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USING THE FARADAY EFFECT IN INVESTIGATIONS OF MAGNETIC FIELDS

ABSTRACT *The paper presents results of magnetic field investigations using the Faraday effect. The magnetic field source was the current flowing through an additional winding in a magnetoelectric motor. The possibility of using an optical fibre sensor for determining the value of an external magnetic field was analysed which can affect the permanent magnet during motor operation. Results of measurements of the tangential component of the magnetic induction in the air gap of the motor are presented, obtained using an optical fibre as a magnetic field sensor. The effect of the magnetic system design on the possibility of measuring the magnetic induction using an optical fibre sensor was analysed.*

Key words: *Faraday effect, magnetic field, permanent magnet*

1. INTRODUCTION

The dynamic development of the optical fibre telecommunications as well as of optoelectronic instruments and subassemblies caused a new technology

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to emerge for measuring physical magnitudes which is based on application of optical fibre sensors. Their basic features are:

1. nonelectrical output signal,
2. short decay time of the optical anisotrophy (10^{-12} s),
3. high processing sensitivity,
4. irreversibility,
5. wide transmission band (some GHz),
6. resistance to electromagnetic interference,
7. small mass and dimensions,
8. possibility of coupling with telecommunication systems,
9. possibility of contactless operations (in many cases).

A nonelectrical output signal, the so called isolativeness of optical fibres is one of the most important advantages of optical fibres in measurements of electric magnitudes. This feature causes the area of optical fibres applications in electrotechnics to increase continuously. The advantage mentioned above gained the most important significance at present in applications of optical fibres in the field of high power electrical engineering for measuring high currents and voltages (over 1 kA and 1 kV respectively). References to optical fibres applications in the area of high power electrical engineering concern mainly power plants and electric stations and substations on some territories particularly of the USA, Canada and some European countries (Sweden, France) [1, 2, 3].

Optical fibres playing the role of optical transducers are used in measurements of magnetic fields, electric fields, current intensity, voltage, temperature or vibrations [4, 5, 6, 7, 8]. Various optical effects are used in the measurements e.g. of Faraday, Kerr, Pockels. The subject of investigations was measurements of magnetic fields using optical fibres.

In magnetic field measurements it is important for the measuring sensor to be resistant to any kind of electromagnetic interference and not to cause any changes in its distribution (the so called notinvasiveness of sensors). Optical fibres fulfil both the criteria. Taking into account the short disappearance time of the optical anisotrophy (10^{-12} s, in other words the time in which the change in the light signal occurs under the influence of the measured magnitude) and the small dimensions of optical fibres, the present Author used a glass fibre as a sensor in magnetic field investigations.

The aim of the work were experimental investigations of a magnetic field affecting a permanent magnet in an electric machine using the magnetooptical Faraday effect in an optical fibre playing the role of the magnetic field sensor.

In a magnetoelectric machine the permanent magnet is during machine operation subjected to the action of an external magnetic field which among others affects its energy state. The source of such a field can be the magnetic field of armature reaction. Demagnetization of the permanent magnet can follow in particular cases.

In the investigations the source of the external magnetic field was a current of a high value (above 1 kA) flowing through an additional winding placed in the stator of the machine being investigated. Because of the fact that the processes demagnetizing the permanent magnet can occur in very short time, current pulses with duration times of maximum some a dozen or so ms were applied in these investigations. The investigations were conducted using the magnetooptical Faraday effect, which can be observed in an optical environment (among others in an optical fibre) being under the influence of a magnetic field.

2. THE FARADAY EFFECT

The magnetooptical phenomena are the result of the action of external magnetic field on a light beam propagating in a given medium. Magnetooptical effects of the first order, i.e. proportional to the first power of the external magnetic field intensity have an essential significance in sensor applications. The Faraday effect is an example of the first order effect. The name of the effect originates from its discoverer. It was discovered by M. Faraday in 1845. It depends on rotation of the polarization plane of light (polarized light changes its state of polarization, SOP) propagating in the medium subject to action of a magnetic field (the so called forced birefringence of the medium).

Assuming that the light beam propagates in the medium in direction ***s*** forming with the axis *z* of the Cartesian coordinate system the angle θ (the angle between the direction of the light beam propagation and the direction of the magnetic field, Fig. 1) and that the direction of the magnetic field $\boldsymbol{H}_z$ is consistent with the axis *z* we obtain [9]:

$$\frac{1}{n^2}=\frac{1}{2}\left(\frac{\varepsilon_f\left(2-\sin^2\theta\right)}{\varepsilon_f^2-\varepsilon_k^2}+\frac{\sin^2\theta}{\varepsilon_g}\right)\pm\sqrt{\frac{\sin^4\theta}{4}\left(\frac{\varepsilon_f}{\varepsilon_f^2-\varepsilon_k^2}-\frac{1}{\varepsilon_g}\right)^2+\frac{\varepsilon_k^2\cos^2\theta}{\left(\varepsilon_f^2-\varepsilon_k^2\right)^2}} \tag{1}$$

where:

- ε_f, ε_g, ε_k – components of the tensor of electric permeability,
- n – the absolute light refractive index,
- θ – the angle between the direction of the light beam propagation and the direction of the magnetic field,
- $\boldsymbol{H}_z$ – the external magnetic field intensity vector.

The components of the tensor of electric permeability assume different values, depending on the degree of dependence on the magnetic field. The Faraday effect is a linear magnetooptic effect, where $\varepsilon_f = \varepsilon_g = \varepsilon = n^2$, $\varepsilon_k << \varepsilon$ which is equivalent with $\varepsilon_k / \varepsilon \approx 0$, where *ε* is the tensor of the electric permeability. Then we obtain:

$$\frac{1}{n^2} = \frac{1}{\varepsilon} \pm \frac{\varepsilon_k \cos\theta}{\varepsilon^2} \tag{2}$$

After transforming equation (2) we obtain:

$$n^2 = \frac{\varepsilon^2}{\varepsilon \pm \varepsilon_k \cos\theta} \approx \varepsilon\left(1 \mp \frac{\varepsilon_k \cos\theta}{\varepsilon}\right) \tag{3}$$

The approximated solutions to the equation (3) can be written as:

$$\begin{aligned} n_1 &= n + \frac{\varepsilon_k}{2n}\cos\theta \\ n_2 &= n - \frac{\varepsilon_k}{2n}\cos\theta \end{aligned} \tag{4}$$

