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Magnetic Field Strength Sensor

***Abstract**. In this paper a new kind of sensor for magnetic field strength measurement in soft materials by direct method has been presented. The sensor consists of induction coil and ferromagnetic electrodes. Its construction makes possible to measure the magnetic field strength directly at the sample surface. The principle of operation and construction of sensor were provided. Also, preliminary experimental study of the sensor was presented. The values of strength of magnetic field measured by the sensor were compared with the values obtained by means of Epstein frame. The obtained results showed that designed magnetic field strength sensor is adequate to test electrical steel.*

***Streszczenie.**W artykule przedstawiono nowy rodzaj czujnika do pomiaru natężenia pola magnetycznego materiałów magnetycznie miękkich metodą bezpośrednią. Czujnik składa się z cewki indukcyjnej i elektrod ferromagnetycznych. Jego konstrukcja umożliwia pomiar natężenia pola magnetycznego bezpośrednio na powierzchni próbki. Przedstawiono zasadę działania i budowy czujnika oraz wyniki badań wstępnych. Wartości natężenia pola magnetycznego mierzone przez czujnik porównano z wartościami uzyskanymi za pomocą ramy Epsteina. Uzyskane wyniki wykazały, że zaprojektowany czujnik pola magnetycznego jest odpowiedni do badań blach elektrotechnicznych.(**Czujnik natężenia pola magnetycznego**).*

Keywords: magnetic field sensor, magnetic field strength measurement, direct method of magnetic field strength measurement.
Słowa kluczowe: czujnik pola magnetycznego, pomiar natężenia pola magnetycznego, metoda bezpośrednia pomiaru pola.

Introduction

For assessment of magnetic properties of an object, measurement and appropriate assignment of basic magnetic quantities are necessary. The quantities include induction and strength of magnetic field. A way of magnetizing a tested sample should enable determining magnetic properties of the material not the object. This enforces using uniform distribution of a tangent component of magnetic field strength in the measurement region of the tested object. Fulfilling of this condition is very difficult even in case of standardized test circuits, such as an Epstein frame, Single Sheet Tester (SST) or toroidal sample in which absolute values of magnetic properties of electrotechnical sheets are determined from flow and magnetic induction laws.

From the metrological point of view, a proper acquisition of measuring signals, reflecting magnetic parameters of a tested object, is necessary. Simultaneously measured pairs of magnetic quantities should be assigned to the same measurement region, unambiguously defined in terms of magnetization state. In standardized test systems with a closed magnetic circuit and defined sample cross-section, the magnetic field strength measurement causes essential problems regardless of the way of its realization.

In practice, different methods of measurement of magnetic field strengths are used. They impose different requirements on the methods of magnetization and acquisition of signal from an examined object, the way of conversion the measured signal, influence of disturbances on the measured signals and so on.

The possibility of measuring magnetic field strength in a ferromagnetic material follows from the second Maxwell equation. In standardized test circuits forming a closed magnetic circuit, the strength of magnetic field is determined by indirect method based on a connection with magnetizing current, expressed by the dependence:

(1)
$$\oint \boldsymbol{H} \cdot d\boldsymbol{l} = I$$

where: $\boldsymbol{H}$ – vector of magnetic field strength, $d\boldsymbol{l}$ – vector tangent to the integration path, I – current enclosed by the integration path l.

It enables us to determine magnetic field strength from a measurement of a current magnetizing an examined object. In real conditions, Eq. (1) is not accurate. A reason of non-uniform material magnetization is its inhomogeneity, existence of air gaps at the sample-yoke contacts and influence of geometrical dimensions of sample (even in case of a toroidal sample that is often considered as ideal). The factors result in a dependence of effective path of magnetic flux in a tested object on the method and state of its magnetization, its magnetic properties, frequency of magnetizing field [1 - 4] etc.

For this reason, a mean length of magnetic flux path for an Epstein frame and SST has arbitrarily been chosen [5, 6]. Due to the above mentioned reasons, the value of magnetic field strength determined by the indirect method is burdened by significant error [1, 7].

