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Compensation of Cross Talk Error for Optical Voltage Sensors

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This paper discusses the errors associated with electric field cross talk for optical voltage sensors in a three-phase electric system and provides a solution to compensate the errors. For many practical conductor configurations, the electric field cross talk may cause errors unacceptable for the accuracy requirements of the sensors. We devised a real time compensation method for the cross talk and built an electronic circuits based on it. The mechanism of the compensation and the corresponding error reduction were discussed.

OCIS codes : 120.0120, 120.1880

I. INTRODUCTION

Optical voltage sensors (OVSs) have been applied to monitor high voltage cables over the past 30 years. Such sensors offer a range of potential improvements such as reduced insulation requirements, increased operational bandwidth, weight and space minimization, and safe failure modes [1-3]. In modern electric equipment where many conductors are packed closely, the electric fields between the conductors are superimposed, which makes the measurement error large [4]. To measure the voltages accurately for these systems we need to build a compensation method for the electric field cross talk from adjacent conductors.

The compensation methods proposed so far were based on the dielectric shield of the interfering electric field. For example, Jaeger et al. utilized a dielectric cylinder in which the OVS was installed. The cylinder was made of material with high dielectric constant and had two electrodes at the top and bottom planes. The top electrode was in contact with the conductor whose voltage to be measured. The bottom electrode was connected to the ground. The inside of the cylinder was filled with nitrogen gas. The OVS measured the electric field within the cylinder. Using a cylinder with 4 m length and 10 cm thickness, they reported voltage measurement error of 0.2% for 230 kV [5].

However this kind of approach loses the major advantage of OVS's superiority in the point of insulation and results in a measurement system too bulky to apply to modern compact power electric equipment such as gas insulated switchgears (GISs).

This paper analyzes the electric field cross talk between conductors placed closely as in a GIS and proposes for the first time a means whereby the cross talk can be compensated without using any electric field shield.

II. PRINCIPLE OF OPERATION OF OPTICAL VOLTAGE SENSOR

Figure 1 shows a schematic structure of the optical voltage sensor used in this study. The light from the source (light emitting diode, LED) was transmitted through the optical fiber, collimated by the rod lens, and linearly polarized by the polarizing beam splitter (PBS). A Pockels cell of BSO ($Bi_{12}SiO_{20}$) was placed so that its two principal optical axes both made an angle of 45 degree with the axis of the linearly polarized light. Thin films of ITO (Indium Tin Oxide) were coated on both sides of the Pockels cell as transparent electrodes. One of the electrodes was in contact with the conductor as shown in Figure 1. The other electrode was floated. Therefore, the electric field or voltage between two electrodes was applied to the Pockels cell.

The Pockels cell split the linearly polarized light into two linearly polarized lights with phase difference δ. If the incident plane of the light is (001), the phase difference δ can be described as

$$\delta = \frac{2\pi}{\lambda} n_0^3 \gamma_{41} E_a L = \pi \frac{V_a}{V_\pi} \qquad (1)$$

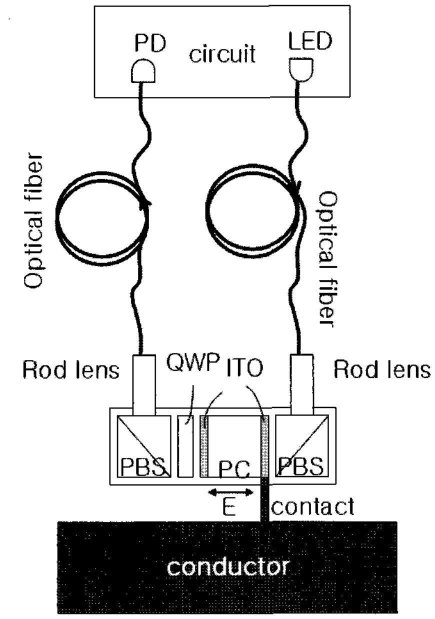

FIG. 1. Schematic structure of optical voltage sensor used. LED: Light Emitting Diode, PD: Photo-Diode, PBS: Polarizing Beam Splitter, PC: Pockels Cell, E: Electric field, ITO: Indium Tin Oxide thin film, QWP: Quarter Wave Plate.

where λ is the wavelength of the light, n_0 is the refractive index of ordinary light, γ_{41} is electro-optic coefficient or Pockels effect coefficient, E_a is the electrical field applied between two ITO electrodes, L is light pass length or the thickness of the Pockels cell parallel to the light pass, V_π $(= \lambda/2n_0^3\gamma_{41})$ is half wavelength voltage where $\delta = \pi$, and V_a $(= E_aL)$ is applied voltage.