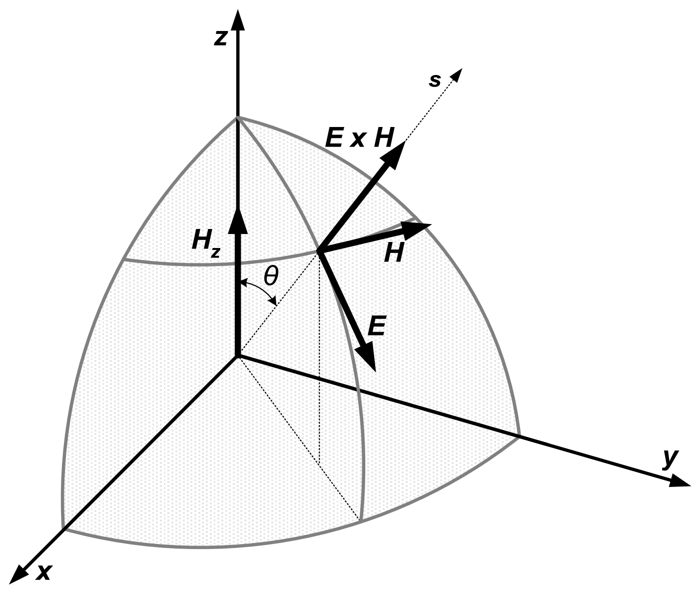

Fig. 1. The angle *θ* between the direction of light beam propagation and the direction of the magnetic field vector

The birefringence caused by the magnetic field (Faraday effect, difference between refractive indexes) can be described by the equation:

$$\Delta n = n_1 - n_2 = \frac{\varepsilon_k}{n}\cos\theta \tag{5}$$

2.1. Rotation of the polarization plane

The light beam polarized linearly can be mathematically presented in the form of two component waves polarized circularly with opposite rotation. As the circular components propagate in the material medium with different velocities, the difference of phases appears at the output of the medium, whose value depends on the length of light propagation in the magnetic field [9]:

$$\delta = \frac{2\pi L}{\lambda}\Delta n \tag{6}$$

where:

δ – difference of phases,
L – length of light propagation in the magnetic field,
n_l – refractive index of the wave circularly polarized left,
n_p – refractive index of the wave circularly polarized right,
$\Delta n = n_l - n_p$, difference of refractive indexes.

On the basis of the equation (6) it is possible to determine the rotation angle of the polarization plane of light polarized linearly by α:

$$\alpha = \frac{1}{2}\delta = \frac{\pi L}{\lambda}\Delta n \tag{7}$$

Taking into consideration equation (5) the rotation angle of the polarization plane α can be written:

$$\alpha = \frac{\pi L}{\lambda}\frac{\varepsilon_k}{n}\cos\theta \tag{8}$$

The component of the electric permeability tensor ε_k depends linearly on the external magnetic field intensity ($\varepsilon_k = k_{mat} H_z$, where k_{mat} is the material constant of the medium) [9]. Then equation (8) can be written in the form:

$$\alpha = \frac{\pi}{\lambda}\frac{k_{\text{mat}}}{n} L H_{\text{z}} \cos\theta \tag{9}$$

Figure 2 shows 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.

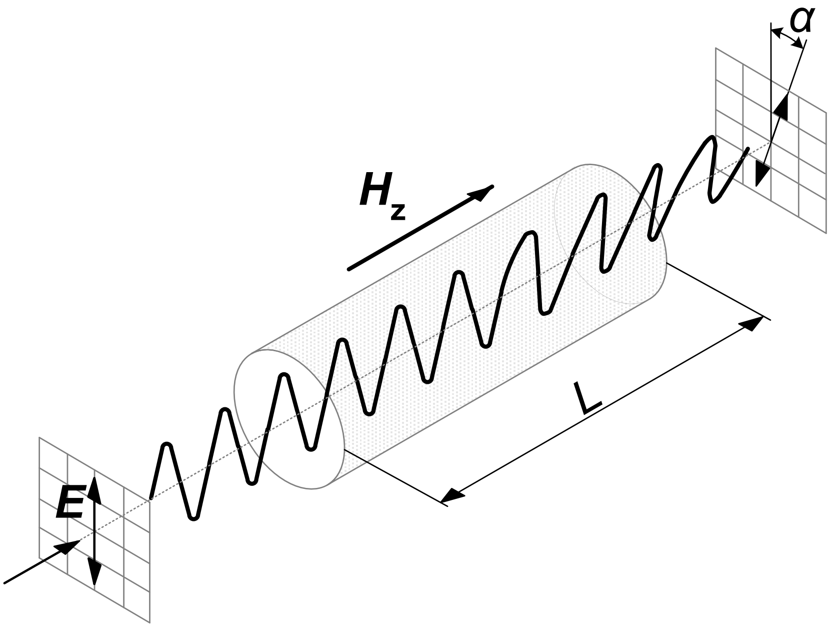

Fig. 2. Rotation of the polarization plane of light beam linearly polarized under the influence of magnetic field with its direction being parallel to the propagation direction of light

2.2. Verdet constant

Equation (9) can be written in a simplified form:

$$\alpha = k_{\text{V}} L H_{\text{z}} \cos\theta \tag{10}$$

where:

- L – length of the path which the light travels in the medium being under the influence of a magnetic field,
- H_{z} – magnetic field intensity,
- k_{v} – Verdet constant which characterizes the capability of a given substance to rotating the polarization plane in a magnetic field:

$$k_{\text{V}} = \frac{k_{\text{mat}}\pi}{n\lambda} \tag{11}$$

The concept of the effective Verdet constant can be found in references [10], determining the value of attenuation of the forced circular birefringence by the effect of the forced linear birefringence caused e.g. by bending the optical fibre.

The value of the Verdet constant depends to a high degree on the wave length of light, on the density of the medium and temperature. The higher is the wave length of light the lower is the value of the Verdet constant. Increase in temperature causes in general a decrease in the Verdet constant. However the dependence of the Verdet constant on temperature becomes visible at temperatures above 100°C.

The unit of the Verdet constant described by equation (11) is [A/m]. Expressing the magnetic field by magnetic flux density B_z, equation (10) can be written in the form:

$$\alpha = k_V L B_z \cos\theta \tag{12}$$

The Verdet constant is them expressed in [rad/Tm]. Table 1 shows values of the Verdet constant for selected materials for the wave length of 632.8 nm. From equation (12) it follows that the Faraday effect is the greatest for $\theta = 0^o$, i.e. when the directions of light wave propagation and of magnetic field are parallel to each other. The rotation angle of the polarization plane α depends on the length L of the path travelled by light in the medium in magnetic field and on the value of magnetic field intensity H_z or its magnetic flux density B_z (Fig. 2). For $\theta = 0^o$ the rotation angle of polarization plane given by equation (12) can be written in the form:

$$\alpha = k_V L B_z \tag{13}$$

TABLE 1
The Verdet constant k_V of selected materials for λ = 632.8 nm

Medium	k_V [rad/(T · m)]	Medium	k_V [rad/(T · m)]
Glass SF22	30.85	Calcite	5.52
Glass SF3	18.30	Quarz	4.84
Glass SF10	17.90	Water	3.78
Bromid of potassium	12.37	Acetone (20º C)	3.25
Cooking salt	10.04	Ethyle alcohol (25º C)	3.23

The essential feature of the Faraday effect is its irreversibility, i.e. the rotation of light wave polarization plane propagating in a medium being subjected to a magnetic field with a consistent and opposite propagation direction with respect to the field ("there and back") will not get compensated but it will be doubled. This phenomenon has found application in laser technology and at light modulation.