The main reason is the difficulty in setting up a test magnetic circuit ensuring exact relation (1) between magnetizing current and strength of magnetic field along the whole length of a tested magnetic core. In spite of this, the method of indirect measurement of magnetic field is standardized and commonly used.

A possibility of elimination of the mentioned shortcomings follows also from the second Maxwell equation. In case, when no currents flow at the ferromagnetic-air boundary, equation (1) takes a form:

(2)
$$\oint \boldsymbol{H} \cdot dl = 0$$

It implies continuity of the tangent component of magnetic field strength at the ferromagnetic-air boundary and enables its measurement in a direct way. This eliminates drawbacks of direct method because the state of uniform magnetization of a tested object is required only in measurement region. On the other hand, the measurement of field strength must be performed directly on the surface of a tested object. Such condition is almost impossible to fulfil from technical point of view as the distance between the sensor and the surface of the tested object results in an error of method of direct measurement of magnetic field strength. The error is also influenced by geometrical dimensions, magnetic properties and state of magnetization of the tested object. The factors decide about distribution of demagnetizing poles on the surface of the tested object, and in consequence, on a gradient of the tangent component of magnetizing field over the surface of the object. It should be noticed that the demagnetizing field, which is always nonuniform, causes that the tangent component of the field magnetizing the object is also nonuniform and nonlinear as a function of distance from its surface. Furthermore, it depends also on geometrical dimensions and the way of magnetization as well as on magnetization state of the sample. Theoretical estimation of the influence of these factors on correctness of the measurement of magnetic field strength is very difficult and time consuming. Besides, it is not precise due to necessity of taking up a priori assumptions concerning, among others, the tested object and boundary conditions corresponding to different states of magnetization of the object. Because of the mentioned reasons, in spite of many advantages of this method, the direct measurement of magnetic field strength is employed sporadically, mainly in case of local measurement of magnetic properties of soft materials.

Direct measurement of magnetic field strength is performed with a help of passive and active inductive sensors and various semiconductor and thin-film sensors, widely reported in the literature [8 - 11].

However, in every case, the error of measurement method caused by a distance between a sensor and surface of tested object occurs. The error can be reduced by using an appropriate method of magnetization of the tested object. Due to the gradient of magnetic field strength over the surface of the tested object, the sensors of the tangent component of this field (H_T) should be located possibly close to the sample surface. Usually, due to design restrictions, the distance of sensors for direct measurement of magnetic field strength ranges in few millimeters.

For this reason, the measurement of magnetic field gradient is carried out at several heights over a sample surface and the value of the field on the surface of the object is determined by linear extrapolation method. The method is employed for the measurement of a tangent component of magnetic field strength using both a flat coil [12 - 14] and Hall sensors [15, 16].

However, this raises a number of concerns which include uncertainty of assessment of linear change in the strength of field magnetizing a given object in a function of distance from its surface, and uncertainty in determining very small distances of the sensor (or sensors) from the surface. A reason of nonlinear gradient of magnetizing field can be the sources of poles of nonuniform demagnetizing field resulting from the change in the normal component of magnetization at the boundary surfaces of tested object. This is an essential message for designing optimal test circuits.

Stupakov [15] and Perevertov [16], point out also a significant influence of the field dissipated in the gaps at the contact: magnet yoke – tested object and in the yoke itself. They indicate also the necessity of using shields from soft magnetic materials on both sides of magnetic field sensors, which may reduce the gradient of magnetic field over the surface of tested object by five to ten times and thus diminish the error of magnetic field strength measurement [17], [18].

It should be underlined here, that the smallest possible distance between a sensor and surface of electrochemical sheet is determined by the thickness of electroinsulating coating. Typically, it ranges within a few micrometers, and for such distance, a direct measurement of magnetic field strength by non-destructive method is possible. Such distance from the sample surface is possible to achieve with an inductive sensor containing ferromagnetic electrodes, developed by the authors. Hence, it has been called "sensor with ferromagnetic electrodes for direct measurement of magnetic field" The novel sensor combines the advantages of an induction coil for direct measurement of magnetic field strength and Rogowski-ChattockPotentiometr (RCP).

