Compensation of Electric Field Interference for Fiber-optic Voltage Measurement System

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In this paper, we analyze the errors associated with electric field interference for fiber-optic voltage sensors working in a three-phase electric system. For many practical conductor arrangements, the electric filed interference may cause errors unacceptable for the accuracy requirements of the sensors. We devised a real time compensation method for the interference by introducing geometric and weight factors. We realized the method using simple electronic circuits and obtained the real time compensated outputs with errors of 1 %.

Keywords : Fiber-optic voltage transducer, Optical voltage sensor, Pockels cell, Voltage measurement, Electric field interference

1. INTRODUCTION

Optical voltage sensing techniques have been internationally researched 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]. We describe in this paper the operation of optical voltage sensors using Pockels cell within environments that will be encountered in field applications. In these environments high voltage cables are often placed closely to save space so that the electric field interference from adjacent cables made measurement error large[4]. This paper evaluates the magnitude of the interference and proposes a means whereby the interference can be removed.

2. PRINCIPLE OF OPERATION OF OPTICAL VOLTAGE SENSOR

The optical Pockels cell voltage sensor detects the voltage of an electric conductor by measuring the electric field density within the vicinity of the conductor[5]. The electric field strength is determined by the phase difference between two linearly polarized lights induced as the light propagates through a sensitive crystal or Pockels cell.

The phase difference is a function of field strength, the interaction length, and the Pockels effect coefficient of the material used. The phase difference δ experienced by the light passing through the sensor is described as

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

where λ is 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 to the Pockels cell, 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 $(= E_a L)$ is applied voltage.

The sensors used in this research had two transparent electrodes of ITO (Indium Tin Oxide) thin films coated on both side of the Pockels cell. One of the electrodes was electrically contacted with the electrode using a metal wire and the other was electrically floated. The Pockels cell was a BSO ($Bi_{12}SiO_{20}$) single crystal.

3. ELECTRIC FIELD INTERFERENCE

Consider a system in which three conductors with three-phase voltage are equally separated on a plane and the optical voltage sensors are attached on top of the conductors, respectively. 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 they can be related as shown in equation (2).

$$g_{11}V_1 + g_{12}V_2 + g_{13}V_3 = V_1^S \quad (2a)$$
$$g_{21}V_1 + g_{22}V_2 + g_{23}V_3 = V_2^S \quad (2b)$$
$$g_{31}V_1 + g_{32}V_2 + g_{33}V_3 = V_3^S \quad (2c) \qquad (2)$$

In equation (2) 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 of the sensors and conductors. The first term $g_{11}V_1$ in equation (2a) represents the electric filed 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 interference 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 interfering 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 interfering terms.

Therefore unless the conductors placed far enough so that the interfering terms can be ignored, the interference can not be avoid.

To measure the electric interfernce we built an experimental set up as shown in Fig. 1. Alternating voltages have been applied to the conductors using voltage sources. The phases of the voltages were different from each other as 120 degree. The raw signals (V_1^S, V_2^S and V_3^S) of the sensors were monitored by oscilloscopes (not shown in the figure). 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 interfering electric field of the adjacent conductors could be ignored.