3. THE INVESTIGATED OBJECT AND THE TEST STAND

A DC electric motor with permanent magnets (Fig. 3) was chosen for investigations. It was assumed that the source of the magnetic field is the current flowing through additional winding (so called magnetizing winding) but not the magnetic field of the armature reaction. In this conjunction the cylindrical sloted rotor was replaced with a smooth ferromagnetic core on a part of which was placed the optical fibre (Fig. 4) [11].

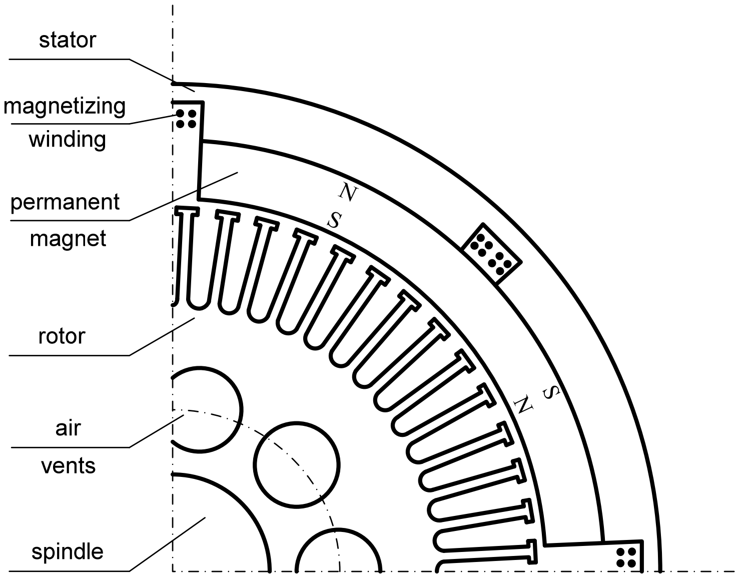

Fig. 3. Part of the cross-section of the magnetoelectric motor being investigated

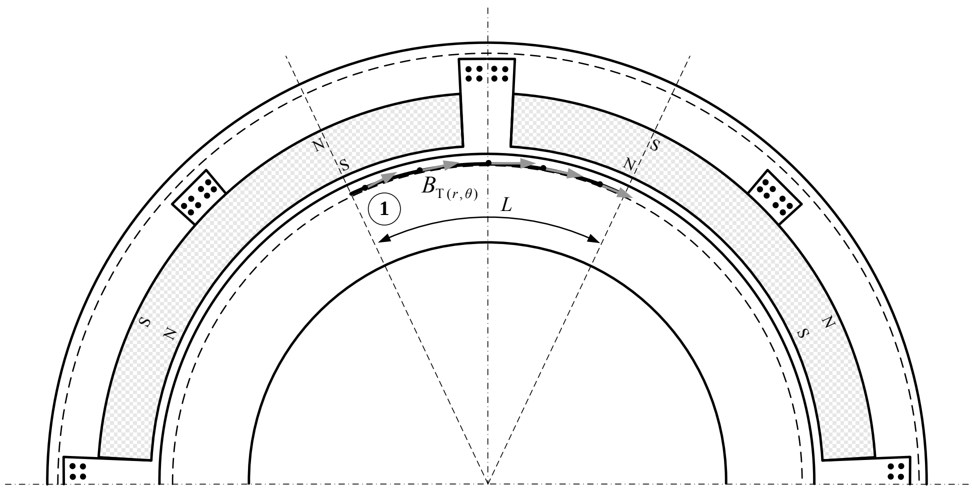

Fig. 4. Part of the cross section of the investigated magnetic system with the place of the optical fibre situation indicated

Figure 5 presents a schematic diagram of the measuring stand for investigating the magnetooptic Faraday effect in the optical fibre constituting the magnetic field sensor in the investigated object. Under the influence of the magnetic field generated by the current flowing through the magnetizing winding followed a change in the state of polarization (SOP2) of the light wave propagating in the optical fibre sensor (OFS). Light with a state of polarization different from that at the input and a different azimuth was introduced into the polarimeter, where it was analysed. A light wave of a length λ = 1550 nm was used in the investigations.

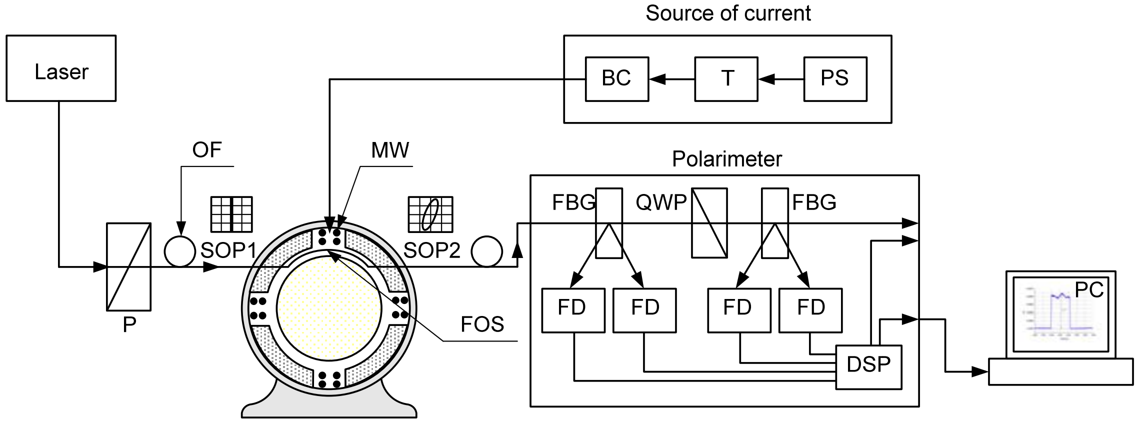

Fig. 5. Schematic diagram of the measuring stand for investigating the Faraday effect in a optical fibre situated in the tested object: P – polarizer, SOP1 – state of polarization of the light wave at the object input, SOP2 – state of polarization of the light wave at the object output, MW – magnetizing winding, FOS – fibre optic sensor of magnetic field, BC – bank of capacitors, T – thyristor and control set, PS – power supply, FBG – fibre Bragg grating, QWP – quarterwave plate (λ/4), FD – photodetector, DSP – detection and signal processing, PC – computer

4. CALCULATION AND MEASURING RESULTS

4.1. Calculation results

Numerical calculations of the magnetic field in the electric motor were made in the framework of simulation investigations. The aim of the calculations was recognition of magnetic field distribution (its components) in the particular fragments of the magnetic circuit. Numerical calculations of the magnetic field in the motor were performed using the FLUX software based on the finite element method. The magnetostatic field was analysed.