The induction coil sensor is made of a coil wounded on a paramagnetic core. According to Faraday law, a sinusoidal alternating magnetic field, induces a sinusoidal electromotive force e in the coil, according to the dependence

(3) $$e = n\frac{d\Psi}{dt} = 2\pi f n A B_m cos\omega t$$

where: f – frequency [Hz], n – number of turns, A – cross - section area of induction coil [m^2], B_m – magnetic induction [T]

The sensitivity of a sensor depends only on its turns area (n·A). It is the only parameter of conversion characterized by high stability. Its directivity makes possible to perform measurements of the components of magnetic field strength vector by a non-invasive method if only its sensitivity is high enough. Additionally, as a passive sensor it does not disturb the distribution of measured fields.

Disadvantages of an induction coil sensor are low sensitivity, ability of measurement of alternate fields only and dependence of the output signal on a derivative of magnetic flux. Using an integrating circuit is therefore necessary however, it is a potential source of error in the process of conversion of measured signal. On the other hand, there is a possibility to adapt it to the measurement of a constant component of magnetic field.

Rogowski coil (RCP) is a special kind of sensor with a coil uniformly winded on an elastic and non-magnetic core bent in such way that its ends come up to the surface of a tested object. Such solution ensures bringing the sensor closer to the surface of the tested object at a distance equal to the radius of diameter of the winding wire. The output signal of such sensor is proportional to the difference of magnetic potentials at the ends of the sensor. When the distance between the ends is known, the average tangent component of magnetic field strength in this region can be estimated [19]. However, relatively low sensitivity of such sensor (the best reported in literature is 0.412 nV/(A·m^{-1}) [20]) as well as sensitivity to nonuniform fields, limit its application in soft magnetic materials measurements. Sensitivity of RCP can be enhanced by increasing the number of turns area (nA) of the coil. The length of non-magnetic core should be much larger than the distance between the points of measurement of potential difference on the sample surface to minimize the error of averaging the coil length.

In this paper a new kind of sensor, not applied so far, for magnetic field strength measurement in soft materials by direct method has been presented. Its essential property is significant limitation or even complete elimination of typical shortcomings of methods commonly used for measurement of magnetic field strength.

Theory and experiment

The principle of the sensor operation

A principle of operation of the sensor is based on measurement of magnetic potential difference. It is a combination of a passive induction coil sensor and RCP sensor. The inductive coil sensor can in some conditions play a role of an inductive magnetic voltage sensor.

An element of cross section of a single-layer coil (Fig. 1) located in magnetic field is associated with a magnetic flux defined as

(4) $$d\psi = \frac{n}{l_c}\mu_0 dA \int_0^{l_c} H_l \, d\boldsymbol{l} = \frac{n}{l_c}\mu_0 u_\mu dA$$

where: $\int_0^{l_c} H_l \quad dl = u_\mu$ - magnetic voltage between the ends of a single-layer coil $\frac{n}{l_c}$ - linear density of the winding, l_c- length of the coil, H_l– a component of magnetic field strength of the coil parallel to its axis.

It seems that ensuring constant magnetic potentials on both faces of the coil is a necessary and sufficient condition for the output signal of passive inductive coil to be proportional to the difference of magnetic potentials or magnetic voltage drop. In case of a multilayer coil, the magnetic flux associated with its winding can be expressed as

$$\psi_c = A_c N \frac{n}{l} \mu_0 u_\mu \tag{5}$$

where: A_c – cross section area of inductive coil, N – number of layers in the coil, n – number of turns in a single layer of the coil, l_c – distance between faces of the coil, μ_0 – permittivity of free space, u_μ- difference of magnetic potentials or magnetic voltage between the faces of the coil, l_p – distance between electrodes.

Magnetic voltage is then defined by the expression

$$u_\mu = \frac{\Psi_c}{\mu_0 A_c N \frac{n}{l_c}} \tag{6}$$

The fact has been used for designing a magnetic field strength sensor with ferromagnetic electrodes in which an inductive coil has been used.