Two linearly polarized beams with phase difference δ after being passed through the Pockels cell were optically biased by the quarter wave plate (QWP), changed into light intensity by the PBS analyzer, and finally converted into electrical signal proportional to the applied voltage by the photodiode (PD) and the electronic circuit [6].

III. ELECTRIC FIELD CROSS TALK ANALYSIS

Consider a system in which three conductors with three-phase voltage are separated on a plane and the optical voltage sensors are attached on top of each conductor. Label the conductors as conductors 1, 2, and 3 and the sensors as S_1, S_2 and S_3.

Let the three-phase voltage of the conductors 1, 2, 3 be V_1, V_2, V_3 and the output signals of the sensors S_1, S_2, S_3 be V_1^s, V_2^s, V_3^s respectively, then we can relate them as

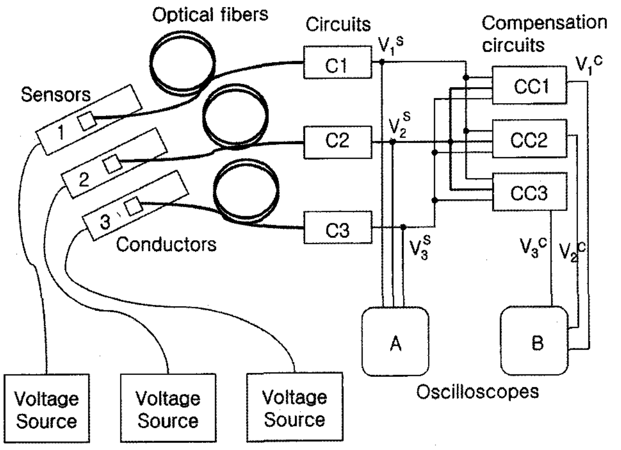

FIG. 2. Schematic diagram of experimental set up to measure the electric field cross talk. Also shown are the compensation circuits CC_1, CC_2, CC_3 to reduce the cross talk.

$$g_{11}V_1 + g_{12}V_2 + g_{13}V_3 = V_1^S \quad (2a)$$

$$g_{21}V_1 + g_{22}V_2 + g_{23}V_3 = V_2^S \quad (2b)$$

$$g_{31}V_1 + g_{32}V_2 + g_{33}V_3 = V_3^S \quad (2c) \qquad (2)$$

where g_{11}, g_{12}, g_{13}, g_{21}, g_{22}, g_{23}, g_{31}, g_{32}, g_{33} are geometric factors affected by the geometry and configuration of the sensors and conductors. The first term $g_{11}V_1$ in equation (2a) represents the electric field from the conductor 1 with voltage V_1. The second term $g_{12}V_2$ in equation (2a) shows the electric field from the conductor 2 with voltage V_2. The third term $g_{13}V_3$ in equation (2a) denotes the electric field from conductor 3 with voltage V_3.

The first term in equation (2a) is proportional to the voltage V_1 of the conductor 1 that we want to measure. The second and the third terms in equation (2a) play a role of cross talk because they come from conductors 2 and 3.

The sensor S_1 picks up all electric fields represented by the first, second and third terms in equation (2a) and gives output signal V_1^s. Let us call this 'raw signal' to differentiate from the compensated output discussed later.

Similarly the first and third terms in equation (2b) are the cross talk terms when we try to measure the voltage V_2 of the conductor 2. For the voltage V_3 of the conductor 3 the first and second terms are the cross talk terms.

Therefore unless the conductors are placed far enough so that the cross talk terms can be ignored, the cross talk cannot be avoided.

