Tomasz BŁAŻEJCZYK, Henryk SIBILSKI, Krzysztof KRASUSKI

Electrotechnical Institute, Department of High Power

Experimental Comparison of Two Various Optical Fibre Current Sensors Dedicated to High Current Applications

***Abstract**. The analysis of the possibility of applying of fiber optic sensors in power engineering are presented in the article. The paper deals with the results of the experimental investigations of magnetic fields existing in the surroundings of the model of air line conducting the current. Investigations were executed with use of coil-shaped fiber optic sensors designed to the co-operation with the different wavelengths: 635 nm and 1550 nm. The analysis of answer signals from fiber optic sensors is presented.*

***Streszczenie.** W artykule przedstawiono analizę możliwości zastosowania czujnika światłowodowego w kontekście dotychczas stosowanych przekładników prądowych w elektroenergetyce. Zaprezentowano wyniki badań eksperymentalnych pola magnetycznego występującego w otoczeniu modelu linii napowietrznej przewodzącej prąd. Badania wykonano przy zastosowaniu dwóch czujników światłowodowych przeznaczonych do współpracy z innymi długościami fali świetlnej: 635 nm i 1550 nm. Przedstawiono analizę odpowiedzi czujników światłowodowych. (**Eksperymentalne porównanie dwóch różnych światłowodowych czujników prądu przeznaczonych do zastosowań w środowisku wielkich prądów**).*

Słowa kluczowe: pole magnetyczne, efekt magnetooptyczny, czujnik światłowodowy, pomiar prądu.
Keywords: magnetic field, magneto-optic effect, fibre optic sensor, measurement of current.

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Introduction

Over the past 30 years two major product revolutions have taken place due to the growth of the optoelectronics and fiber optic communications industries. The optoelectronics industry has brought about such products as compact disc players, laser printers, bar code scanners, and laser pointers. The fiber optic communications industry has literally revolutionized the telecommunications industry by providing higher-performance, more reliable telecommunication links with ever-decreasing bandwidth cost. This revolution is bringing about the benefits of high-volume production to component users and a true information superhighway built of glass. In parallel with these developments, fiber optic sensor technology has been a major user of technology associated with the optoelectronic and fiber optic communications industry [1,2]. Many of the components associated with these industries were often developed for fiber optic sensor applications. Fiber optic sensor technology, in turn, has often been driven by the development and subsequent mass production of components to support these industries. As component prices have fallen and quality improvements have been made, the ability of fiber optic sensors to displace traditional sensors for rotation, acceleration, electric and magnetic field measurement, temperature, pressure, acoustics, vibration, linear and angular position, strain, humidity, viscosity, chemical measurements, and a host of other sensor applications has been enhanced. In the initial stage of the development of fiber optic sensor technology, most commercially successful fiber optic sensors were squarely targeted at markets where existing sensor technology was marginal or in many cases nonexistent. The inherent advantages of fiber optic sensors as: lightweight, very small size, passive, low-power, resistant to electromagnetic interference, high sensitivity, bandwidth, environmental ruggedness, were heavily used to offset their major disadvantages of high cost end-user [3].

The development of magneto-optic sensors has brought some new opportunities in current and magnetic field measurement. Electric current measurement using fiber optic sensors (FOSs) in 1977 is probably the earliest application of FOSs in the electric power industry [4]. After more than two decades of development, fiber optic current sensors recently entered the market [5]. These current sensors based on the Faraday effect have found important applications in fault detection and metering.

Instrument transformers for measuring current and voltage are key elements in the generation, transmission, and distribution of electrical energy. Optical fiber sensors exploiting the Faraday effect have been intensively researched and developed for measurement of large currents at high voltages in the power distribution industry. However, problems associated with induced linear birefringence, temperature, and vibration have limited the application of this technique [6, 7, 8, 9].

Authors focused on experimental comparison of two various optical fibre current sensors dedicated to high current application in this article.

Theoretical Fundamentals

The principle of Faraday effect is based on the interaction between magnetic field and the phenomenon of light refraction and reflection in transparent medium and on its surface [10, 11]. It depends on rotation of the polarization plane of light (polarized light changes its state of polarization) propagating in the medium subject to action of a magnetic field. The phenomenon of polarization plane rotation of the light beam linearly polarized under the influence of the magnetic field whose direction is parallel to the direction of propagation is shown in Figure 1.

The basic relation for Faraday magneto-optic effect is equation (1) [12]:

$$\theta = \mu V H l = V B l \tag{1}$$

where: θ – the polarization rotation angle, μ – the permeability of Faraday rotator material, V – Verdet constant, H – the magnetic field intensity, B – the magnetic flux density, l – length of interaction magnetic flux density and light beam.

