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Integrated Electro-optic Sensor based Transient Voltage Measuring System and its Applications

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***Abstract*—Measuring the transient voltage including lightning or switching impulse overvoltage is helpful for accident analysis of power system and insulation design. In this paper, a transient voltage measuring system based on the integrated electro-optic electric field sensor was proposed. The principle of the system was introduced and the measuring system was developed. The performances of transient voltage measuring system was tested by simulation experiments and compared with that of standard divider. The field data of the transient overvoltage on a 220kV bus during the process of putting a capacitor voltage transformer into operation were given. The measuring results were coincide with the related physical process.**

Keywords-measuring system; transient voltage; integragted eletro-optic sensor; lightning impulse; switching impulse

I. INTRODUCTION

In electric power system, transient voltage, including lightning overvoltage and switching overvoltage, is one of the main factors that can threat the safety of the power system. Of high frequency and amplitude, the unaffordable transient voltage leads to the insulation degradation or even direct damage to the equipment. Thus, to obtain the waveform of transient voltage can provide evidence for the accident analysis and help to the optimize insulation design of power apparatus.

Despite the importance of transient voltage data, most related research still largely depends on theoretical analysis and numerical simulations, and only several different types of sensors have been proposed. Traditional capacitive voltage divider is the main method at present [1]. To make it capable in the ultra-high voltage grid, a new design of voltage divider was developed based on the capacity effect of transformer bushing. The low-voltage arm which was connected to the transformer bushing end and the transformer bushing formed a capacitive voltage divider to measure the overvoltage [2][3]. Floating electrode was also used as a non-contact voltage sensor, which utilized the stray coupling capacitance between conductor and electrode. Different shapes of the electrodes have been designed, such as the ring [4], plate [5], and sphere [4][6]. Another practical measuring method is based on the electro-optic effect. In reference [7], the overvoltage was captured first by a capacitive voltage divider, then transformed to an optical signal by an electro-optic sensor, which solved the insulation problem [7].

While those sensors mentioned above each has several drawbacks. The capacitive voltage divider may need to connect to the power system or have metal structures. As the voltage increases, the safety risk increases. Floating electrode has no contact with the grid, but its precision is limited by the metal component since they will distort electric field and the stray coupling capacitance is greatly influenced by environmental condition. Another problem that needs to be solved for this sensor is that in a three-phase system, the measurement results will be influenced by the other phases. In reference [7], by the optoelectronic conversion of electro-optic sensors, the voltage gained by electrode was converted to optical signal, which can be precisely transmitted for a long distance by the fiber, but the other disadvantages of the floating electrode method also exists in this method.

In this paper, a transient voltage measuring system based on the integrated electro-optic sensors was proposed and implemented. The characteristic of the measuring system is calibrated by different experiments. Finally, field measuring data obtained by the system was described to verify the effectiveness of the system.

II. MEASURING SYSTEM

A. *Principle of transient measurement*

For quasi-static field, the electric field around the conductor can be considered proportional to the applied voltage and vice versa. Thus the voltage including the waveform and frequency can be acquired indirectly by measuring the electric field.

In addition, calibration shows the designed electric field sensor’s response to power frequency signals is almost the same as that of high frequency pulse. So we can use the same integrated electro-optic sensor (IEOS) to measure signals from power frequency to very high frequency signals including most transient electric field and voltage in power systems.

When using the sensor to measure the transient voltage, the power frequency signal which is always applied on the conductor is taken as the real-time reference, so the calibration is not required for outdoor use if the overvoltage factors are wanted, which makes the measuring process easier.

B. The integrated pptical E-field sensor

The IEOS for transient voltage measurement is based on the Pockels effects [8]. The structure of sensor is shown in Fig 1. The waveguide is fabricated on a $LiNbO_3$ substrate by titanium diffusion. The input and output are connected to two polarization maintaining fibers (PMF).