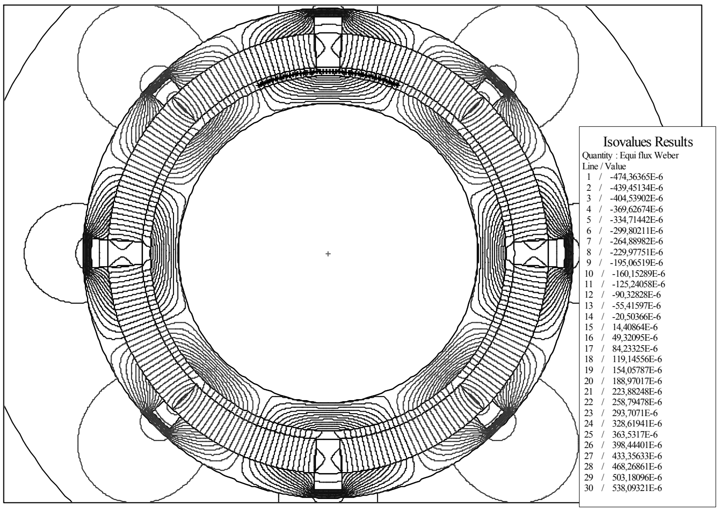

Fig. 6. Magnetic field distribution in the magnetic circuit presented in Fig. 4

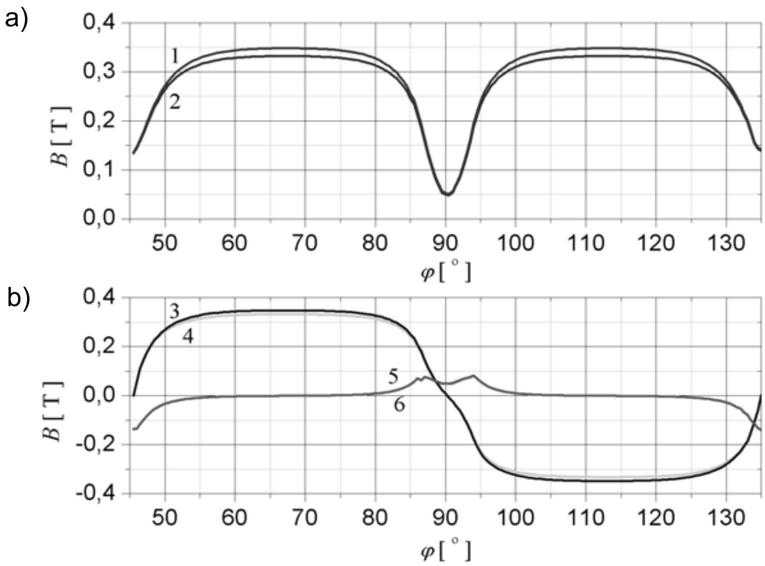

Fig. 7. Results of numerical calculations of magnetic flux density for magnetic field originating from the current in the magnetizing winding in the system as in Fig. 4, in half of the air gap height: a) distribution of the modulus of magnetic flux density (I = 2600 A – curve 1, I =1900 A – curve 2), b) distribution of the components of magnetic flux density: radial – curve 3 (I = 2600 A) and curve 4 (I = 1900 A); tangential – curve 5 (I = 2600 A) and curve 6 (I = 1900 A)

4.2. Measuring results

Measurements of the magnetic field were made in the framework of experimental investigations in the electric motor shown in Fig. 4. The measured magnitudes were the components (parameters) of the Stokes vector. This vector permits the light beam SOP to be determined. For a fully monochromatic light (laser light) and with time constant amplitudes, the Stokes vector of polarized light assumes the form:

$$[S] = \begin{bmatrix} I \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} 1 \\ \cos 2\vartheta \cos 2\alpha \\ \cos 2\vartheta \sin 2\alpha \\ \sin 2\vartheta \end{bmatrix} \tag{14}$$

where:

I – full intensity of light,

ϑ – elipticity angle of light SOP,

α – azimuth of light SOP,

S_1, S_2, S_3 – components (parameters) of the Stokes vector.

The azimuth of light SOP was determined on the basis of measured component values of the Stokes vector of light wave propagated in the optical fibre being under the influence of magnetic field, in accordance with equations as below:

$$\frac{b}{a} = tg\left(\frac{1}{2} arcsin\left(\frac{S_3}{\sqrt{S_1{}^2 + S_2{}^2 + S_3{}^2}}\right)\right) \tag{15}$$

where:

b/a – elipticity of light SOP,

$$\vartheta = arctg\left(\frac{b}{a}\right) \tag{16}$$

$$\alpha = \frac{1}{2}\arccos\left(\frac{S_1}{\cos 2\vartheta}\right) \tag{17}$$

The difference $\Delta\alpha$ between SOP before appearance of magnetic field (current in the magnetizing winding $I = 0$) and SOP during occurrence of magnetic field ($I \neq 0$) was determined on the basis of the mean component values of the Stokes vector. The mean value of magnetic flux density was determined from the characteristic $\Delta\alpha = f(B)$ [11], obtained for the optical fibre used as magnetic field sensor.

According to equation (12), the Faraday effect is the highest for $\theta = 0^o$, i.e. in the case when the directions of light wave propagation and magnetic field are parallel to each other. For $\theta = 90^o$ the rotation of the polarization plane $\alpha = 0$ (no Faraday effect). In this conjunction, when the optical fibre is situated as in Fig. 4, the propagation direction of the light wave in the optical fibre is parallel to the tangential component of magnetic flux density $B_{\varphi(r,\ \varphi)}$ at the length L [11]. The value of tangential component of magnetic flux density at this length, determined basing on measurements using the optical fibre is the mean value.

Figs. 8 and 9 show selected measuring results of Stokes vector components expressing the light SOP propagating in the optical fibre (situated in position 1) under the influence of the magnetic field generated by the current flowing in the magnetizing winding (Fig. 4) [11]. The t_p denotes the measurement time.

Measurements of the radial component of magnetic flux density in the air gap of the system were made in the framework of experimental investigations of the magnetic field in the magnetic arrangement shown in Fig. 4 with current flowing in the magnetizing winding. Measurements were made using a meter with a Hall sensor.