The Verdet constant characterizes the capability of a transparent medium to rotating the polarization plane in a magnetic field and can be described by equation (2):

$$V = \frac{k_{\mathrm{mat}}\pi}{n\lambda} \tag{2}$$

where: k_{mat} – the material constant of medium, n – the absolute light refractive index, λ – the wavelength.

The Verdet constant determines magneto-optic properties of medium which propagating light beam and depends on the wavelength.

The fiber optic current sensors (FOCSs) are used usually as the integrate FOSs. Single mode optical fiber serves as a magneto-optic element, which is called Faraday rotator. The basic configuration of integral FOCS is shown in Figure 2.

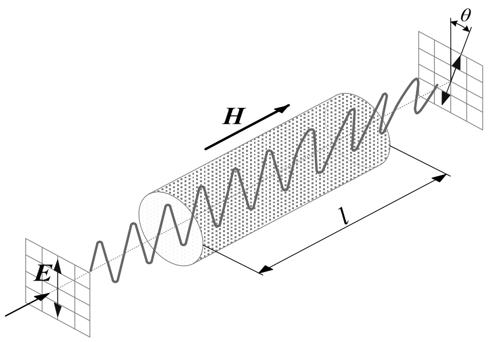

Fig.1. The principle of Faraday effect

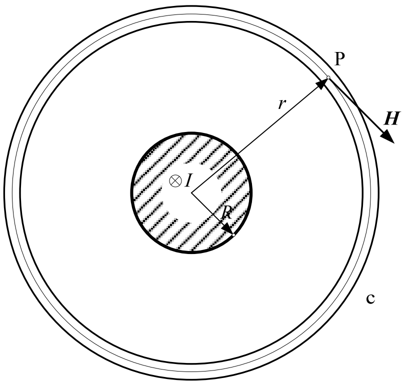

Fig.2. The principle of integral FOCSs

The integral FOS principle based on the Ampere's law:

$$\oint_c \boldsymbol{B}\mathrm{d}l = \mu I \tag{3}$$

where: $\boldsymbol{B}$ – the magnetic flux density vector, I – the current flowing in conductor encircles by loop of optical fiber.

For diamagnetic and paramagnetic materials $\mu = \mu_0$. Magnetic flux density vector $\boldsymbol{B}$ circulates round the conductor with the current I. Faraday rotator in the form of loop of optical fiber encircles the conductor. The curve c in Figure 2 (including point P) is the integration loop (equation 3). Only currents which are encircled by the integration loop contribute to the flux density $\boldsymbol{B}$. Further, the magnitude of integral (3) is not affected by the conductor position in the loop and does not depend on the integration loop length [10]. In order to improve the sensitivity, the fiber optic sensors are used as wound like a coil around the current conductive rod. Taking into consideration Ampere's law the polarization rotation angle θ can be written:

$$\theta = \mu V \oint_c \boldsymbol{B}\mathrm{d}l = \mu_0 VNI \tag{4}$$

where: N – the number of turns of coil-shaped optical fiber sensor.

Relation between the polarization rotation angle θ and number of turns N can be described by equation (4).

The fiber optic sensor with several turns around the conductor makes possible use a sensitive sensor based on optical fiber with low Verdet constant. For a given rotator with Verdet constant V the polarization rotation θ depends only on the measured current I. The rate of the polarization rotation and the measured current value can be evaluated by means of polarimetry.

The basic properties of Faraday effect are high linearity (in the case of paramagnetic and diamagnetic materials), temperature dependence and the dependence on the wavelength. The magnitude of the effect depends further on the magneto-optic material constant (Verdet constant) and on the interaction length through which the wave travels in material.

Experiments

The schematic diagram of the current measuring system is shown in Figure 3. The two sources of light (lasers), operating on wavelengths λ_1 = 635 nm and λ_2 = 1550 nm, were used in experiments. Investigations were executed with use of coil-shaped single mode fiber optic sensors designed to the co-operation with the wavelengths λ_1 and λ_2 and with number of turns around the conductor equal to N_1 = 9 and N_2 = 34 respectively. The coil-shaped fiber optic sensors are shown in Figure 4. The current I, magnetic flux density B and the output voltage of the processing the light system U_d were the main measured quantities.