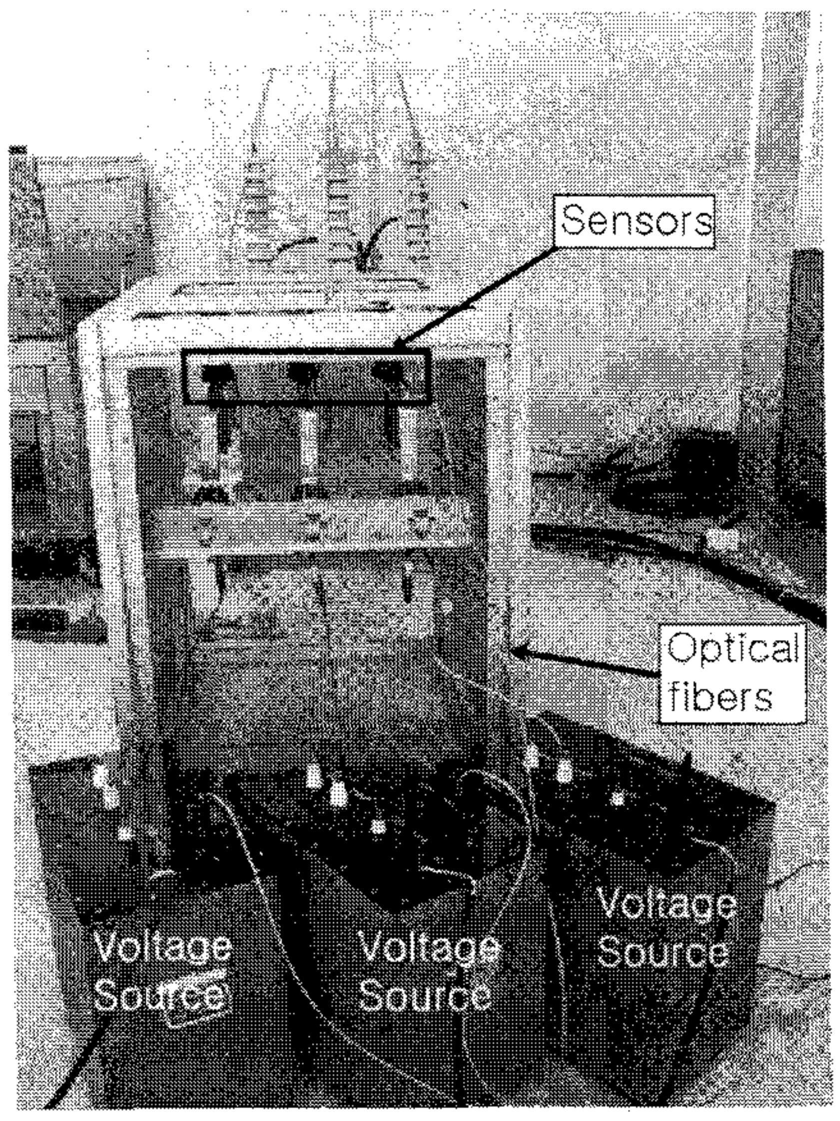

Fig. 1. Photograph of experiment setup to measure the electric field interference. Optical voltage sensors (small black boxes) were placed on top of the electric conductors or bus bars connected to the voltage sources.

Table 1. The errors e_1^S, e_2^S and e_3^S of raw signals V_1^S, V_2^S and V_3^S of the sensors S_1, S_2 and S_3 experimentally obtained.

V_1 (kV)	V_2 (kV)	V_3 (kV)	e_1^S (%)	e_2^S (%)	e_3^S (%)
22.90	22.90	22.90	-16	-24	-16
22.90	27.50	22.90	-18	-44	-18
22.90	27.50	16.00	-17	-41	12
18.30	22.90	20.60	5	21	5
18.30	22.90	17.20	5	-19	10
16.00	22.90	22.90	14	-20	-15
27.50	29.80	22.90	-40	-57	-20
32.10	36.60	22.90	-64	-89	-24

Table 1 shows the errors (e_1^S, e_2^S and e_3^S) of the raw signals (V_1^S, V_2^S and V_3^S) of the sensors. As shown in the table the errors were unacceptably large before being compensated due to the electric field interference from the adjacent conductors.

Table 2. 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 (V)	V_3 (V)	V_1^S (mV)	V_2^S (mV)	V_3^S (mV)
22.9	0	0	1000	122	31
0	22.9	0	125	100	123
0	0	22.9	35	129	1000

4. INTERFERENCE COMPENSATION

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

First, we applied 22.9 kV (V_1) to conductor 1 and zero voltages to conductors 1 and 2 ($V_2 = V_3 = 0$). 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}.