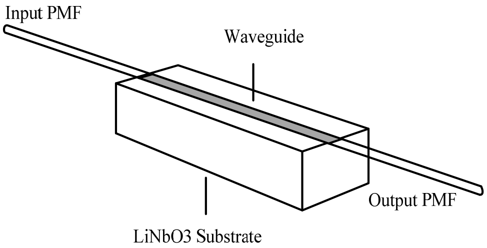


Fig 1 The structure of IEOS

The incident linearly polarized laser light is divided into two modes and propagates in the waveguide. According to the Pockels effects, the light wave is modulated by E-filed, leading to a phase difference between the two modes of the light. The phase difference is proportional to the E-field and interference occurs at the output point of the waveguide. So the E-field can be acquired by measuring the light intensity of either axis of the PMF. The light intensity of slow or fast axis can be expressed as

$$
\begin{aligned}
P_1 &= \frac{P_{in}}{2}(1+\cos(\varphi(E)+\varphi_0)) \\
P_2 &= \frac{P_{in}}{2}(1-\cos(\varphi(E)+\varphi_0))
\end{aligned} \tag{1}
$$

where $\varphi(E)$ is the phase difference by E-field and φ_0 is the optical bias due to the natural birefringence.

C. Setup of the measuring system

The setup of measuring system is shown in Fig. 2, which consists of laser source, polarization-maintaining optical fiber, polarizer, sensor, polarizing beam splitter (PBS), optical receiver and oscilloscope.

The implemented IOES is about 3 cm long and 1 cm wide after packaging and has no metal structures which introduces little electric field distortion when putting near the conductors, so it is suitable to work in high voltage environment.

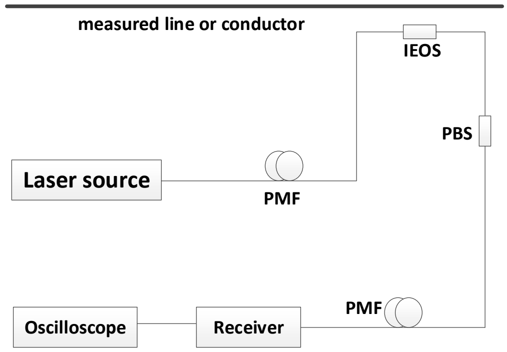


Fig. 2. The structure of the measuring system

The light from the laser is polarized and propagates into the IEOS. After the interference of the light of two modes demonstrated above, the light transporting in either axis of PMF can represent the E-field. After the PBS, one path of light is converted to voltage signal by the optical receiver, then the voltage output can be captured by the oscilloscope or other digital system.

Taking photoelectric conversion ratio, the loss of the whole system into account, the transfer function of the whole measuring system can be expressed as

$$V_{\text{out}} = A\cdot\left[1+b\cdot\cos(\varphi_0+\frac{\pi}{E_\pi}\cdot E)\right] \tag{2}$$

A represents the photo-electric conversion coefficient and the transmission loss; b stands for the extinction ratio. Generally, φ_0 can be controlled near π/2 through the production of the sensor. Assuming the E-field is much smaller than the half-wave electric field (E_π), Eq (2) reads:

$$V_{\text{out}} = A\cdot\left[1+b\cdot(\frac{\pi}{E_\pi}\cdot E)\right] \tag{3}$$

Under this condition, the waveform of V_{out} is linear to the electric field thus can represent the waveform of the voltage to be measured.

D. A comparison of the measuring system with exsiting systems

Compared with the system reviewed in the introduction section, the proposed system has no metal components, and has several advantages: (1) it can directly connect with the high voltage bus or be placed very close to the bus without any insulation problems; (2) the measuring system has almost no influence to the power system; (3) its distortion to the electric field is small; (4) it has a very wide bandwidth.

III. SIMULATION EXPERIMENT

To validate the measuring method and the system based on the IEOS, a simulation experiment was carried out in the laboratory.

The test circuit was built with high voltage impulse generator and power-frequency power supply, to simulate the working condition that the overvoltage was superimposed on the power frequency voltage signal.

A. Design of the experiment circuit

Fig. 3 shows the configuration of the experiment system.