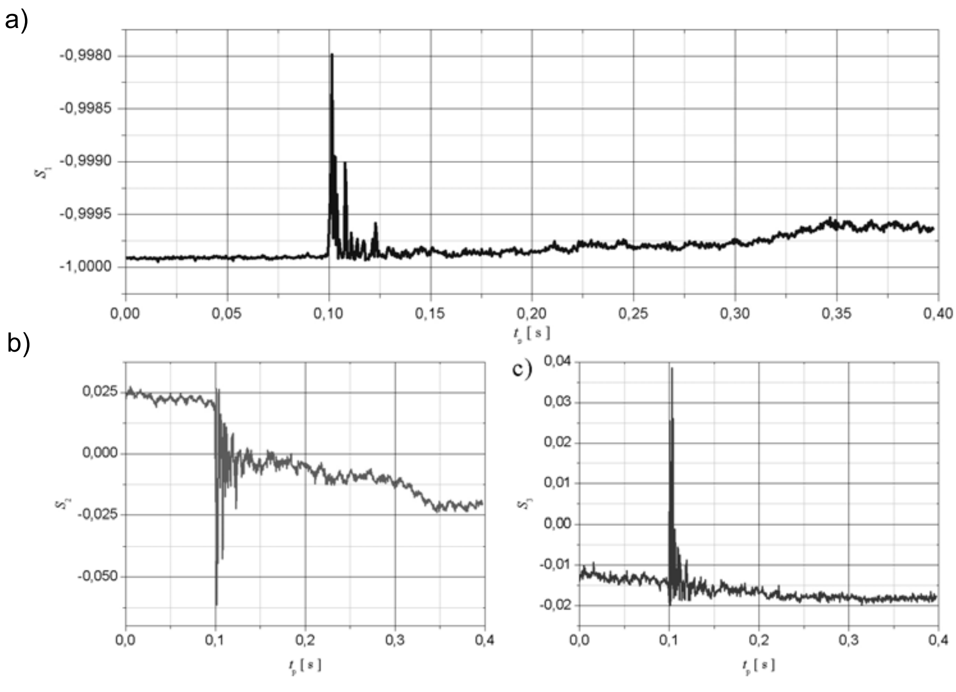

Fig. 8. The curves of Stokes vector components expressing the light SOP propagating in the optical fibre, placed in situation 1 as in Fig. 4, with current flowing in the magnetizing winding *I* = 1900 A: a) component S_1, b) component S_2, c) component S_3

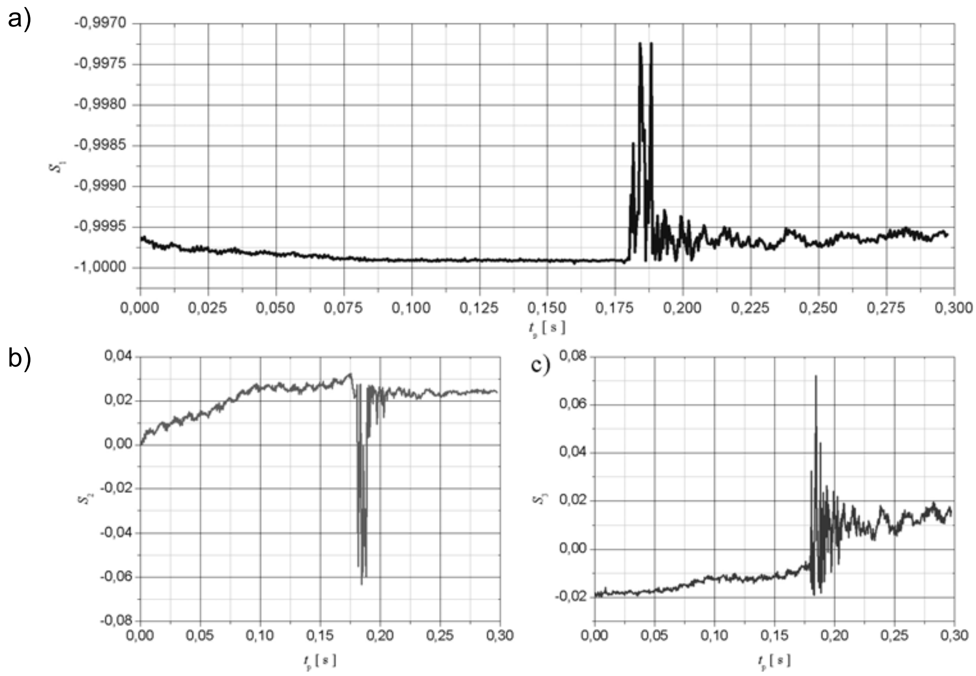

Fig. 9. The curves of Stokes vector components expressing the light SOP propagating in the optical fibre, placed in situation 1 as in Fig. 4, with current flowing in the magnetizing winding *I* = 2100 A: a) component S_1, b) component S_2, c) component S_3

4.3. Magnetic flux concentrators

The radial component has a significant contribution to the magnetic field modulus in the air gap of an electric machine. The tangential component of magnetic flux density should be taken into consideration in machines with larger heights of air gapes (usually machines of medium and high power). Taking into consideration that the situation of the optical fibre as in Fig. 4 allows for measuring only the tangential component of the magnetic flux density in order to apply an optical sensor (in general) in machines during their operation, it is reasonable to apply an optical sensor with higher sensitivity of processing and situated at a place ascertaining measurement of the significant component in the magnetic flux density modulus.

In a cylindrical uniform air gap, where the magnetic permeability of the medium μ_0 = const, the magnetic field is described by equations:

$$\nabla \cdot \mathbf{B} = 0 \tag{18}$$

$$\nabla \times \mathbf{B} = 0 \tag{19}$$

In the cylindrical system of coordinates (r, φ) the above equations take the form of:

$$r\frac{\partial B_{\mathrm{r}}}{\partial r}+B_{\mathrm{r}}+\frac{\partial B_{\varphi}}{\partial \varphi}=0 \tag{20}$$

$$r\frac{\partial B_{\varphi}}{\partial r}+B_{\varphi}+\frac{\partial B_{\mathrm{r}}}{\partial \varphi}=0 \tag{21}$$

where: B_{r}, B_{φ} – the radial and tangential components of magnetic flux density.
After differentiating equations (20) and (21) by the coordinates r and φ and after eliminating variables we obtain:

$$\frac{\partial^2 B_{\mathrm{r}}}{\partial \varphi^2}+r^2\frac{\partial^2 B_{\mathrm{r}}}{\partial r^2}+3r\frac{\partial B_{\mathrm{r}}}{\partial r}+B_{\mathrm{r}}=0 \tag{22}$$

$$\frac{\partial^2 B_{\varphi}}{\partial \varphi^2}+r^2\frac{\partial^2 B_{\varphi}}{\partial r^2}+3r\frac{\partial B_{\varphi}}{\partial r}+B_{\varphi}=0 \tag{23}$$

In general the solutions for the components B_{r} and B_{φ} are fund using the method of separation of variables. In this paper, for comparison with values measured using an optical fibre, the solutions for magnetic flux density components were obtained in the way of numerical calculations.