Second, we applied 22.9 kV (V_2) to conductor 2, and zero voltages to conductors 1 and 3 ($V_1 = V_3 = 0$). 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_2, $V_1 = V_3 = 0$, V_1^S, V_2^S and V_3^S into simultaneous equations (2) and calculated g_{12}, g_{22} and g_{32}.

Third, we applied 22.9 kV (V_3) to conductor 3, and zero voltages to conductors 1 and 2 ($V_1 = V_2 = 0$). 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_3, $V_1 = V_2 = 0$, V_1^S, V_2^S and V_3^S into simultaneous equations (2) and calculated g_{13}, g_{23} and g_{33}.

Table 2 shows the raw signals V_1^S, V_2^S and V_3^S of the sensors so obtained. By substituting the V_1, V_2, V_3, V_1^S, V_2^S and V_3^S into equation (2) we obtained the geometric factors as follows.

$$g_{11} = 0.0437,\ g_{12} = 0.0054,\ g_{13} = 0.0015$$
$$g_{21} = 0.0053,\ g_{22} = 0.0437,\ g_{23} = 0.0052$$
$$g_{31} = 0.0014,\ g_{32} = 0.0054,\ g_{33} = 0.0437 \quad (3)$$

Because the conductors and the sensors of the set up were placed in a plane and separated almost equally, g_{11}, g_{22} and g_{33} were similar, g_{12}, g_{21}, g_{23} and g_{32} were similar, and g_{13} and g_{31} were similar. 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 will give us simultaneous equations of the form of equation (4).

$$V_1 = \alpha_{11}V_{S_1} + \alpha_{12}V_{S_2} + \alpha_{13}V_{S_3} = V_1^C \quad (4a)$$
$$V_2 = \alpha_{21}V_{S_1} + \alpha_{22}V_{S_2} + \alpha_{23}V_{S_3} = V_2^C \quad (4b)$$
$$V_3 = \alpha_{31}V_{S_1} + \alpha_{32}V_{S_2} + \alpha_{33}V_{S_3} = V_3^C \quad (4c) \qquad (4)$$

The coefficients α_{11}, α_{12}, α_{13}, α_{21}, α_{22}, α_{23}, α_{31}, α_{32}, α_{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.

Equation (5) shows the weight factors calculated by substituting the geometric factors into equation (2) and solving the equation about V_1, V_2 and V_3.

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

Note that the signs of α_{11}, α_{22}, and α_{33} were positive and those of rest of the weight factors were negative reflecting the compensation process. Because the conductors and the sensors of the set up were placed in a plane and separated almost equally, α_{11}, α_{22} and α_{33} were similar, α_{12}, α_{21}, α_{23} and α_{32} were similar, and α_{13} and α_{31} were similar.

To obtain the compensated outputs an experimental set up has been built as shown in Fig. 2. Three compensation circuits (CC_1, CC_2, CC_3) were added to the set up shown in Fig. 1.