To measure the electric field cross talk we built an experimental set up as shown in Figure 2. The set up was composed of three conductors, voltage sources, and sensors installed on top of the conductors. Alternating voltages have been applied to the conductors using the voltage sources. The phases of the voltages were different from each other by 120 degrees. The raw signals (V_1^s, V_2^s and V_3^s) of the sensors were monitored by the oscilloscope A. The voltages applied were monitored using standard *VTs* (Voltage Transducers, not shown in the figure) at the position where the conductors were separated far enough so that the cross talk electric field of the adjacent conductors could be ignored. Figure 3 shows the photograph of the experimental setup.

Figure 4 shows the photograph of the raw signal (V_1^s, V_2^s and V_3^s) curves of the sensors obtained from the oscilloscope A when $V_1=V_2=V_3=$ 10 kV. Of three pairs of curves in the figure the ones smaller in amplitude are the curves of the standard VTs. As shown in the figure the phase and amplitude errors were unacceptably large before being compensated due to the electric field cross talk from the adjacent conductors.

IV. CROSS TALK COMPENSATION

To compensate the cross talk we need to know the geometric factors. They were determined experimentally as follows.

We applied 22.9 kV (V_1) to conductor 1 and zero voltages to conductors 2 and 3 ($V_2=V_3=0$). We read the raw signals V_1^s, V_2^s and V_3^s of the sensors. We substituted the known values of V_1, $V_2=V_3=0$, V_1^s, V_2^s and V_3^s into simultaneous equations (2) and calculated g_{11}, g_{21} and g_{31}. Similarly g_{12}, g_{22}, g_{32}, g_{13}, g_{23} and g_{33} were obtained.

Table 1 shows the raw signals V_1^s, V_2^s and V_3^s of the sensors so obtained. Equation (3) shows the geometric factors so obtained.

$$\begin{bmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{bmatrix} = \begin{bmatrix} 0.0437 & 0.0054 & 0.0015 \\ 0.0053 & 0.0437 & 0.0052 \\ 0.0014 & 0.0054 & 0.0437 \end{bmatrix} \tag{3}$$

Because the conductors and the sensors of the set up were placed in a plane and separated almost equally, the geometric factor matrix was almost symmetric against the diagonal elements g_{11}, g_{22} and g_{33}. If the conductors and the sensors were placed differently, a different set of geometric factors would be obtained.

Because what we want to know are the voltages V_1, V_2 and V_3 in conductors 1, 2, and 3, we need to substitute the geometric factors obtained into the simultaneous equations (2) and solve them about V_1, V_2 and V_3, which gave us simultaneous equations of the form of

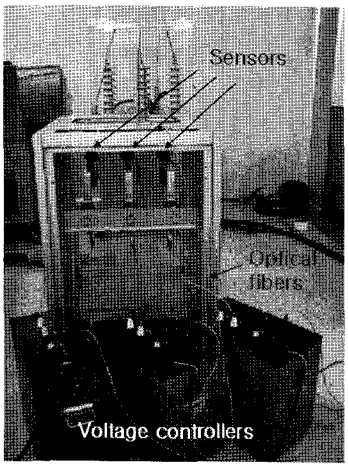

FIG. 3. Photograph of the experimental set up.

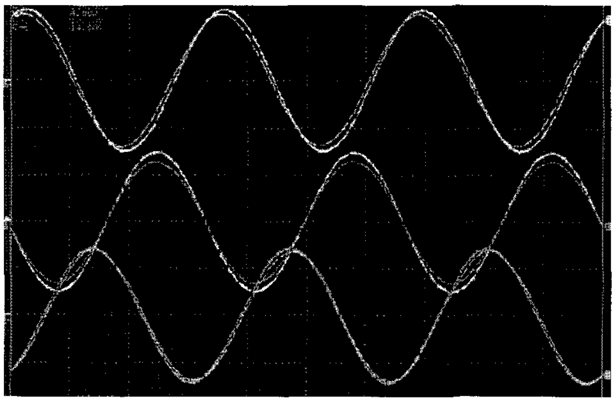

FIG. 4. Photograph of the raw signal (V_1^S, V_2^S and V_3^S) curves before being compensated of the sensors obtained from the oscilloscope A when $V_1=V_2=V_3=$ 10 kV.

