Vol. 05, No. 3 (2023) 417-424, doi: 10.24874/PES05.03.006

Proceedings on Engineering Sciences

www.pesjournal.net

MAIN CHARACTERISTICS OF NONCONTACT CONVERTERS OF LARGE CURRENTS WITH LONGITUDINALLY DISTRIBUTED PARAMETERS FOR CONTROL AND MONITORING SYSTEMS

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Received 22.12.2022.
Accepted 10.06.2023.
UDC – 621.316.

Keywords:

Noncontact Converter, Direct Current, Hall Element, Water Supply, Reduced Error, Monitoring And Control Systems, Integrating Loop

ABSTRACT

The article shows that the necessity of breaking current circuits to temporarily switch on electric measuring instruments, the presence of large power losses on shunts, undesirability or impossibility under technological process conditions of breaking circuits, as well as safety requirements have caused noncontact conversion and measurement of large direct currents in circuits without breaking them in metallurgy, electrochemical industry, railway transport, melioration, irrigation and in general in agriculture. The results of the development of one of them are presented in the paper. Considered its static characteristic, the error of calculation, which does not exceed 3 percent, its degree of nonlinearity, and its average and current sensitivity, which throughout the range of current transformed practically remain constant in magnitude. The developed galvanomagnetic noncontact converter can be widely used in control and management systems in water supply, melioration, and irrigation, industry, railway transport, metallurgy, science, engineering, as well as for the verification of electric meters at the place of their installation for non-contact control of direct and alternating currents.

1. INTRODUCTION

Unstable operation of current control systems, the presence of additional resistances due to oxidation of contacts lead to a decrease in performance of powerful water supply plants, rolling mills, vacuum arc melting furnaces, chemical apparatus, downtime, and large voltage drops on shunts lead to unjustified loss of capacity (Kazakov, 1998; Plakhtiev, 2017). At the same time in automated systems of control and management

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of various technological and physical processes in the agro-industrial complex are widely used primary means of collecting and processing information (Semenko & Gamazov, 1984). The primary converter in them is a link of any information-measuring or control system and completely defines its main metrological characteristics. In this case, losses in accuracy and reliability of the final result, connected with erroneous application of a primary converter, cannot be recovered even by the most perfect information conversion system. Thus the task is much more complicated in case of the influence of external factors, such as the influence of aggressive environments, electric and magnetic fields, vibrations, radiations, changes in temperature, the humidity of the environment, etc. (Andreev & Abramzon, 1979; Yusupbekov et al., 2007).

Ever-increasing requirements for modern elements and technical means of control and management systems in the agricultural power industry and electrical technology in agriculture, as well as in industry, have ensured the development of energy-saving noncontact ferromagnetic measuring converters of large direct currents (LDC) with a split integrating loop, allowing to grip a conductor or busbar with a transformed current without violating the structural and schematic integrity of the device (Spector, 1988; Bolotin et al., 2012).

As a result of the analysis of non-destructive non-contact control LDC places, the main requirements for non-contact ferromagnetic measuring transducers of large direct currents were identified, which include: high sensitivity, accuracy, reliability, low weight, dimensions, material capacity, cost, manufacturability of design, absence of errors caused by the influence of external magnetic fields, return conductor with current, displacement of the conductor with current from the center of the integrating circuit, ferromagnetic masses, absence of energy consumption from the measured circuit, the ability to work in an aggressive environment, explosion protection, as well as the absence of galvanic coupling between the monitored alternating current and the measuring circuit and availability in some cases of both fixed sensitivity control of non-contact ferromagnetic measuring converters in a wide controlled range and making them portable or stationary (Plakhtiev, 2017).

In practice, a large number of individual noncontact converters and large direct current meters are known, the most widely used galvanomagnetic noncontact ferromagnetic converters of large direct currents (Gilardi, 2013; GB Patent No. 4575111, 2016), but the known converters have some drawbacks, the main of which are: a narrow controlled current range, low accuracy and sensitivity, large dimensions, and mass, and the absence of fixed regulation of their sensitivity. In this regard, the elimination of these disadvantages is an important necessity and the purpose of this work.

2. MATHERIALS AND METHODS

We have developed some lightweight, universal, energy-saving galvanomagnetic noncontact large direct current converters (GNC), which allow conversion of both direct and alternating large currents in various control and monitoring systems without breaking the circuit. They use different designs of split closed magnetic cores with transversely and longitudinally distributed magnetic parameters and increased path length of working magnetic flux on steel (Plakhtiev, 2017; Plakhtiev et al., 2020).

One of the developed ones is the GNC shown in Figure 1. It is developed based on a galvanomagnetic non-contact ferromagnetic converter of large direct currents (Plakhtiev, 1985). Let's consider its features and static characteristic, its degree of nonlinearity, as well as the issues of its sensitivity.