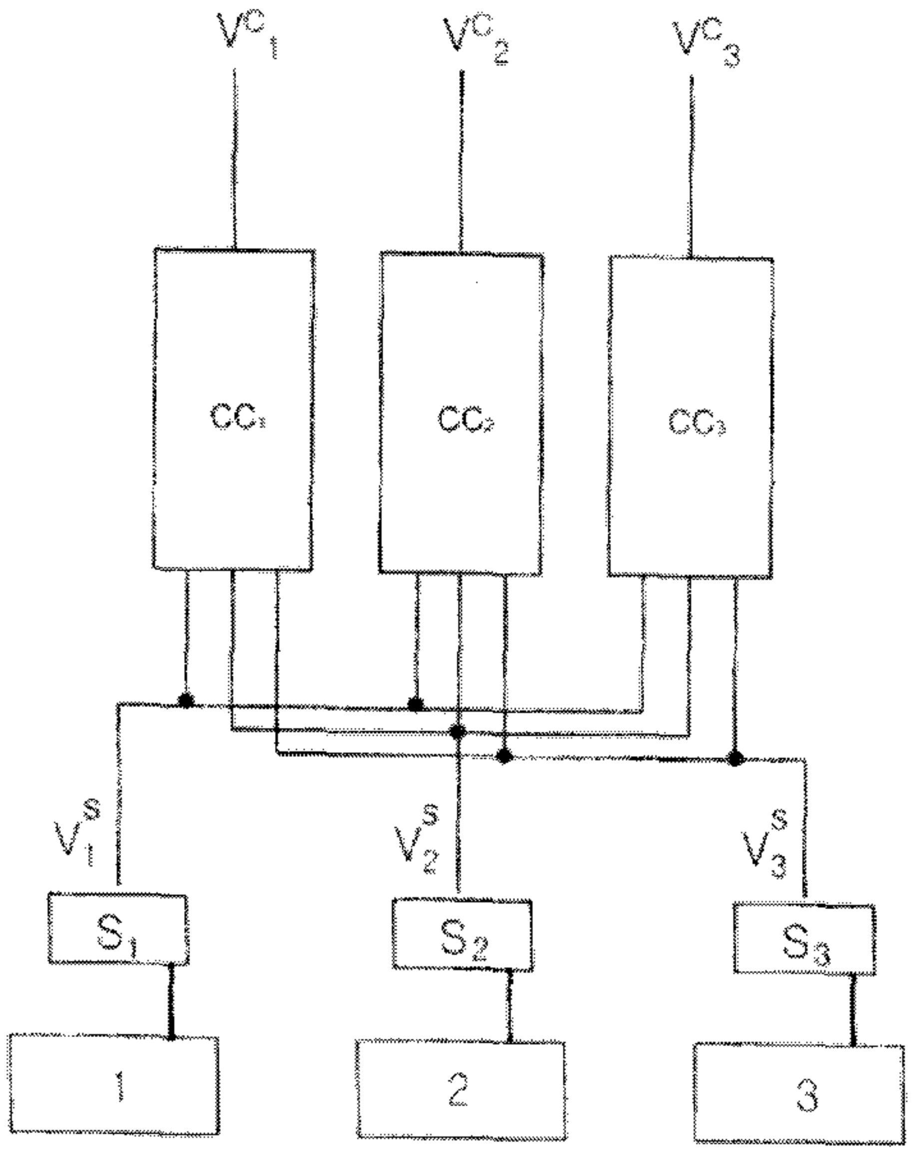

Fig. 2. Schematic diagram of experiment setup for the cross talk compensation. Optical voltage sensors (S_1, S_2, S_3) were placed on top of the electric conductors (1, 2, 3). The raw signals (V_1^S, V_2^S, V_3^S) from the sensors were compensated in the circuits CC_1, CC_2, CC_3 to produce compensated outputs (V_1^C, V_2^C, V_3^C) proportional to the voltages.

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 conducting calculations based on equation (4), and produced the compensated output proportional to the voltage of the conductor to be measured.