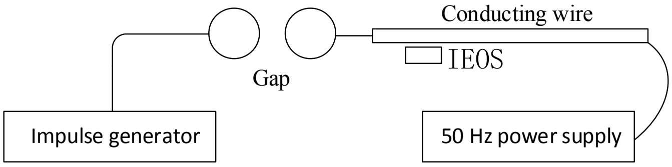
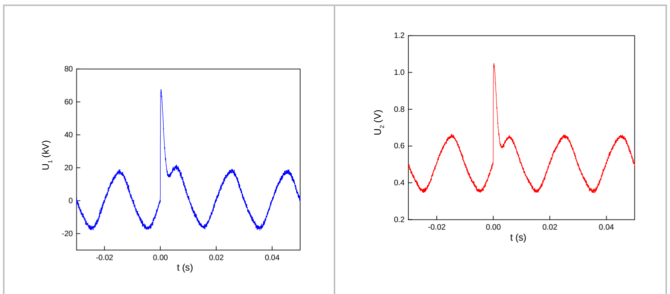


Fig 3. The configuration of the simulation experiment

An iron stick with a diameter of 0.8 cm was used to represent the conducting wire. The 50 Hz power supply was directly connected with the iron stick. The sphere-sphere gap was adjusted to an appropriate length to avoid breakdown under the power frequency voltage. When the impulse voltage was generated by the generator, the gap broke down and the impulse voltage was applied to the iron stick and superimposed on the 50 Hz voltage signal. The sensor was placed near the stick at a distance of 3 cm to measure the electric field.

B. The experimental result for switching impulse measuring

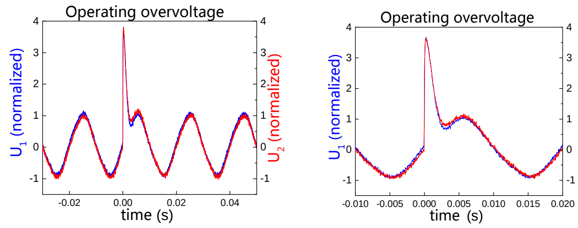
First, a switching impulse and a power frequency voltage was implied to the iron stick. Fig 4(a) shows the measured waveforms by the standard voltage divider and Fig4(b) is the output of measuring system based on the IOES.



(a) Output by the voltage divider (b) Output by the sensor system

Fig.4 Waveforms of operating overvoltage experiment

As mentioned in section II, there is no need to obtain the absolution value of the voltage because the power frequency voltage can be used as the reference. By taking the power frequency voltage as a reference, the normalized waveforms are depicted in the figure 6.



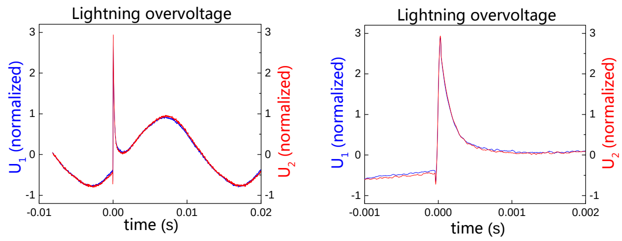
(a) (b)

Fig.5 Normalized waveforms of operating overvoltage experiment

The results of two measurement are similar and the relative error in figure 5(a) and (b) is less than 3% .

C. The experimental result for lightning impluse measuring

Secondly, a lightning impulse and a 50 Hz voltage supply was applied. The normalized measured waveforms of are shown in Fig 6.



(a) (b)

Fig.6 Normalized waveforms of lightning overvoltage experiment

According to Fig 7(a) and (b), there is about 2.5% error for the results obtained by the standard divider and the sensor.

The experiments indicates the measuring system can measure switching and lightning transients with the error less than 3%. So it is feasible for both internal and external overvoltage measuring in power system.

IV. FIELD TEST RESULTS

Using the measuring system, we measured the transient voltage on a 220kV bus when the switch was operated to put the CVT (Capacitor Voltage Transformers) into operation. We used 3 electric-filed sensors to measure the three phase voltage. The placement is showed in Fig 7. Each sensor was placed besides the bottom of each insulator of the CVT side. The distance from ground to insulators was about 2.6 m, and the height of the insulators was about 2.4 m. The distance between two phases was 3.0 m. The other devices such as lasers, receivers and oscilloscope were placed in the central control room, and connected with the sensors by 100-meter-long optic fibers.