Table 1. The raw signals V_1^S, V_2^S and V_3^S of the sensors S_1, S_2 and S_3 experimentally obtained to determine the geometric factors.

V_1 (kV)	V_2 (kV)	V_3 (kV)	V_1^S (mV)	V_2^S (mV)	V_3^S (mV)
22.9	0	0	1000	122	31
0	22.9	0	125	1000	123
0	0	22.9	35	129	1000

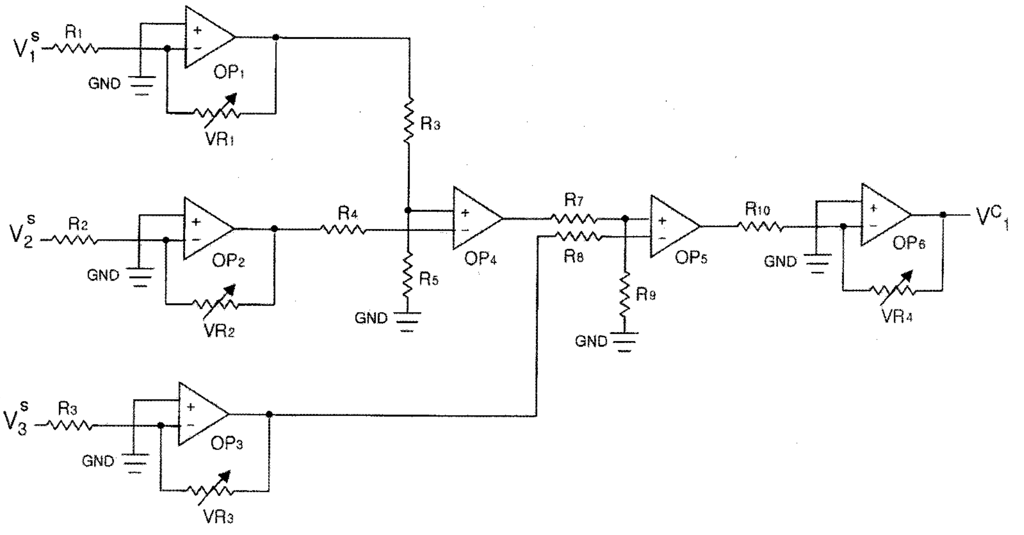

FIG. 5. Circuit diagram of a compensation circuit (CC_1). The V_1^S, V_2^S and V_3^S denote the raw signals from the sensors S_1, S_2 and S_3. The *R*, *VR* and *OP* represent resistor, variable resistor, and op amp. The *GND* denotes ground.

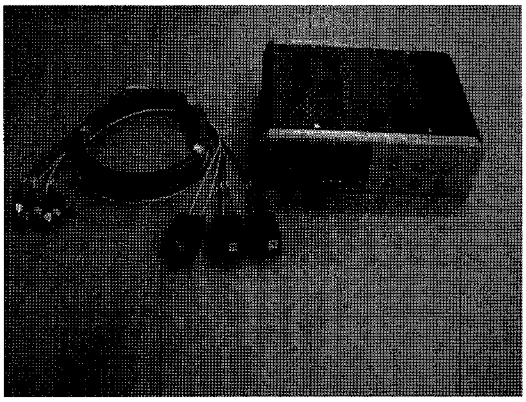

FIG. 6. The photograph of compensation circuits fabricated (box) and optical voltage sensors used.

$$V_1 = \alpha_{11}V_1^S + \alpha_{12}V_2^S + \alpha_{13}V_3^S = V_1^C \qquad (4a)$$

$$V_2 = \alpha_{21}V_1^S + \alpha_{22}V_2^S + \alpha_{23}V_3^S = V_2^C \qquad (4b)$$

$$V_3 = \alpha_{31}V_1^S + \alpha_{32}V_2^S + \alpha_{33}V_3^S = V_3^C \qquad (4c) \qquad (4)$$

with

$$\begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix} = \begin{bmatrix} 23.240 & -2.817 & -0.462 \\ -2.773 & 23.581 & -2.712 \\ -0.402 & -2.824 & 23.232 \end{bmatrix} \qquad (5)$$