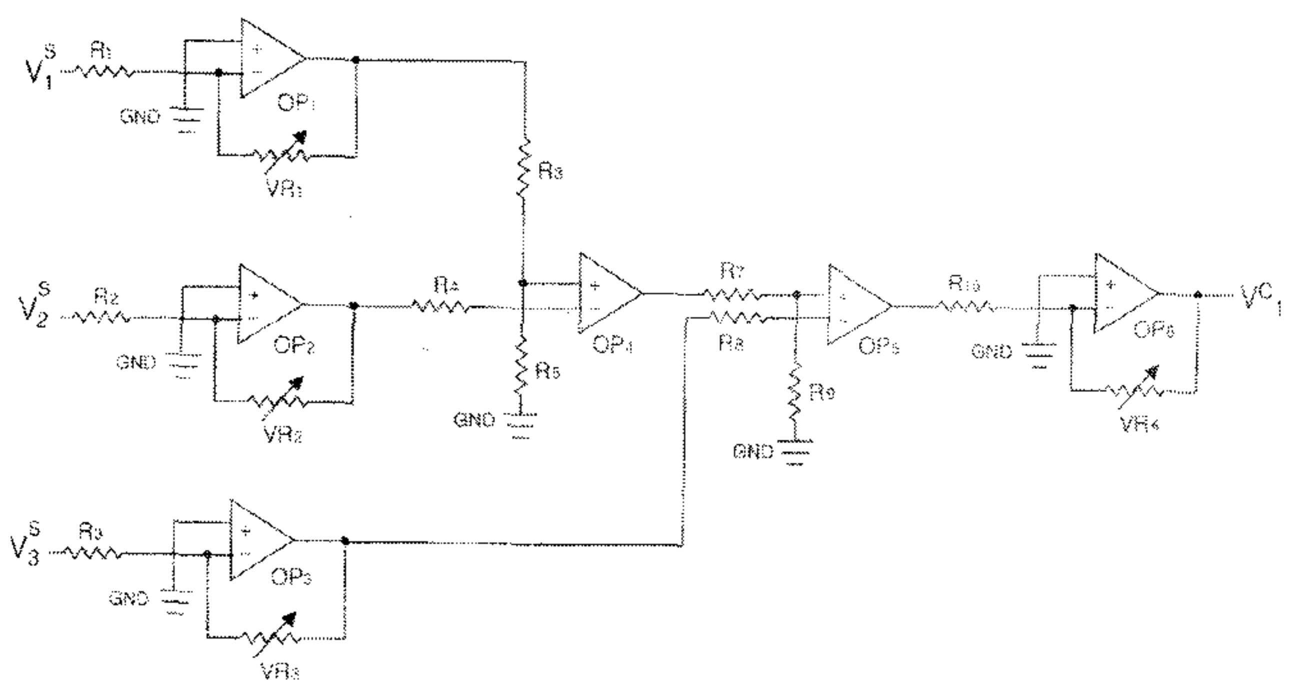

Fig. 3. Circuit diagram of a compensation circuit. The V_1^S, V_2^S and V_3^S denote the raw signals from the sensors S_1, S_2 and S_3. The *R*, *VR* and *OP* represent resistor, variable resistor, and op amp. The *GND* denotes ground.

Figure 3 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 α_{11}, α_{12}, α_{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 4 shows the photograph of the sensors and the compensated circuit fabricated.