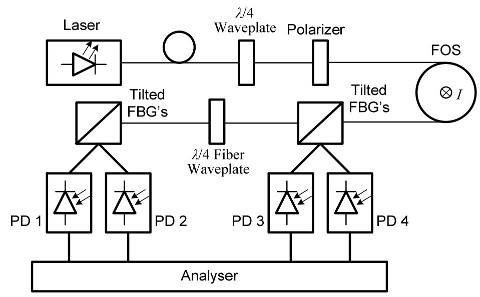

Fig.3. The schematic diagram of the current measuring system

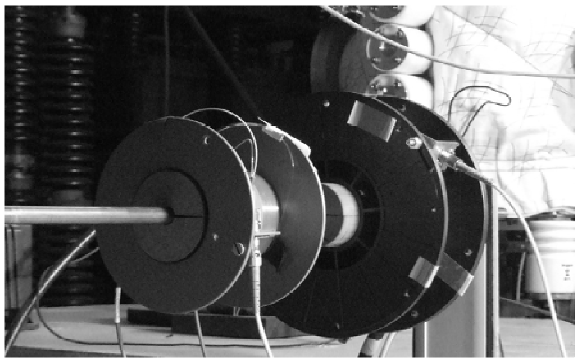

Fig.4. The view of the coil-shaped fiber optic sensors

Results

The results of the experiments with use of two various optical fiber current sensors shown in Figures 5 to 13.

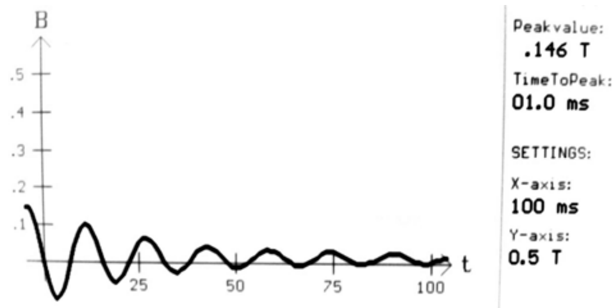

Fig.5. The result of measurement of magnetic flux density in surroundings conductor with the current I_{max} = 10,87 kA [9]

Measurements made for wavelength equal to 635 nm and with 9 turns are designated S635 and similarly measurements for wavelength equal to 1550 nm and with 34 turns are designated S1550.

The data of measurements was recorded by multichannel register. The waveforms of current $I(t)$ and the waveforms of photodetector's output voltages $U_d(t)$ are presented in figures. Used in figures the t_p symbol is the time of measurement.

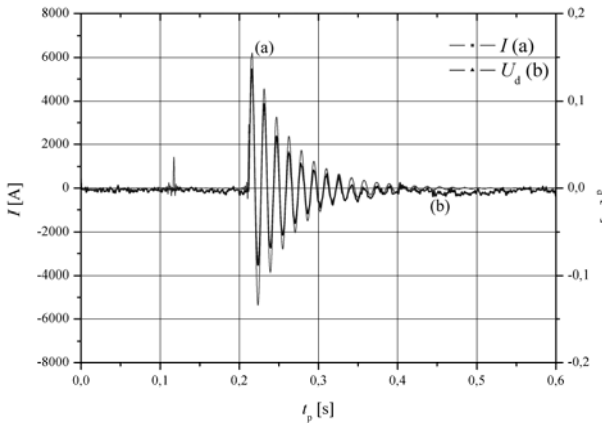

Fig.6. The results of measurements with use S635 FOS for I_{max} = 6,20 kA: a) waveform of current $I(t)$, b) waveform of photodetector's output voltage $U_d(t)$

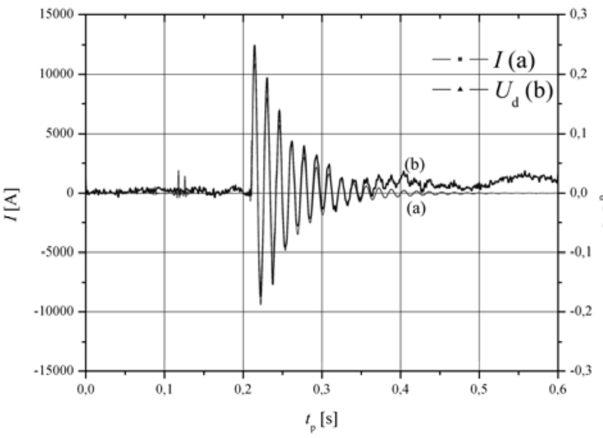

Fig.7. The results of measurements with use S635 FOS for I_{max} = 11,00 kA: a) waveform of current $I(t)$, b) waveform of photodetector's output voltage $U_d(t)$