The greatest interest in sensoric applications constitute groups of magnetooptical materials in the composition of which enter the iron garnets of rare earth and flint glass with admixtures. In comparison with other materials (Table 1) they are characterized by a significantly higher value of the Verdet constant. For iron garnets of rare earth the Verdet constant is of the order 10^3 rad/T*m (e.g. for $Y_3Fe_5O_{12}$ at λ = 700 nm, k_{V} = 6457,7 rad/T*m) [12, 13]. This property enables to design sensors in which the measurement of polarization plane rotation is possible at the length of cooperation of magnetic field and light wave propagation at the level of single millimeters. The production technology of these materials is being constantly developed. Despite unusually valuable properties of iron garnets of rare earth, these materials are featured by significant influence of temperature on the value of Verdet constant (over 100°C) and by chemical instability.

The sensitivity of measuring magnetic fields using optical sensors can be increased by applying magnetic flux concentrators (Fig. 10) [11, 14].

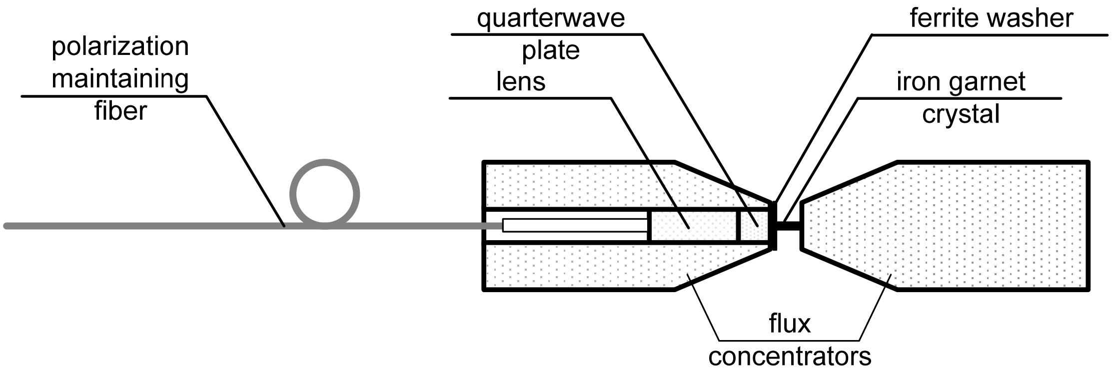

Fig. 10. Optical fibre sensor of magnetic field with flux concentrator

Figure 11 presents a part of the cross section of a magnetoelectric motor with pole shoes, whose shapes permit the magnetic field to be concentrated for measuring using an optical sensor. In such an configuration of the magnetic system the optical sensor would constitute an integral part with the polarizer and analyzer in one casing [15]. Distributions of magnetic flux density components in such a system were determined by simulation investigations. The results have been presented in Figures 12 to 16 [11].

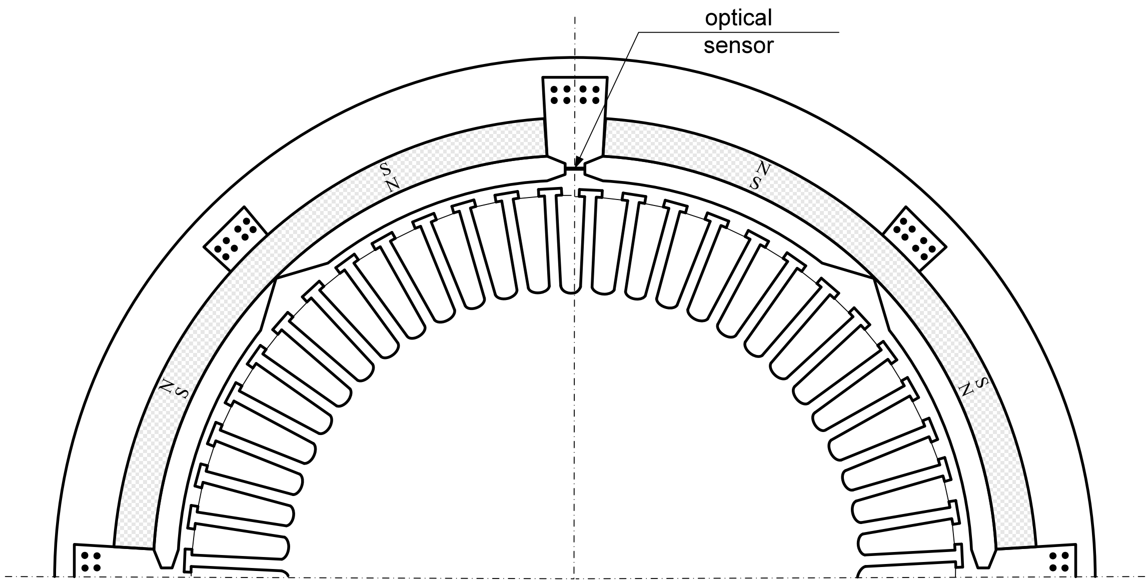

Fig. 11. Part of the cross section of a magnetoelectric motor with pole shoes used as flux concentrators

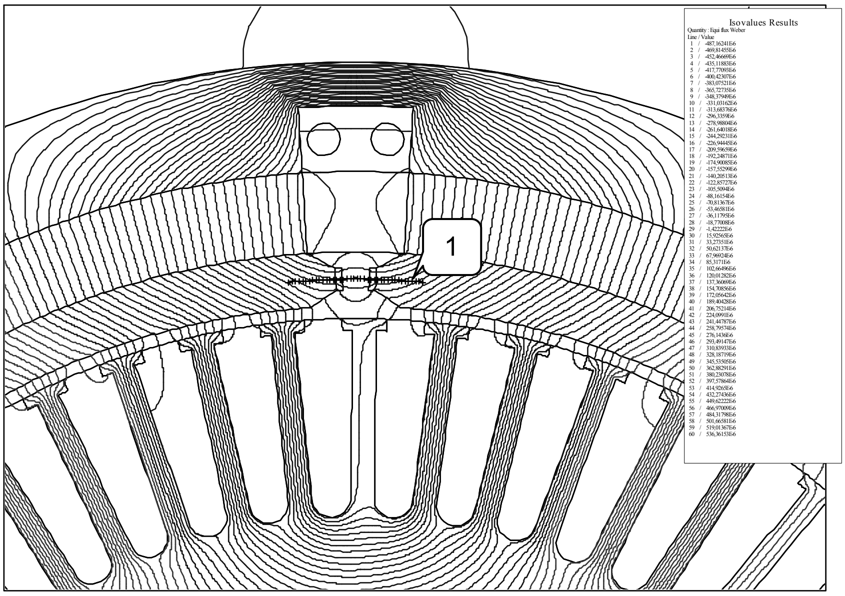

Fig. 12. Magnetic flux distribution in the magnetic circuit shown in Fig. 11, 1 – distributions of magnetic flux density were determined for this angular width (in half of the height of the magnetic flux concentrators**)**