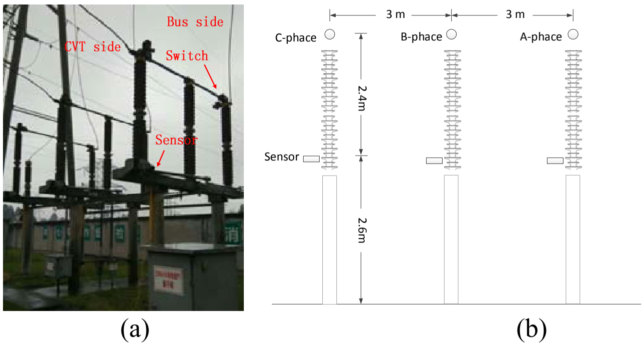


Fig. 7 Placement of the sensors in the substation

Before the operation, the switch was off. The bus side was charged while the CVT side not. Fig 8 shows the waveform of the overvoltage during the operation obtained by the measuring system. The process consists of two physical processes, namely charging process when the arc established and the discharging process when the arc extinguished. The capacity of the CVT is only about 5 nF, and the resistor of the charging circuit, including the conductor and the arc, is about several ohms, so the time constant of the charging process is about 10^{-9}~10^{-8} s by calculation, which can be inferred that the charging process completed instantaneously when the arc established. During the discharging process, the CVT mainly discharged through stray capacitance and leakage resistance. Since the resistance was of MΩ~GΩ magnitude, the time constant of the discharging process was about 10^{-2}~10^{-1} s, which led to a much slower discharging process compared to the charging process. Besides, the maintaining of the arc during the operation depends on the arc current, which equaled to the current of the CVT. The CVT current is about 0.3A in accordance with the voltage of 220 kV, the capacitance of 5 nF and the frequency of 50Hz. The current is too small to maintain the arc of dozens of cm. The whole progress can expressed as:

1) The progress began and the distance of the switch gap became smaller.

2) The gap cannot withstood the voltage and broke down. The voltage of the CVT became that of the bus.

3) As the current became too small, the arc cannot maintain and extinguished. The CVT started to discharge and the voltage decreased.

4) While there was a sufficient voltage difference between the bus and the CVT, the switch gap broke down again and process 2) ~ 4) repeated.

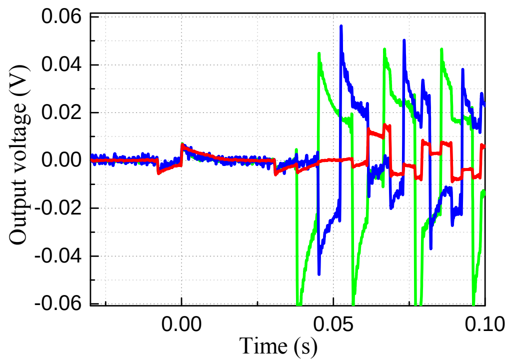


Fig.8 Waveform of the transient voltage (Blue-phase A; Red-phase B; Green-phase C)

The process reflected by the waveform in Fig 8 is consistent with the analysis above. Take phase C as an example, the output rose to -0.06V from 0, the switch gap broke down, and the CVT was charged to the bus voltage; then the arc extinguished, CVT began to discharge, the voltage decreases; about 0.045s, bus voltage changed to positive, there was sufficient voltage difference and the gap broke down again, and the output of the CVT voltage changed to the 0.045V.

Besides, from the waveform, voltage jumps can also be observed in the discharging process (see Fig 9). For example, the red circle and blue circle marked the voltage jumps of phase C at the time of 0.068s and 0.073s, respectively. They can match the time of the first charge process of phase B and phase A. That is to say, the measurement of the voltage of phase C is influenced by the other two phase.