where a_{11}, a_{12}, a_{13}, a_{21}, a_{22}, a_{23}, a_{31}, a_{32}, a_{33} are weight factors and V_1^C, V_2^C, V_3^C are the compensated outputs for conductor 1, 2, 3. Note that the compensated outputs V_1^C, V_2^C, V_3^C are expressed by the raw signals V_1^S, V_2^S, and V_3^S of the sensors. Also note that the signs of the diagonal elements a_{11}, a_{22}, and a_{33} of the weight factor matrix were positive and those of off-diagonal elements were negative reflecting the compensation nature. In addition note that the weight factor matrix was almost symmetric against the diagonal elements, because the conductors and the sensors of the set up were placed in a plane and separated almost equally.

To obtain the compensated outputs we built three compensation circuits (CC_1, CC_2, CC_3) as shown in Figure 2. Each compensation circuit gathered three raw signals V_1^S, V_2^S, V_3^S from three sensors, compensated the electric field cross talk from adjacent conductors by performing calculations based on equation (4), and produced the compensated output proportional to the voltage of the conductor to be measured.

Figure 5 shows a circuit diagram of one (CC_1) of the compensation circuits used to obtain the compensated output V_1^C for the voltage of conductor 1. The circuit was mainly composed of op amps and variable resistors. In the figure, V_1^S, V_2^S, V_3^S were the raw signals obtained from the sensor S_1, S_2, S_3, respectively. By adjusting the variable resistors VR_1, VR_2, VR_3, the weight factors a_{11}, a_{12}, a_{13} in equation (4a) have been set. Then the weighted signals have been added using op amps OP_4, OP_5. The final variable resistor VR_4 and op amp OP_6 were used to adjust the magnitude of the compensated output signal.

The compensation circuits CC_2 and CC_3 were composed and operated similarly to the compensated circuit CC_1. Figure 6 shows the circuits fabricated (box) and sensors used.

Now we applied alternating voltages to the conductors and monitored the compensated outputs V_1^C, V_2^C and V_3^C using the oscilloscope B in Figure 2. The voltages were varied in the range from 5 kV to 40 kV, maintaining $V_1 = V_2 = V_3$.

Figure 7 shows the photograph of the compensated output (V_1^C, V_2^C and V_3^C) curves obtained from the

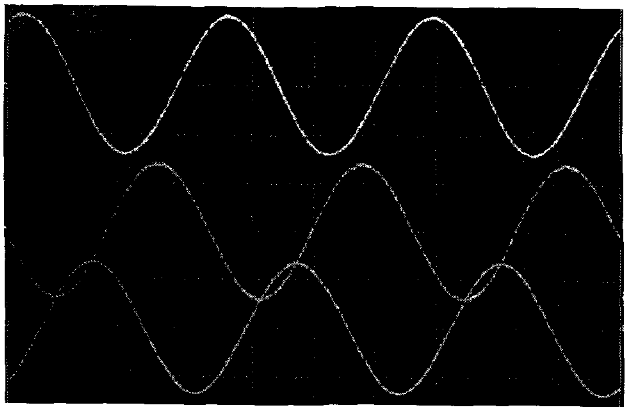

FIG. 7. The photograph of the compensated output (V_1^C, V_2^C and V_3^C) curves obtained from the oscilloscope B when $V_1 = V_2 = V_3 = 10$ kV.