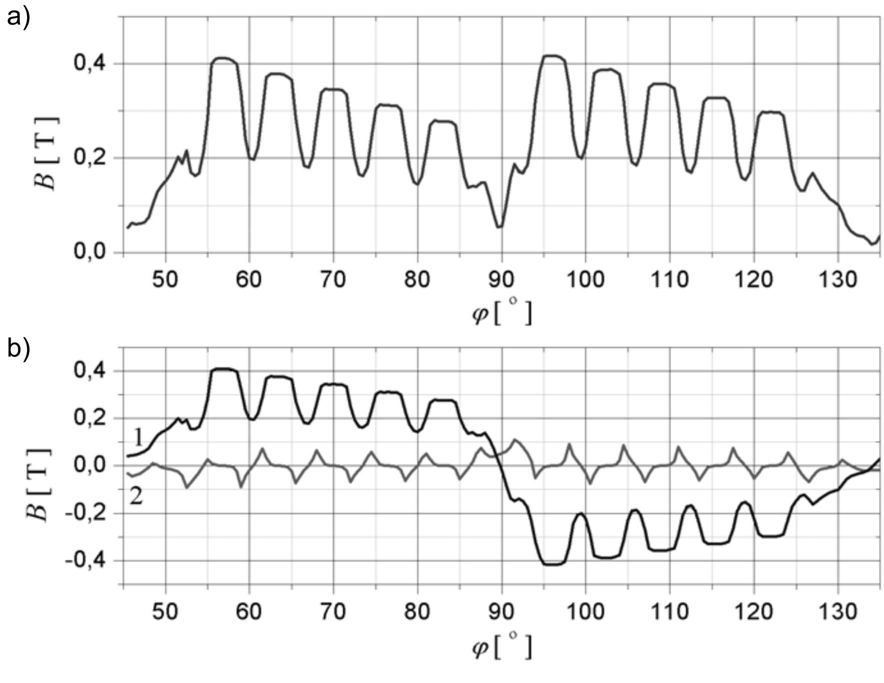

Fig. 13. Result of numerical calculations of the resultant magnetic field (originating from permanent magnets and armature) in an electric machine with pole shoes like in Fig. 11, at half of the air gap height: a) distribution of the magnetic flux density modulus, b) distribution of the magnetic flux density components: radial – curve 1, tangential – curve 2

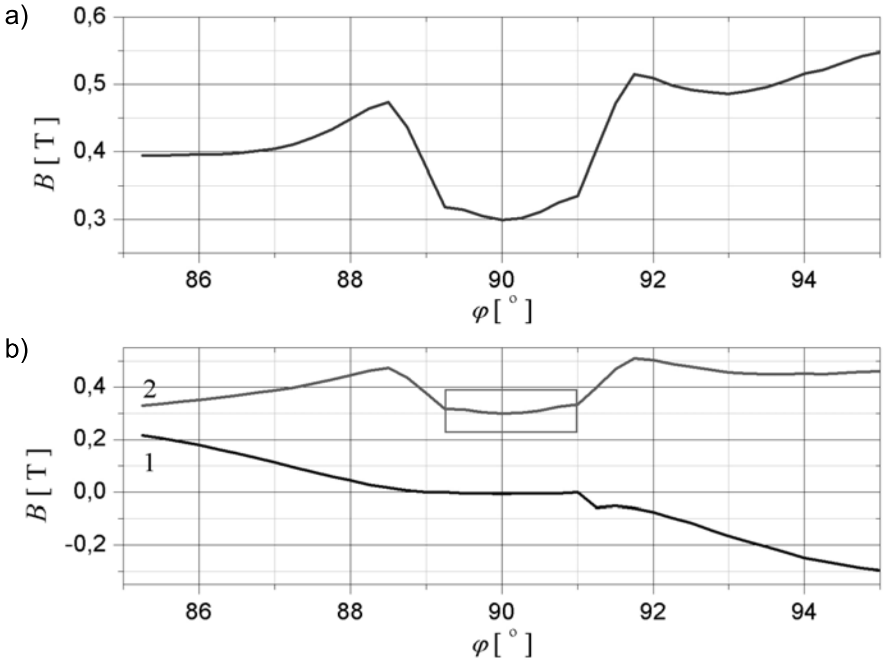

Fig. 14. Result of numerical calculations of the resultant magnetic field (originating from permanent magnets and armature) in an electric machine with pole shoes like in Fig. 11, at half of the height of concentrators, for the angular width shown in Fig. 12: a) distribution of the magnetic flux density modulus, b) distribution of the magnetic flux density components: radial – curve 1, tangential – curve 2

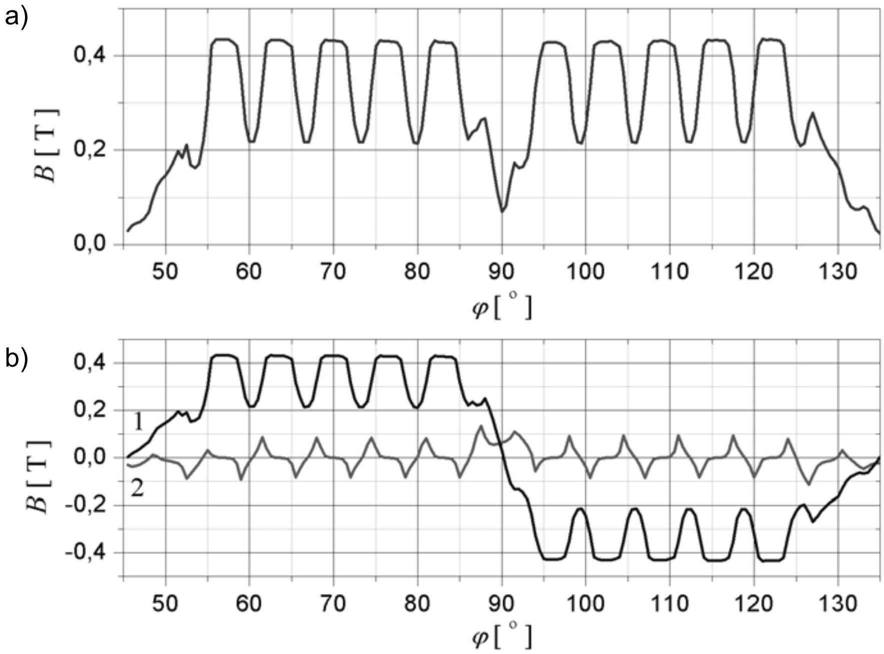

Fig. 15. Result of numerical calculations of magnetic field originating from the current in the magnetizing winding (*I* = 2600 A) in an electric machine with pole shoes like in Fig. 11, at half of the air gap height: a) distribution of the magnetic flux density modulus, b) distribution of the magnetic flux density components: radial – curve 1, tangential – curve 2

a)
b)

