Studies in electromagnetic compatibility of optical and digital current and voltage transformers

V D Lebedev and A A Yablokov

Ivanovo State Power Engineering University, 34, Rabfakovskaya str., Ivanovo, 153003, Russia

E-mail: AndrewYablokov@yandex.ru

Abstract. The use of microprocessor devices for relay protection and automation, devices for measuring and determining electric power quality permits the introduction and development of digital circuits leading from primary current and voltage transformers. The use of optical channels for digital circuits addresses the problem of offsetting electromagnetic interference and voltage shift. Creating optical and digital current and voltage transformers with digitization of signals already at high measuring transformer voltage is the best solution for the above problem of mechanical engineering in the field of electromagnetic compatibility of high voltage measuring transformers. However, a difficulty arises in ensuring electromagnetic compatibility of sensors and microelectronic equipment adjoining live parts. The present study is devoted to examining the impact of electromagnetic fields on sensors and solving the problems of electromagnetic compatibility of optical and digital current and voltage transformers.

1. Introduction

The development of electric power involves introduction of modern microprocessor devices for relay protection, automation, diagnostic and measurement means etc. [1-3] With all the above devices, information on current and voltage has traditionally been communicated via secondary circuits from primary measuring converters of current and voltage transformers. Microprocessor devices are the most sensitive elements in the above circuit. No transitional electromagnetic processes in current and voltage measurement transformers are permissible for sensitive microprocessor devices.

To reduce the effect of primary converters there exists the notion of safety coefficient, which, however, does not protect microprocessor equipment against secondary circuit interference. A solution to this problem of mechanical engineering might be to use optical transformers or digital transformers with digitization of signals received from the primary converter at the place of the transformers’ installation [4-6]. The above signals are transmitted via an optic cable as light signals unexposed to the effect of electromagnetic interference resulting from industrial and radio frequency current fields. The most promising approach is digitization of the signals immediately at high potential with simultaneous provision of high voltage insulation [7, 8].

It should be noted that electronics (ADCs, microprocessors, power units, optical transmitters) subjected to high voltage can in real conditions be exposed to intense electromagnetic action. It is therefore important to fulfil measures to ensure conditions of electromagnetic compatibility in accordance with the functional resilience of the microelectronics located next to and even inside live
parts. Providing these conditions is related to theoretical research based on studies of electromagnetic fields, to choosing optimal locations for electronic equipment and to developing shielding harness.

2. Studying electromagnetic compatibility of optical voltage transformers

In recent times, optical current and voltage transformers have gained wide publicity. In optical voltage transformers, the sensors (optical crystals), which are located in the insulating column body (figure 1), respond to an electrical field, rotating the light polarization plane, measured with the aid of optical sensors. The electrical field in the transformer’s insulator body and the actual crystals is determined by the voltage applied to the transformer, and also depends on a number of other factors, such as the nearby presence of high-voltage live parts and earthed units of electrical equipment metal structures. All these elements distort the electrical field not only around but also inside the transformer’s insulator body.

To evaluate the impact of high-voltage conductors we performed analytical calculations to determine the electrical field at the location of optical voltage converters. These calculations were based on the following assumptions: dielectric permittivity of the support structure of the transformer’s insulator being equal to one; the electrical field’s sources being the endless conductors located in the upper part of the transformer (figure 1), which permits us to regard the field as plane-parallel.

Taking into account the above assumptions, we may determine the values of electrical field voltage along the axis of maximum transmitter sensitivity using the method of image charges, and also on the basis of Maxwell’s postulate, assuming earth dielectric permittivity to be equal to infinity, according to the following formulae:

\[
E_y^M = \sum_{i=1}^{n} E_y^{IM},
\]

where \(i\) – conductor number, \(n\) – quantity of conductors; \(E_y^{IM}\) – electrical field intensity created by \(i\)-conductor at point \(M\) and determined according to the following formulae:

\[
E_y^{IM} = |\vec{E}_y^{IM}|; E_y^{2M} = |\vec{E}_y^{2M}| \frac{a_{2M}}{a_{2M}}; E_y^{3M} = |\vec{E}_y^{3M}| \frac{a_{3M}}{a_{3M}};
\]

\[
E_y^{4M} = |\vec{E}_y^{4M}|; E_y^{5M} = |\vec{E}_y^{5M}| \frac{b_{2M}}{b_{2M}}; E_y^{6M} = |\vec{E}_y^{6M}| \frac{b_{3M}}{b_{3M}}.
\]