Equipotential faces of the coil were achieved by using rectangular stripes of a ferromagnetic material with high initial magnetic permeability, closely adjacent to the coil faces. The shorter side of the stripes was not smaller than the outer diameter of the coil (D) and the longer one served to transferring magnetic potential from the tested object to the faces of the induction coil (Fig. 1).

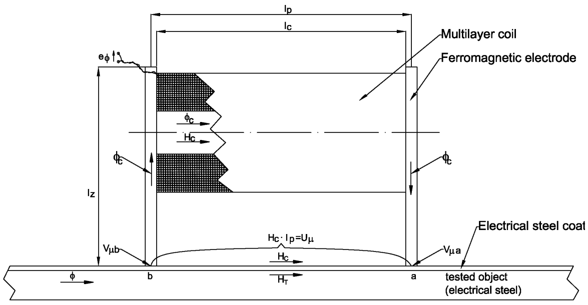

Fig. 1 Scheme of sensor operation

Taking into account very high magnetic resistivity of the sensor coil it can be assumed that magnetic resistivity of the ferromagnetic electrodes in a form of sheets is negligibly small. It causes also that there is a negligibly small magnetic voltage drop in the sheets adjacent to the sensor faces. As a result, the close to zero magnetic voltage drop in the ferromagnetic electrodes ensures equipotentiality on their surfaces and thus magnetic equipotentiality of the coil faces. Consequently, the ferromagnetic electrodes positioned on the surface of a tested object will take the magnetic potentials of those points and transfer them lossless on the coil faces. As a result, the output signal of the inductive sensor will be proportional to the magnetic potential difference of the sensor faces, generating magnetic flux of appropriate value.

Difference of magnetic potentials of a sensor determines the value of magnetic flux associated with the coil (Eq. 5). It should be pointed out that orthogonality of ferromagnetic electrodes to the coil axis eliminates almost completely the influence of nonuniform demagnetizing field of tested object on the output signal of the sensor. A very valuable advantage of the presented sensor is practically complete lack of influence of the distance of sensor coil from the surface of tested object provided that its ferromagnetic electrodes are magnetically equipotential.

Values of magnetic flux associated with the coil cannot be accurately estimated from Eq. (5). The reason is so called additional virtual coil created by every layer of winding located along the coil axis. It results from helical winding of the coil. Its negative effect can be almost completely eliminated by using a multilayer coil with an even number of layers. Additional and very desired effect of such procedure is an improvement of coil sensitivity. It rises also with a decrease of coil cross-section and shortening of its length.

It should be noted, that shortening of the coil causes a harmful increase of magnetic flux resulting in magnetic voltage drop on electrodes of the sensor coil. A tradeoff between the length and sensitivity of the coil is then required, depending on the requirements imposed on magnetic flux of the measuring system. Some effect on inaccuracy of Eq. (5) has also the loop of connections transferring the output signal of the sensor. Its effect decreases with an increase in the number of sensor layers. Assuming that there is no magnetic voltage drop on the air gaps of a sensor circuit and its electrodes, magnetic voltage in points a and b in Fig. 1 and on the surface of tested object is transferred without losses on the coil faces, as

$$u_{\mu_{ab}} = H_T l_p = H_c l_c \tag{7}$$

where: $H_T l_p$- magnetic voltage between points a and b and on the surface of tested object, $H_c l_c$magnetic voltage between the faces of coil of the sensor.

If the length of the sensor coil is equal to the distance between points a and b, we get on the surface of tested object:

$$H_T = H_c \tag{8}$$

Average value of magnetic field strength in the investigated region is equal to the strength of magnetic field in the sensor coil.

This discussion points out that the measured magnetic voltage depends only on fixed and stable sensor parameters and magnetic permeability of ferromagnetic electrodes.

The construction of the sensor

In order to verify empirically the theoretical assumptions, a sensor consisting of an induction multilayer coil with a length of 10.0 mm and 18 000 windings was made. To the faces of the coil with a diameter of 9.1 mm, we fixed closely adhering rectangular electrodes made from electrical steel of M350-50A type, with a width of 9.1 mm and length of 15.0 mm. The longer side of the electrodes was aligned with the rolling direction of the electrical steel. Before fixing, the sheets were stress relieved to remove mechanical stress developed during their cutting. The sensor of tangent component of magnetic field strength and its details are shown in Fig. 2.