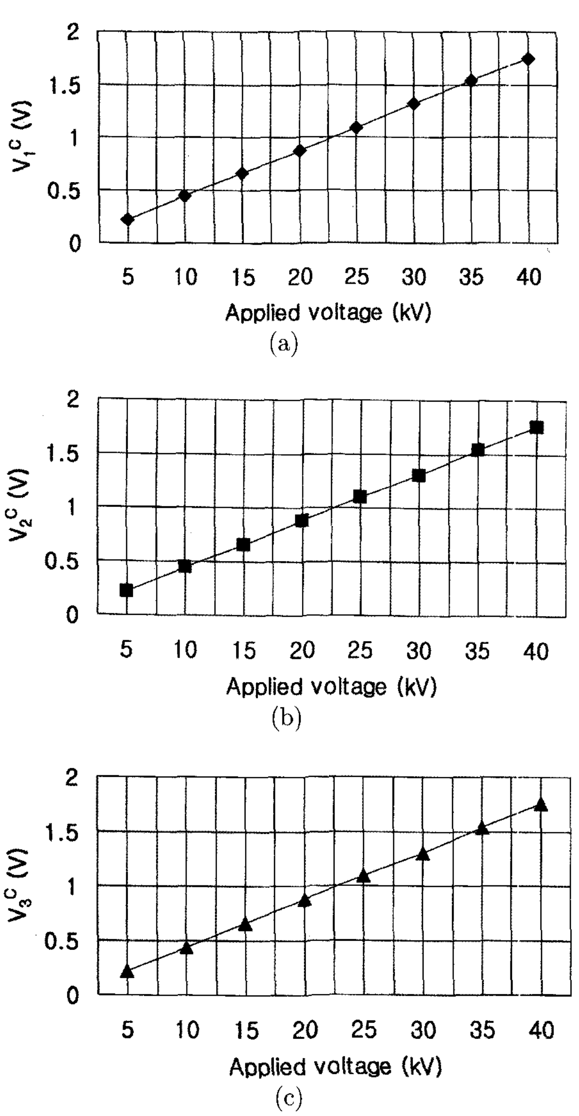

FIG. 8. The compensated outputs, (a) V_1^C, (b) V_2^C and (c) V_3^C, respectively, as a function of applied voltage ($V_1 = V_2 = V_3$).

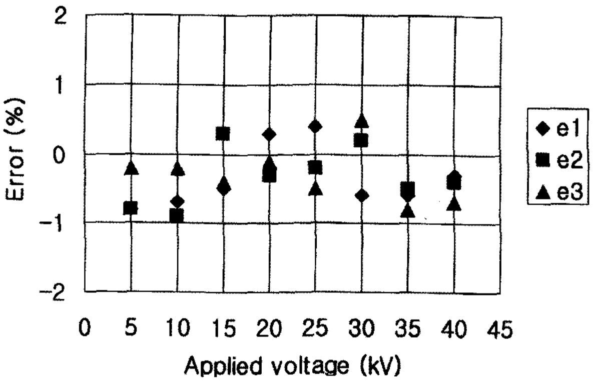

FIG. 9. Errors, e_1, e_2 and e_3, for the compensated outputs V_1^C, V_2^C and V_3^C, respectively.

oscilloscope B when $V_1 = V_2 = V_3 = 10$ kV. As shown in the figure the three pairs of curves of the compensated output and the standard VTs were overlapped, showing errors in phase and amplitude were reduced considerably by the compensation.

Figure 8 (a), (b) and (c) show the compensated outputs V_1^C, V_2^C and V_3^C, respectively, as a function of applied voltage ($V_1 = V_2 = V_3$). The outputs were root mean square values obtained from the output curves of the oscilloscope B similar to Figure 7. As shown in the figure a good linearity has been obtained for all three compensated outputs. Figure 9 shows linearity errors e_1, e_2, e_3 for the compensated outputs V_1^C, V_2^C and V_3^C. As shown in the figure the errors were within ± 1%.

The above results show that the compensated outputs can be obtained from the linear combination of the raw signals of the sensors. The compensation method discussed here can be applied to other voltage transducers. They can be fiber optic voltage transducers using piezoelectric or electrostrictive elements or Mach-Zehnder interferometers. They need not to be optical transducers. They can be electromagnetic voltage transducers that pick up electric fields to detect the voltage.

The compensation method is not restricted to the system with three conductors discussed here but can be generalized for the system having more or less conductors.

V. CONCLUSIONS

We have shown that for the conductor arrangements in many practical electric systems, the electric field cross talk may cause errors unacceptable for the accuracy requirements of the sensors. We devised a real time compensation method to reduce the cross talk by introducing geometric and weight factor matrices. The cross talk and the compensation natures were reflected in the matrices. We realized the method using simple electronic circuits and obtained the compensated outputs with errors considerably reduced.

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