The module of electrical field intensity of an endless line conductor is determined by the formula:

\[
|\vec{E}_y| = \frac{\tau_i}{2\pi\varepsilon_0 r_M},
\]

where \(\tau_i\) – conductor charge, C; \(r\) – distance from \(i\)-conductor to point \(M\), m; \(\varepsilon\) – dielectric medium permittivity.

Conductor charges may be determined according to the second group of Maxwell equations:

\[
\begin{align*}
\tau_1 &= \beta_{11}\phi_1 + \beta_{12}\phi_2 + \beta_{13}\phi_3; \\
\tau_2 &= \beta_{21}\phi_1 + \beta_{22}\phi_2 + \beta_{23}\phi_3; \\
\tau_3 &= \beta_{31}\phi_1 + \beta_{32}\phi_2 + \beta_{33}\phi_3;
\end{align*}
\]

where \(\beta_{11}\beta_{33}\) – volume coefficients related to potential coefficients \(\alpha_{11}\alpha_{33}\) of the first Maxwell equation group as:

\[
[\alpha] = [\beta]^{-1}.
\]
Figure 1. Optical voltage transformer: a – three-dimensional model; b – structure; c – location on open switchgear; d – diagram for calculating sensor electrical field.

Potential coefficients are determined using formulae obtained by the image charges method (figure 1, d):

$$\alpha_{km} = \frac{1}{2\pi\varepsilon_0} \ln \frac{h_{km}}{\alpha_{km}}, \quad \alpha_{kk} = \frac{1}{2\pi\varepsilon_0} \ln \frac{2h}{r},$$  \hspace{1cm} (6)

where \( h \) – distance from conductor to earth’s surface, m; \( r \) – conductor radius, m.

Analysis of the impact of live parts is performed for standard equipment layout at a substation’s open switchgear. Research shows that the greatest impact on transformer sensors is caused by bus conductors under high voltage of their own phase (at which voltage is measured) and neighbouring phases.

Calculations made according to the above analytical formulae show that the level of interference from neighbouring phases is rather high, and may reach 10% of the useful signal.

For more detailed study, we developed two-and three-dimensional mathematical models based on differential equation solutions using the finite element method with MATLAB and COMSOL Multiphysics software.
The computed electrical field pattern for positioning of three voltage transformers is shown in figure 2.

![Figure 2. Distribution of electrical potential (contours) and electrical field (arrows).](image)

The results of our calculations enable us to determine electrical field values in a measuring transformer’s sensors caused by both applied voltage and neighbouring phase voltage (figure 3). Studies based on the developed mathematical models confirmed earlier results obtained with analytical formulae.

![Figure 3. Electric field intensity created by first conductive: 1 – field distribution in the first voltage transformer; 2 – field distribution in the second voltage transformer (interference); 3 – field distribution in the third voltage transformer (interference).](image)

Table 1 shows the results of examining the dependence of optical voltage transformer error due to interference from neighbouring phases on the number and location of Pockels cells.

The impact of interference on measuring accuracy may be reduced by:
- using metal shields with sufficient insulation gaps;
- using materials with high dielectric permittivity;
- algorithmic processing of signals, taking into account neighbouring phase voltage.
None of these solutions can entirely preclude the shortcomings described earlier, being technically difficult to implement [9]. Furthermore, external factors (temperature, pressure and vibration) have an impact on the output signal of optical transformers, which adversely affects the accuracy of measurement [12-14].