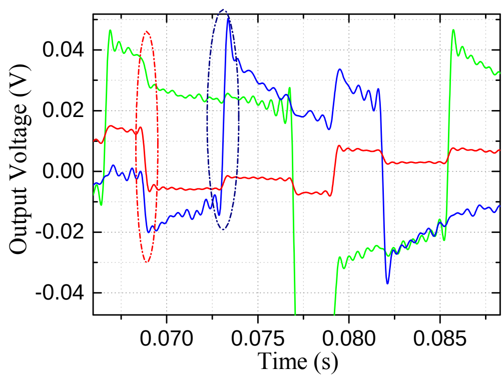


Fig.9 Partial waveform of the transient voltage

The output waveform after decoupling is shown in Fig. 10.

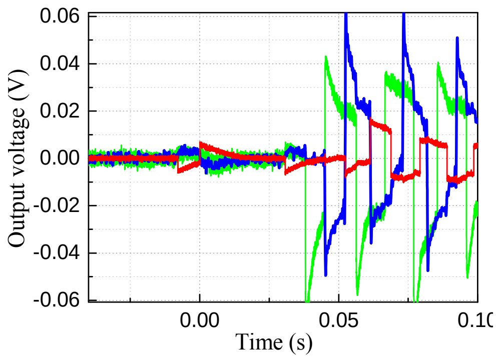


Fig.10 Waveform of the transient voltage after decoupling (Blue-A phase; Red-B phase; Green-C phase)

After the operation finished, the power frequency voltage was also measured. The decoupled waveform is shown in Fig 11. Comparing the amplitude of overvoltage with that of power frequency voltage, the three-phase overvoltage factors are 1.76, 1.46 and 1.82, respectively. Fig 12 shows a detailed waveform of a voltage jump during one charging process, whose front time was about 3μs.

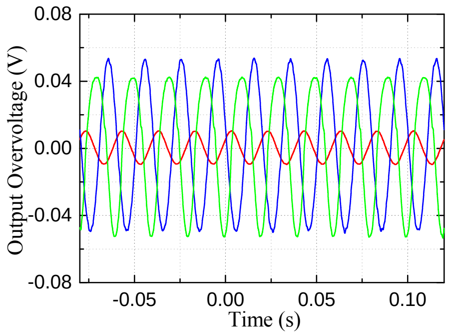


Fig.11 Waveform of power frequency voltage after decoupling (Blue-A phase; Red-B phase; Green-C phase)

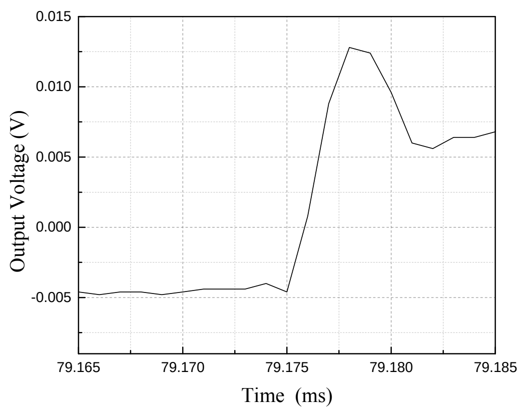


Fig.12 Detailed waveform of a voltage jump during one charging process

V. CONCLUSIONS

In this paper, a transient voltage measuring system based on the integrated electro-optic electric field sensor was proposed.

(1) The principle of the system was introduced and a transient voltage measuring system based on an integrated electro-optic sensor was implemented. For quasi-static field, the electric field around the conductor is proportional to the applied voltage and vice versa, which makes it possible to measure the electric field to obtain the transient voltage waveform.

(2) The performances of transient voltage measuring system was tested by simulation experiments in the laboratory. Experiments show the measuring error for both switching impulse transients and lightning impulse transients were within 3% compared to that of the standard divider.

(3) The field data of the transient overvoltage during the switching of a capacitor voltage transformer on a 220kV bus were proposed and discussed in detail according to the measured waveform, which indicates us that the transient measurement is helpful for process analysis.

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