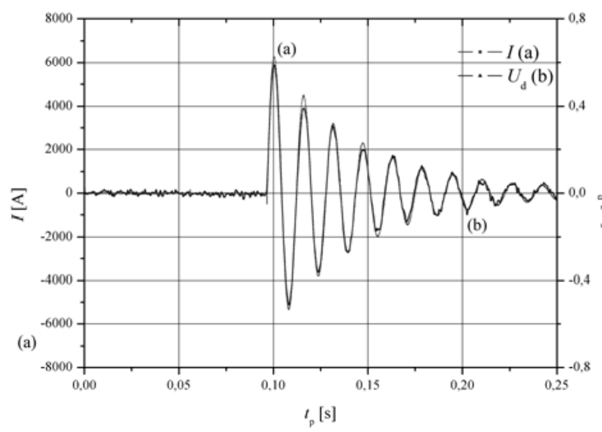

Fig.8. The results of measurements with use S1550 FOS for I_{max} = 6,26 kA: a) waveform of current $I(t)$, b) waveform of photodetector's output voltage $U_d(t)$

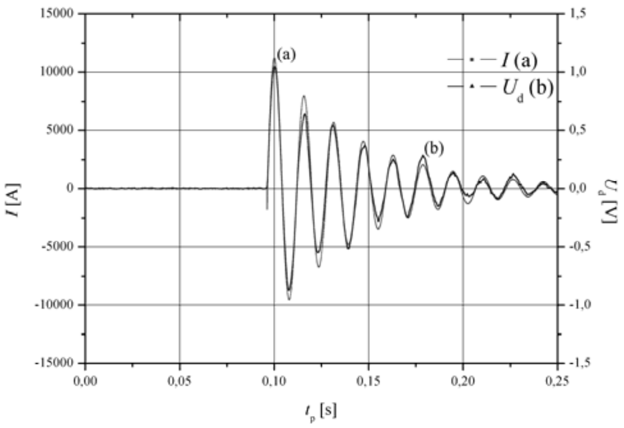

Fig.9. The results of measurements with use S1550 FOS for I_{max} = 11,20 kA: a) waveform of current $I(t)$, b) waveform of photodetector's output voltage $U_d(t)$

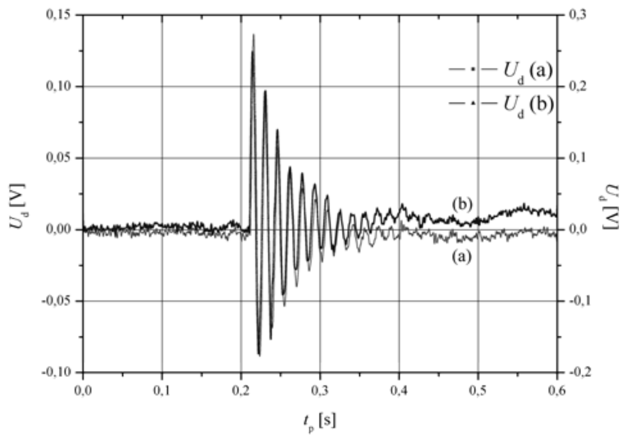

Fig.10. The waveform of photodetector's output voltage $U_d(t)$ for S635 with the current in conductor equal to: a) I_{max} = 6,20 kA, b) I_{max} = 11,00 kA

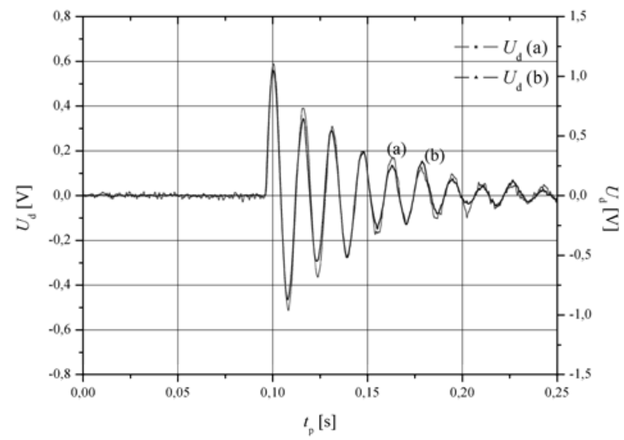

Fig.11. The waveform of photodetector's output voltage $U_d(t)$ for S1550 with the current in conductor equal to: a) I_{max} = 6,26 kA, b) I_{max} = 11,20 kA

For the comparison of answers of FOSs having the various number of turns around the conductor introduced the k_i coefficient:

$$k_i = \frac{U_{dm}}{N_i} \tag{5}$$

where: U_{dm} – the photodetector's output voltage for m-half-period of the waveform, N_i – the number of turns of investigated fiber optic sensors.