It should be noted that this problem does not exist in conventional electromagnetic and capacitor transformers, as the electric field is formed by the voltage divider created by single transformer cascades in electromagnetic transformers, or by capacitor cascades in capacitor transformers.

| Number of cells | Location of cells* | Amplitude error, % | Phase error, degrees |
|-----------------|--------------------|--------------------|---------------------|
| 1               | top 1              | 5.929              | 3.134               |
|                 | top 2              | 2.596              | 1.586               |
|                 | centre             | 3.392              | 2.046               |
|                 | bottom 2           | 3.841              | 2.257               |
|                 | bottom 1           | 4.106              | 2.377               |
| 2               | top 1, centre      | 4.487              | 2.420               |
|                 | top 1, bottom 1    | 5.713              | 3.031               |
|                 | centre, bottom 1   | 3.469              | 2.082               |
|                 | top 2, centre      | 2.827              | 1.718               |
|                 | top 2, bottom 2    | 2.879              | 1.736               |
|                 | centre, bottom 2   | 3.580              | 2.134               |
| 3               | top 1, centre, bottom 1 | 4.330 | 2.342 |
|                 | top 2, centre, bottom 2 | 3.002 | 1.810 |
| 5               | top 1, top 2, centre, bottom 2, bottom 1 | 1.986 | 1.110 |

* Top1 presupposes cell position at height of 1.113 m above support level; Top 2 – 0.86 m; Centre – 0.613 m; bottom 2 – 0.363 m; bottom 1 – 0.113 m

The authors’ design for digital voltage transformers uses low-power voltage dividers with sufficient intrinsic conductance to ensure the target accuracy class, taking into account the impact of electromagnetic field interference [10, 11].

3. Examining electromagnetic compatibility of digital current and voltage transformers

Digital current measuring transformers (DCT) and combined digital current and voltage transformers (DCVT) contain electronic units on the primary side i.e. under the primary conductor’s potential in the zone of intense magnetic fields.

Digital transformers envisage arrangement of microprocessor equipment with ADC inside the conductive shield used directly as a conductor (figure 4, a).

Arranging electronic equipment inside the cylindrical conductor is the most effective option, as demonstrated by our studies. In accordance with the law of total current

\[
\int \vec{H} \vec{dl} = i,
\]

and bearing in mind axial symmetry, there is no magnetic field inside an infinitely long live cylindrical conductor. Numerical calculation of electromagnetic field in a real conductor (figure 4,b) also confirms minimal field inside the conductor.

For initial evaluation of electromagnetic impact, the field may be resolved into two components – longitudinal and lateral.
Let us consider a cylindrical conductor in a longitudinal magnetic field. Here the external magnetic field $\vec{H}_0$ causes electromagnetic induction in the electromotive force conductor, determined by the equation:

$$\oint \vec{E} \, d\vec{l} = -\frac{d\Phi}{dt}. \quad \text{(8)}$$

For sinusoidally varying magnetic fields the equation may be written as:

$$\oint \vec{E} \, d\vec{l} = -\frac{j\omega \vec{H}_0 \mu}{2} \cdot \vec{dl}. \quad \text{(9)}$$

![Figure 4](image)

**Figure 4.** Geometry of a current conductor with internal space to accommodate microelectronics (a) and calculation of magnetic field intensity [A/m] at primary current of 1000 A (b).

The field inside $\vec{H}_i$ is determined by external field $\vec{H}_0$ taking into account the compensating effect of a field created by current along the circumference of the cylinder, the density of which is determined by the equation $\delta = \vec{E} \cdot \gamma$, where $\gamma$ - material conductance. It is not difficult to show that the higher the conductance, the higher the shielding constant, because material conductance is a finite value and it will therefore be impossible to absolutely exclude magnetic field inside the tube. Moreover, the shielding effect depends on frequency and is entirely absent with magnetic field that is constant in time (table 2).

Magnetic permittivity of the cylinder significantly influences emergence of the magnetic field pattern, though as a rule, magnetic field strength inside the tube is not reduced.