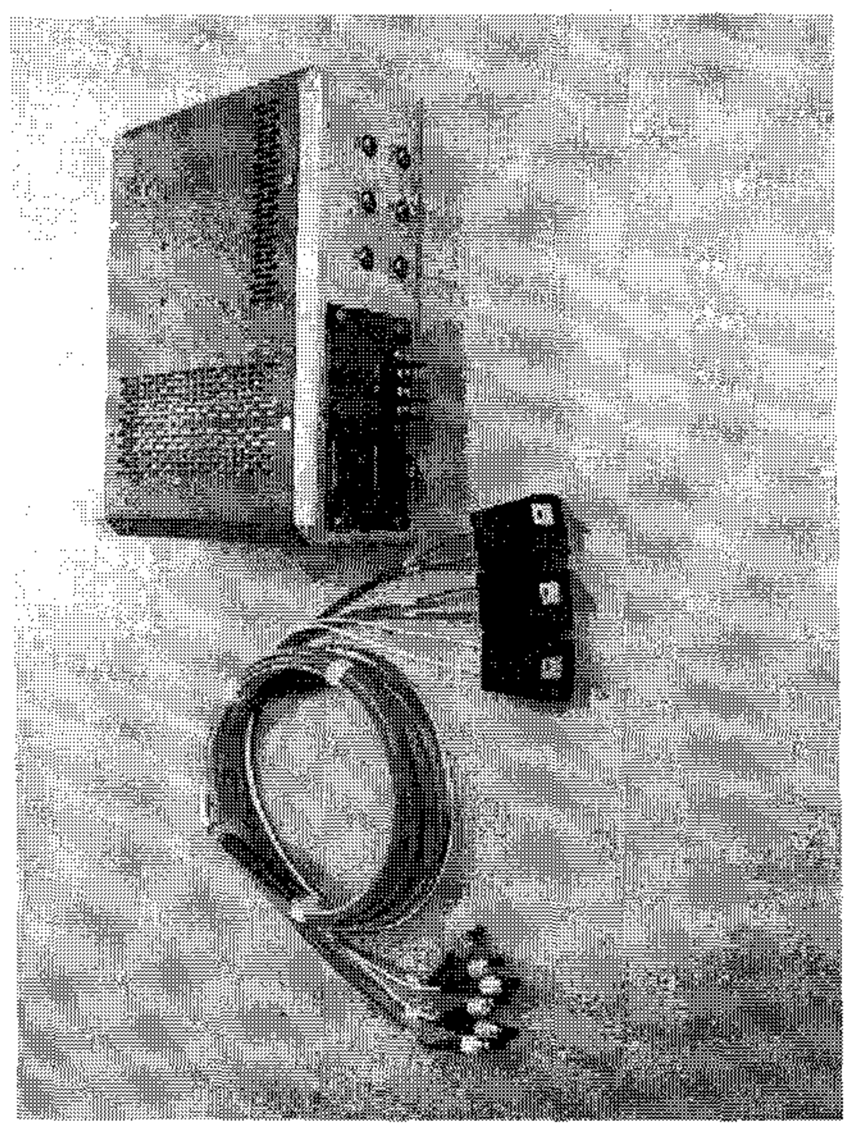

Fig. 4. Photograph of the sensors and the compensated circuit fabricated.

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 oscilloscopes.

Table 3 shows V_1^{CC}, V_2^{CC} and V_3^{CC} converted from the compensated outputs V_1^C, V_2^C and V_3^C read from the oscilloscopes. The errors e_1, e_2, and e_3 between V_1^{CC}, V_2^{CC}, V_3^{CC} and V_1, V_2, V_3 are also shown. As shown in Table 3, the errors after being compensated were reduced to 1.0 %.

Table 3. The V_1, V_2 and V_3 denote the voltages applied to the conductors 1, 1, and 3. The V_1^{CC}, V_2^{CC} and V_3^{CC} represent converted voltages from the compensated outputs V_1^C, V_2^C and V_3^C, respectively. The e_1, e_2, and e_3 are the errors between V_1, V_2, V_3 and V_1^{CC}, V_2^{CC} and V_3^{CC}. The units of voltage and error are kV and %, respectively.

V_1	V_2	V_3	V_1^{CC}	e_1	V_2^{CC}	e_2	V_3^{CC}	e_3
22.90	22.90	22.90	22.90	0.0	22.90	0,0	22.88	0.1
22.90	27.50	22.90	22.88	0.1	27.47	0.1	22.85	0.2
22.90	27.50	16.00	22.83	0.3	27.44	0.2	15.97	0.2
18.30	22.90	20.60	18.35	-0.3	22.88	0.1	20.51	0.4
18.30	22.90	17.20	18.37	-0.4	22.85	0.2	17.10	0.6
16.00	22.90	22.90	15.97	0.2	22.90	0.0	22.83	0.3
27.50	29.80	22.90	27.39	0.4	29.71	0.3	22.97	-0.3
32.10	36.60	22.90	32.26	-0.5	36.49	0.3	23.06	-0.7

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

The compensated method can be generalized for the system having more and less conductors. The generalization is straight forward. As the number of conductors increases or decreases, the number of equations accordingly increases or decreases.

5. CONCLUSION

We analyzed the errors associated with electric field interference for fiber-optic voltage sensors working in a three-phase electric system. For the conductor arrangement of the experimental set up resembled practical electric system, the electric filed interference caused errors unacceptable for the accuracy requirements of the sensors. We devised a real time compensation method to eliminate the interference by introducing geometric and weight factors. We realized the method using simple electronic circuits and obtained the real time compensated outputs with errors of 1 %.

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