m. h=1.3m. A sinusoidal voltage signal is applied to the transmission line. When the frequency and peak value of the input voltage are 50 Hz and 16 kV respectively, the response of the sensor is shown in Fig. 7. In Fig.7, the wave form of the voltage on transmission line is represented by black line, the wave form of the output voltage of the sensor is represented by red line. The peak value of output voltage is 24 mV, the voltage division ratio of the sensor can be calculated as 666667 : 1.

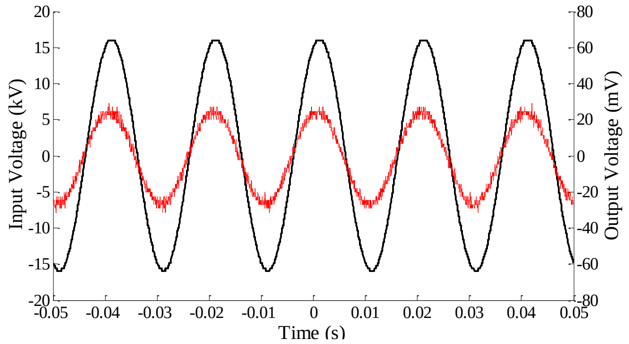


Figure 7. Sinusoidal wave response

When the distance between the metal plate and transmission line is kept to be 1.3 m unchanged, an impulse voltage is applied to the line. The front time and tail time of the impulse voltage is 1.2μs and 75μs respectively. The response of the sensor is shown in Fig. 8, in which the waveforms are normalized.

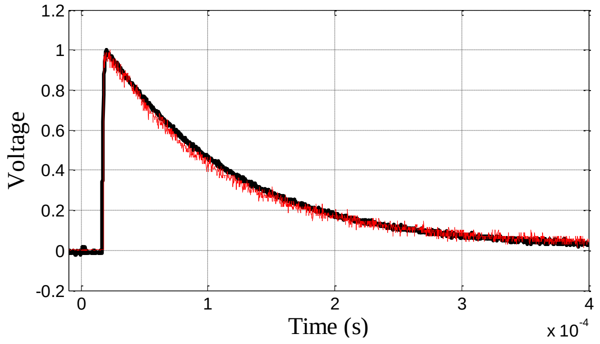


Figure 8. High frequency impulse voltage response

Results show that the sensor has a good SNR (Signal to Noise Ratio) and high linearity in input/output characteristics. And it has wide enough frequency band to be applied to acquiring lightning overvoltage.

V. APPLICATION

The sensor is applied to the online monitoring of the voltage on transmission line in a 500 kV transformer substation in Yunnan province, China. The installation of the sensor is shown in Fig. 9. It is placed right under the transmission line, and the laser source, PD (photoelectric detector) and data acquisition device are installed in the control room.

Figure 9. Location of the sensor in practice

A practical switching overvoltage is acquired by the sensor, as shown in Fig. 10. The peak value of the overvoltage is 780kV.

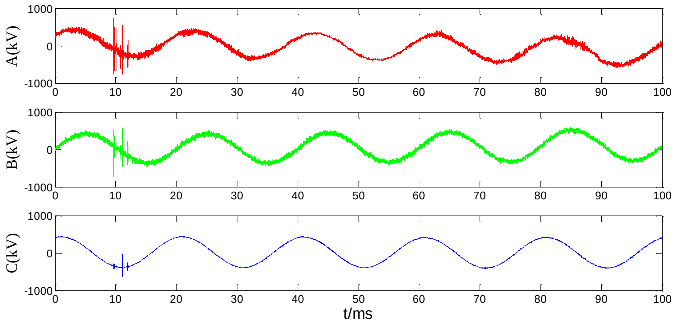


Figure 10. Practical switching overvoltage aqcuired by the sensor

VI. CONCLUSION

The experimental results indicate that the sensor has a good SNR, high linearity in input/output characteristics and wide frequency band for lighting overvoltage measurement. The application in the transformer substation in EHV power grid demonstrates that the sensor is convenient for installation and maintenance. It is of great practical value for popularization.

ACKNOWLEDGMENT

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