Screen attenuation $b_0$ for high and low frequencies may be approximately determined by the following formula Dyakov et al [15]:

$$b_0 = \ln \left[ \frac{\vec{H}_i}{\vec{H}_0} \right] \approx \begin{cases} \frac{1}{2} \ln \left[ 1 + \left( \frac{\omega \mu_0 \gamma D d}{2m} \right) \right] & \text{for } d < \delta, \\
\frac{d}{\delta} + \ln \left( \frac{\mu_0 D}{\mu} \right) - \frac{D}{2\sqrt{2m}} & \text{for } d > \delta, \end{cases} \quad \text{(10)}$$

where $D$ – tube inner diameter, $d$ – wall thickness, $\delta = \left( \frac{2}{\omega \mu_0 \gamma} \right)^{1/2}$ - equivalent depth of penetration, $m$ – coefficient, for cylindrical shields equal to two.

Lateral magnetic field is also attenuated inside the cylindrical conductor (figure 5). With low frequency electromagnetic impact a significant factor is the field’s magnetic component. In this case, the shielding effect is significantly influenced by the magnetic permittivity of the material $\mu$ (as distinct from the shielding effect in a longitudinal magnetic field). For a cylindrical shield with
internal tube radius $\mu$, external radius $r_2$ and relative magnetic permittivity of the shield metal $\mu$ the shielding coefficient (constant) for a homogeneous field with intensity $H_0$ is determined by the formula

$$k_s = \frac{H_0}{H_r} = 1 + \frac{(\mu - 1)}{4\mu} \left(1 - \frac{r_1^2}{r_2^2}\right).$$

Electromagnetic shielding predominates at high frequencies. The field’s induced electrical component along the conductor (figure 5) results in the emergence of currents which in turn create a compensating magnetic field inside the cylinder (Table 2).

Figure 5. Cylindrical shield with lateral magnetic field.

The above resolution into the conducting tube’s own field and external homogeneous longitudinal and lateral fields permits evaluation of the shielding effect. However, examination of the impact of the magnetic field of a digital transformer’s live parts requires proper three-dimensional field simulation, taking into account the live parts total geometry. For this purpose we created a field model, the geometry of which is shown in figure 6, a, enabling us to study magnetic field distribution both within and outside the measuring and converting parts of a digital current transformer.

For our simulation we used the following space-frequency equations:

$$-\nabla \left((j\omega\gamma)\vec{A} + (\gamma)\nabla U\right) = 0,$$

$$(j\omega\gamma)\vec{A} + \nabla \times (\mu_0^{-1}\mu^{-1}\nabla \times \vec{A}) + (\gamma)\nabla U = 0.$$

To solve this equation (12) requires addition of the necessary border conditions. The task was fulfilled with the aid of COMSOL Multiphysics software, in which the obtained three-dimensional patterns (figure 6) enable us to accurately determine levels of electromagnetic activity, select the material and dimensions for additional shielding elements.

Figure 6. Geometry of a three-dimensional model of a digital transformer’s live part (a), and the magnetic field pattern (b).
### Table 2. Magnetic field power lines pattern

| Freq., Hz | Relative magnetic permittivity | \( \mu = 1 \) | \( \mu = 10 \) | \( \mu = 100 \) |
|-----------|--------------------------------|---------------|----------------|----------------|
| Longitudinal external field |                      |               |                |                |
| 0         | ![Image](image1.png)          | ![Image](image2.png) | ![Image](image3.png) |
| 10        | ![Image](image4.png)          | ![Image](image5.png) | ![Image](image6.png) |
| 50        | ![Image](image7.png)          | ![Image](image8.png) | ![Image](image9.png) |
| 100       | ![Image](image10.png)         | ![Image](image11.png) | ![Image](image12.png) |

| Lateral external field |                      |               |                |                |
| 0         | ![Image](image13.png)          | ![Image](image14.png) | ![Image](image15.png) |
| 10        | ![Image](image16.png)          | ![Image](image17.png) | ![Image](image18.png) |
| 50        | ![Image](image19.png)          | ![Image](image20.png) | ![Image](image21.png) |
| 100       | ![Image](image22.png)          | ![Image](image23.png) | ![Image](image24.png) |

### 4. Conclusion

The results of our research show significant interference from neighbouring phases and, as a result, significant optical voltage transformer errors.