For the comparison of the two fiber optic sensors the waveform of photodetector's output voltage $U_d(t)$ for S635 and S1550 are presented.

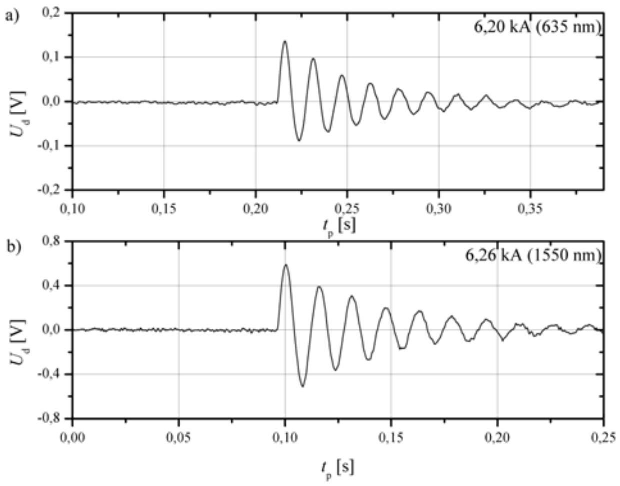

Fig.12. The waveform of photodetector's output voltage $U_d(t)$ of FOSs with similar values of current in conductor I_{max} = 6,26 kA for: a) S635, b) S1550

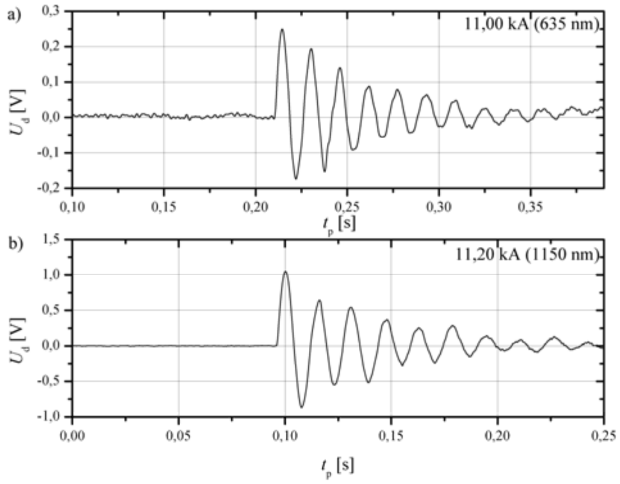

Fig.13. The waveform of photodetector's output voltage $U_d(t)$ of OSs with similar values of current in conductor I_{max} = 11,20 kA for: a) S635, b) S1550

Conclusion

Results of the experiments with use of two fiber optic sensors with two various wavelengths are presented. Table 1 shows values of the k_i coefficient. Comparing the results it shall be stated that for the wavelength λ_2 = 1550 nm and the number of turns N_2 = 34 one can obtain similar the k_i coefficient for λ_1 = 635 nm and N_1 = 9. The S635 and S1550 FOSs have similar sensitivity. On the basis of experiments it shall be stated that the fiber optic sensor with higher number of turns makes possible to use fiber optic sensors with lower Verdet constant. The decrease of Verdet constant followed by increase of wavelength according to equation (2).

Table 1. The values of k_i coefficient

Sensor/ k_i coefficient	k_1 [V/turn]	k_2 [V/turn]
Sensor 635 (N_1 = 9)	0,0164 (I = 6,20 kA)	0,0277 (I = 11,00 kA)
Sensor 1550 (N_2 = 34)	0,0179 (I = 6,26 kA)	0,0313 (I = 11,20 kA)

On the basis of experiments and analytic calculations it shall be stated that up to 7th half-period answers of FOCs (Figures 12 and 13) are proportional to current causes the magnetic field.

The fiber optic sensors which have been described in this paper represents an advantageous way for currents measurement in high current applications.

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***Authors**: Tomasz Błażejczyk, Ph.D, Eng., Electrotechnical Institute, Department of High Power, Pożaryskiego 28, 04-703 Warsaw, E-mail: t.blazejczyk@iel.waw.pl; Prof. Henryk Sibilski, D.Sc, Ph.D, Eng., Electrotechnical Institute, Department of High Power, Pożaryskiego 28, 04-703 Warsaw, E-mail: sibilski@iel.waw.pl; Krzysztof Krasuski, M.Sc, Eng., Electrotechnical Institute, Department of High Power, Pożaryskiego 28, 04-703 Warsaw, E-mail: k.krasuski@iel.waw.pl.*