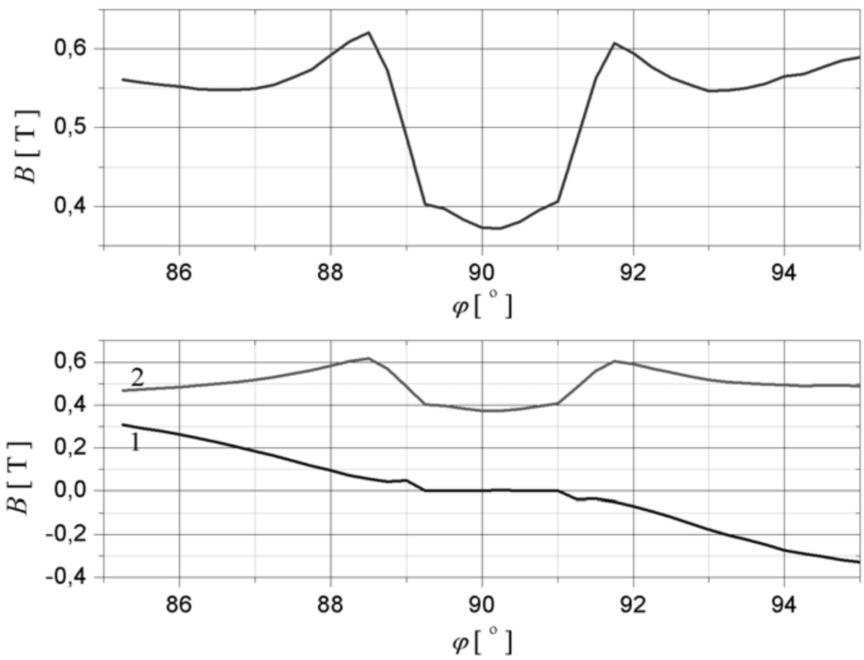

Fig. 16. Result of numerical calculations of magnetic field originating from the current in the magnetizing winding (*I* = 2600 A) in an electric machine with pole shoes like in Fig. 11, at half of the height of concentrators, for the angular width shown in Fig. 12: a) distribution of the magnetic flux density modulus, b) distribution of the magnetic flux density components: radial – curve 1, tangential – curve 2

6. SUMMARY AND CONCLUSIONS

The Verdet constant determined basing on measurements and calculations for light wavelength λ = 1550 nm is k_V = 0,144 rad/T*m. The length of the optical fibre constituting the measuring sensor in situation 1 in Fig. 4 was L_1 = 51 mm. A list of calculation and measurement results is given in Table 2. The values of $\Delta\alpha$ corresponding to values of the determined tangential component of magnetic flux density for selected measurement results are given in the fourth column of the table.

Comparing the results in Table 2 it shall be stated that the value of the tangential component of magnetic flux density in the air gap of the magnetic system in question measured using an optical fibre and determined on the basis of the characteristic $\Delta\alpha = f(B)$ is higher than that determined by numerical calculations. A significant influence on the result of measuring using an optical fibre had the **magnetic** leakage flux between the side surfaces of permanent magnets. On the basis of measurements it shall be stated that at occurrence of magnetic fields with higher values (also depending on the design of the magnetic system) the magnetic leakage flux assumes higher values than it results from numerical calculations. This statement is motivated by measurement results of the radial component of magnetic flux density using a measuring instrument with Hall sensor. Values of magnetic flux density obtained in this way achieve higher values in comparison with the corresponding results obtained by numerical calculations. On this basis it shall be stated that the values of the tangential component of magnetic flux density in the air gap of the investigated magnetic system shall be considered as real.

TABLE 2
List of selected results of calculations and measurements

Item	Value of current in magnetizing winding	Numerical calculations	Measurement of the B_T component using an optical fibre	Measurement of the B_R component using a Hall sensor
1	I = 1900 A	B_{max} = 0.332 T B_{maxR} = 0.332 T $B_{śrT}$ = 0.031 T	$B_{śrT}$ = 0.026 T ($\Delta\alpha$ = 0.202 °)	B_{maxR} = 0.409 T
2	I = 2100 A	B_{max} = 0.337 T B_{maxR} = 0.337 T $B_{śrT}$ = 0.032 T	$B_{śrT}$ = 0.035 T ($\Delta\alpha$ = 0.276 °)	B_{maxR} = 0.428 T
3	I = 2300 A	B_{max} = 0.343 T B_{maxR} = 0.343 T $B_{śrT}$ = 0.033 T	$B_{śrT}$ = 0.051 T ($\Delta\alpha$ = 0.389 °)	B_{maxR} = 0.443 T
4	I = 2600 A	B_{max} = 0.348 T B_{maxR} = 0.348 T $B_{śrT}$ = 0.033 T	$B_{śrT}$ = 0.066 T ($\Delta\alpha$ = 0.515 °)	B_{maxR} = 0.451 T

Application of pole shoes with suitable shapes in the electric machine, fulfilling the role of magnetic flux concentrators allows for measuring the magnetic flux density tangential component, which in a part of the magnetic circuit presented in Fig. 11 can be treated as the modulus (Fig. 14 and 16). The magnetic flux in this part of the circuit is also the leakage flux but with significantly higher density than in the case discussed above. Table 3 shows the results of calculations for the system with pole shoes as concentrators. The value of the tangential component in the air gap between flux concentrators is by an order of magnitude higher than in the air gap between pole shoes and the rotor. Considering the high value of the Verdet constant of some optical materials and on the basis of the results obtained, it shall be stated that with a suitable design of the magnetic system and of the optical sensor it is possible to apply the Faraday effect for investigating magnetic fields appearing in electric machines.

TABLE 3
Selected calculation results for a system with pole shoes

Item	Source of magnetic field	Numerical calculations
1	Magnetic field of armature reaction	$B_{śr}$ = 0.339 T $B_{śrR}$ = 0.008 T $B_{śrT}$ = 0.339 T
2	Magnetic field from the current flowing in magnetizing winding	$B_{śr}$ = 0.423 T $B_{śrR}$ = 0.005 T $B_{śrT}$ = 0.423 T

Magnetic systems presented in Figs. 3, 4 and 11 are not identically the same. The magnetic system shown in Fig. 11 served for presenting conditions enabling measurement of magnetic field in an electric machine using an optical sensor.

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ZASTOSOWANIE EFEKTU FARADAYA W BADANIACH POLA MAGNETYCZNEGO

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STRESZCZENIE *W artykule przedstawiono wyniki badań pola magnetycznego przy zastosowaniu efektu Faradaya. Źródłem pola magnetycznego był prąd przepływający przez dodatkowe uzwojenie w silniku magnetoelektrycznym. Analizowano możliwość zastosowania czujnika światłowodowego do określania wartości zewnętrznego pola magnetycznego, jakie może wpływać na magnes trwały w trakcie pracy silnika. Przedstawiono wyniki pomiarów składowej stycznej indukcji magnetycznej w szczelinie powietrznej silnika, uzyskanych przy zastosowaniu światłowodu jako czujnika pola magnetycznego. Analizowano wpływ konstrukcji układu magnetycznego na możliwość pomiaru indukcji magnetycznej przy zastosowaniu czujnika optycznego.*

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