Our research shows that arranging digital transformer microelectronics inside a cylindrical conductor enables us to exclude the main electromagnetic field component, created by the transformer’s intrinsic current. In addition, the cylindrical conductor is also a shield for fields induced by neighboring conductors. Furthermore, the shielding effect may be evaluated according to approximate formulae, and more accurately on the basis of computer mathematical simulation.
Acknowledgments
This research was conducted with financial support of the Ministry of Education and Science of the Russian Federation at Ivanovo State Power Engineering University within the framework of a federal target programme, ‘Research and Development in Priority Areas of Developing the Russian Scientific and Technological Complex in 2014-2020’ concerning ‘Development and Research Relating to Digital 110 V Transformers Based on Basic Physical Laws with Optoelectronic Interface for Metering Electric Power in an Intelligent Electric Power System with a Smart Grid’ (Agreement No. 14.574.21.0072 on Granting Subsidies, dated 27 June 2014, Unique Identifier for Applied Scientific Research (Projects) RFMEFI57414X0072).

References
[1] Buhagiar T, Cayuela J P, Procopiou A and Richards S 2016 Proc. of 13th Int. Conf. on Development in Power System Protection (Bangkok) vol 1 (Bang Kruai: AESIEAP) pp 4-9
[2] Ma J, Wang T, Wu J and Wang Z 2010 Proc. of 5th Int. Conf. on Critical Infrastructure (Beijing) vol 1 (Beijing: NCEPU) pp 1-5
[3] Huang Q, Jing S, Li J, Cai D, Wu J and Zhen W 1999 IEEE Transactions on Power Delivery 1-6
[4] Igarashi G, Santos J, Junior S and Pellini E 2015 Proc. of 2015 IEEE PES Innovative Smart Grid Technologies Latin America (Montevideo) vol 1 (New York: IEEE) pp 893-7
[5] Thomas R, Vujanic A, Xu D, Sjödin J, Salazar H, Yang M and Powers N 2016 Proc. of 2016 IEEE/PES Transmission and Distribution Conf. and Exp. (Dallas) vol 1 (New York: IEEE) pp 1-5
[6] Chatrefou D 2009 Proc. of 8th Int. Conf. on Adv. in Power System Control, Operation and Management (Hong Kong) vol 561 (Stevenage: IET) pp 456-461
[7] Wang H and Guan Y 2015 Proc. of 2015 Int. Conf. on Intelligent Transportation, Big Data and Smart City (Halong Bay) vol 1 (New York: IEEE) pp 767-770
[8] Grechukhin V 2006 Ivanovo State Power Engineering University J. 4 1-9
[9] Chen J, Li H, Zhang M and Zhang Y 2012 Metrology and Measurement Syst. 3 611-16
[10] Lebedev V, Zhukov V and Yablokov A 2015 IOP Conference Series: Materials Science and Engineering (Tomsk) vol 1 (Bristol: IOP Publishing) pp 93 1-6
[11] Lebedev V and Yablokov A 2015 Appl. Mech. and Mat. 792 220-9
[12] Christensen L 1995 IEEE Transaction on Power Delivery 10(3) 1332-7
[13] Xiao X, Xu Y and Dong Z 2015 Sensors 15 7125-35
[14] Weina G and Wenjie H 2010 Proc. of 2010 Asia-Pacific Conf. on Power Electronics and Design (Wuhan) vol 1 (New York: IEEE) pp 47-50
[15] Dyakov A, Maximov B, Borisov R, Kuzhekin I and Zhukov A 2003 Electromagnetic Compatibility in Electric Power and Electronics (Moscow: Energoatomizdat)