As for a multilayer coil it is impossible to determine analytically, from Eq. (5), an effective cross-section, linear density of winding nor transformation coefficient of the magnetic voltage sensor, experimental determining of a constant of conversion is necessary. For this purpose, the complete sensor was calibrated in the field of solenoid with a length of 600 mm and coil constant C = 33 cm^{-1}. The characteristic of output voltage of the sensor versus magnetic field strength (Fig. 3) is linear. The sensitivity of sensor is 0.204 $mV/(A \cdot m^{-1})$.

Results and discussion

To check the correctness of measurement with the constructed sensor, the values of strength of magnetic field were measured and compared with the values obtained with the help of a standardized test system i.e. an Epstein frame. For this purpose, the sensor was set on one of the four stripes of M350-50A electrical steel, which had been used as a sample for investigations with the Epstein frame, and it was placed together with the sample in one of the frame arms. Measurements of magnetization characteristics of the sample were carried out with the help of a computer measurement system MAG 3.0 by R&J Measurement Co. Derivative of induction with respect to time was approximated with a sinusoidal run. The shape factor did not exceed 1.111. Error of repeatability of induction setting by the system did not exceed 0.3%. The measurements were carried out in induction range of 0.1 – 1.6 T with a step of 0.1 T.

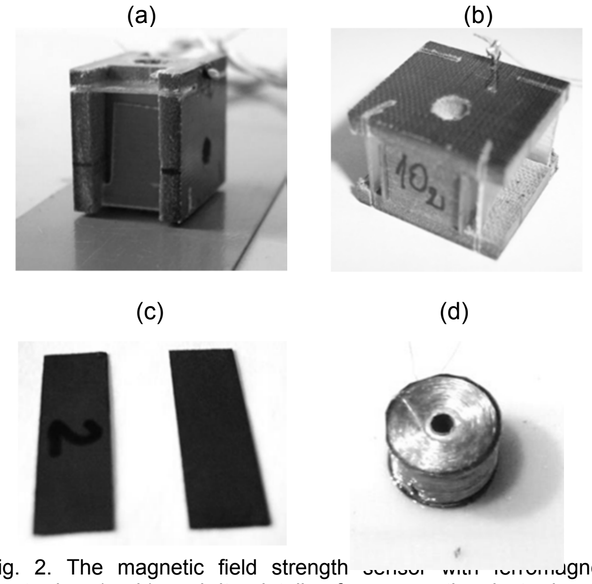

Fig. 2. The magnetic field strength sensor with ferromagnetic electrodes (a, b) and its details: ferromagnetic electrodes (c), multilayer coil (d)

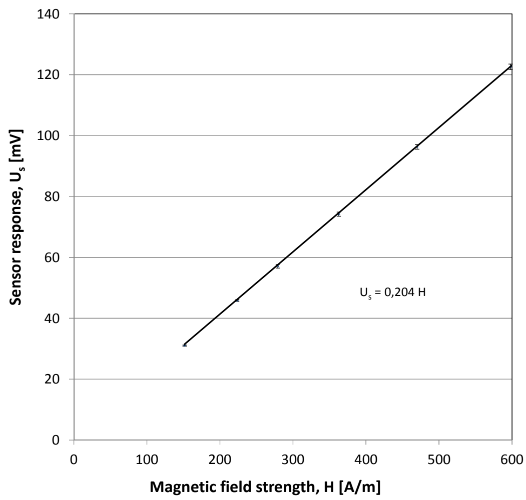

Fig. 3. Characteristics of sensor output voltage U_s on magnetic field strength H determined in the long coil.

The system measured magnetic induction and the values of magnetic field strength by indirect (standardized) method for the whole sample inserted in the Epstein plane whereas the values of magnetic voltage measured with the sensor were measured with a universal measuring instrument containing an average value transducer. The strength of magnetic field measured by the sensor was estimated based on the former calibration of the sensor, from the measured values of voltage.

The sensor measured, the values of magnetic field at two locations on the sample – in the centre of the sample (a region 14.5 – 15.5 cm from the strip end) and in 1/3 of the sample length (in the region 4.5 –5.5 cm from the strip centre). In every case the sensor was located at the centre of the strip width (1 cm from the sample side).

Results of the measurements are shown in Fig. 4. The best conformity of the results was achieved for a sensor located at 1/3 of the sample length.

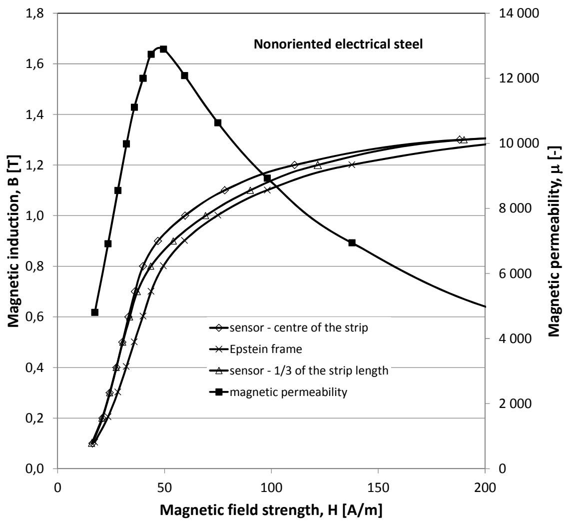

Fig. 4. Magnetization curves for sample M350-50A obtained in the measurement in Epstein frame and with the tested sensor at different locations of the sensor on the sample – centre of the strip and 1/3 of the strip length magnetic permeability of the tested sample

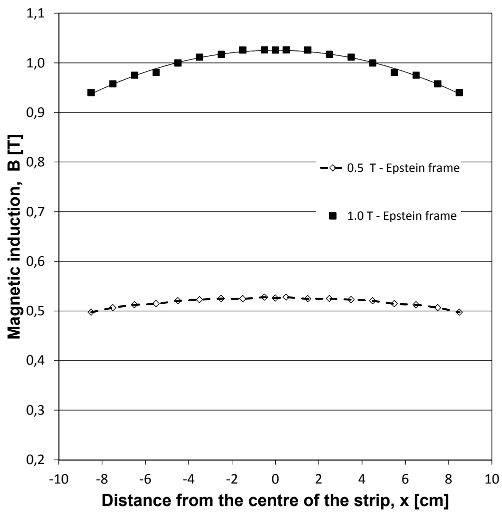

Fig. 5. Distribution of the local magnetization measured along one of the arms of the Epstein frame (0.5T, 1.0 T – Epstein frame – value of induction obtained with Epstein frame).

It is caused by the parabolic distribution of magnetic induction in the arm Epstein frame.

In the centre of the magnetizing coil the induction is the highest (Fig. 5). At a distance of approx. 4 to 6 cm from the centre of the magnetizing coil the induction measured locally corresponds to the average induction measured by means of Epstein Frame. Consequently, the magnetization curve measured locally at that place the most corresponds with the magnetizing curve obtained by Epstein frame in terms of the measured induction value.

The most noticeable differences are in the area of highest magnetic permeability (Fig. 4). This is in line with expectations. As already mentioned, the mean path of magnetic flux in the frame Epstein has an arbitrarily set value of 0.94 m. In fact, in the high permeability area the path length is longer. Due to that, the actual magnetic field strength in the sample is smaller than that measured by means of Epstein frame according to the formula:

$$H = \frac{nI}{l_m} \quad (9)$$

where: I – magnetizing current [A], l_m – mean path length.

Conclusion

This paper demonstrates a new kind of sensor with ferromagnetic electrodes for magnetic field strength measurement in soft materials by direct method. Its essential property is significant limitation of typical shortcomings of methods commonly used for measurement of magnetic field strength like the influence of magnetic field gradient over sample on the measurements results or instability or low sensitivity.

The preliminary study of the sensor was presented. The values of strength of magnetic field in the nonoriented electrical steel were measured by the sensor and compared with the values obtained with the help of a standardized test system i.e. an Epstein frame. As the value of magnetic field strength measured in an Epstein frame is averaged for the whole sample length while the measurement with the sensor was performed locally, in the length of 10 mm, the obtained results can be judged as consistent and confirming a correct operation of the sensor.

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REFERENCES

[1] Antonelli E., Cardelli E., Faba A., Epstein frame: how and when it can be really representative about the magnetic behavior of laminated magnetic steels, *IEEE Trans. Magn.*, vol. 41, (2005), no. 5, pp. 1516–1519
[2] Marketos P., Zurek S., Moses A. J., A Method for Defining the Mean Path Length of the Epstein Frame, *IEEE Trans. Instrum. Meas.*, vol. 43, (2007), no. 6, pp. 2755–2757
[3] Tsai W.-C., A study on core losses of non-oriented electrical steel laminations under sinusoidal, non-sinusoidal and PWM voltage supplies, TENCON 2007 - 2007 *IEEE Reg. 10 Conf.*, 2007.
[4] Hofmann M., Kahraman D., Herzog H., Hoffmann M. J., Numerical Determination of the Effective Magnetic Path Length of a Single-Sheet Tester, *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 18–21 (2014).
[5] Magnetic materials - Part 2: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame, *IEC 60404-2:1996+AMD1:2008*
[6] Magnetic materials – Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester, *IEC 60404-3:1992+A1:2002+A2:2009*
[7] Sievert J., The measurement of magnetic properties of electrical sheet steel – survey on methods and situation of standards, *J. Magn. Magn. Mater.*, vol. 215–216, (2000), pp. 647–651
[8] Tumanski S., Induction coil sensor – a review, *Meas. Sci. Technol.*, vol. 18, (2007), pp. R31-R46
[9] Tumanski S., Handbook of magnetic field measurements, Ch. 4 – Magnetic sensors, *CRC Press* (2011)
[10] Alatawneh N., Pillay P., Calibration of the Tangential Coil Sensor for the Measurements of Core Losses in Electrical Machine Laminations, *IEEE Transaction on Energy Conversion*, vol. 31, (2016), no. 2, pp. 413 – 423
[11] Lenz J., Edelstein A. S., *Magnetic Sensors and Their Applications*, IEEE Sens. J., vol. 6, (2006), no. 3, pp. 631–649
[12] Nakata T., Kawase Y., Nakano M., Miuira M., Analysis and Improvement of Measuring Method of Magnetic Fields in Single Sheet Testers, *TJMJ-1 7*, (1986), pp. 873–874
[13] Tumanski S., A multi-coil sensor for tangential magnetic field investigations, *J. Magn. Magn. Mater.*, vol. 242–245, (2002), pp. 1153–1156
[14] Abdallh A., Dupre L., Local magnetic measurements in magnetic circuits with highly non-uniform electromagnetic fields, *Meas. Sci. Technol.,* Vol. 21, (2010), 045109
[15] Stupakov O., Investigation of applicability of extrapolation method for sample field determination in single-yoku measuring setup, *J. Magn. Magn. Mater.*, vol. 307, (2006), pp. 279-287
[16] Perevertov O., Measurement of the surface field on open magnetic samples by the extrapolation method, *Rev. Sci. Instrum.*, vol. 76, (2005), no. 10, pp. 104701
[17] Perevertov O., Increase of precision of Surface magnetic field measurements by magnetic shielding, *Meas. Sci. Technol.*, vol. 20, (2009), pp. 055107
[18] Stupakov O., Controllable Magnetic Hysteresis Measurement of Electrical Steels in a Single-Yoke Open Configuration, *IEEE Trans. Magn.*, vol. 48, (2012), no. 12, pp. 4718–4726
[19] A.P. Chattock, On a Magnetic Potentiometer, *Philos. Mag.* Ser. 5, vol. 24, (1887), no. 146, pp. 94–96
[20] Abdallh A., Dupre L., A Rogowski-Chattock coil for local magnetic field measurements:sources of error, *Meas. Sci. Technol.*, vol.21, (2010), pp. 107003