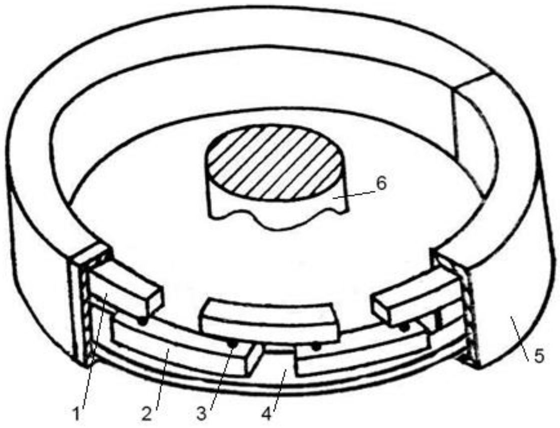

Figure 1. The galvanomagnetic noncontact converter of large direct currents with longitudinally distributed parameters for control and monitoring systems

The GNC contains a closed magnetic core consisting of separate ferromagnetic elements 1 and 2. Ferromagnetic elements 1, as well as ferromagnetic elements 2, are installed with transverse gaps, evenly distributed along the entire length of the split magnetoconductor. Neighboring ferromagnetic elements 1 and 2 form *n* pairs of longitudinal gaps between them, in which Hall elements 3 are placed. The ferromagnetic elements 2 are rigidly fixed on the ring-shaped insulating plate 4, which can be fixedly moved to the set distances, changing the gaps between the ferromagnetic elements 1 and 2, and, consequently, the parameters of transverse gaps. The closed magnetic wire together with the Hall elements 3 is placed in the insulating case 5, which covers busbar 6 with the controlled current in the process of measurement. Current electrodes of Hall elements 3 are connected to the current source. The Hall electrodes of the Hall elements 3 are connected in series with each other, and the Hall electrodes of the Hall elements 3 placed in each pair of transverse gaps formed by one ferromagnetic element 2 and neighboring ferromagnetic elements 1 are connected in opposite directions. To indicate the measurement results, a recording device (not shown) is included in the chain of series-connected Hall electrodes of the Hall elements 3.

The GNC works in the following way. After the busbar 6 with the controlled direct current is encircled by the controlled current, a constant magnetic flux is created in the magnetic core, which, penetrating the Hall elements 3, causes the appearance of the Hall EMF on their Hall electrodes. These EMFs are summed up due to the counter-inclusion of the Hall electrodes of Hall elements 3. As a result, at the output of a chain of series-connected Hall electrodes of Hall elements 3, there is a total output Hall EMF E_x, which depends on the value of the monitored DC I.

The value of this total Hall EMF E_x is measured with a recording device. Increasing the upper limit of measurement of large direct currents is made by increasing the gap between fixed 1 and movable 2 ferromagnetic elements by a fixed transition of plate 4 with ferromagnetic elements 2 at the set distances. This leads to an increase in the longitudinal gaps, and, consequently, to a change in the operating magnetic fluxes, which allows the sensitivity of the GNC to vary over a wide range of currents to be converted. Let's consider the static characteristic of the GNC shown in Figure 1.

3. RESULTS

The static characteristic of GNC is a functional relationship between output and input quantities at their steady-state values (Plakhtiev et al., 2021b).

In the GNC the input quantity is the controlled direct current I, and the output quantity is the Hall EMF E_x, the expression of which is written in the form

$$E_X = K_X I_P B, \qquad (1)$$

where K_x – Hall transducer proportionality coefficient, which depends on the parameters of the semiconductor material, the ratio of the geometric dimensions of the converter, the mode of its operation, and their number;

I_P – Hall cell supply current;

B – magnetic induction in the longitudinal gap of the split magnetic core.

Let us denote

$$a_X = K_X I_P. \qquad (2)$$

For analytical determination of the static characteristic, it is necessary to know in analytical form the dependences $B = f(H)$, where B and H – induction and strength of the magnetic field penetrating the Hall elements.

To reduce the residual magnetic induction in GNCs, it is recommended to use magnetically soft materials (electrotechnical steel) (Danilov, 2004). Therefore, we will approximate the main magnetization curve of electrical steel by the sum of the hyperbolic tangent and the straight line with the angle coefficient as

$$B = C_1 thC_P H + C_3 H, \qquad (3)$$

where C_1, C_2, C_3 – approximation coefficients.

Taking into account (2) and (3), let us rewrite expression (1) as

$$E_X = a_X \frac{C_3}{C_2}\left(C_1 \frac{C_2}{C_3} thH + H_x\right), \qquad (4)$$

where H_x - the strength of the magnetic field permeating the Hall elements, equal to

$$H_X = C_2 H, \qquad (5)$$

where

$$H = \frac{I_u}{\pi D_c} \cdot \frac{(1 + C_v)\beta C_v (1 + C_{mv}) \cdot}{2\beta sh\beta C_v (1 + C_{mv} + 2C_v C_{mv}) -} \cdot$$

$$\cdot \frac{(1 - ch\beta - 4sh\beta)}{-(1 - ch\beta) - 2(C_v(1 + C_{mv}) + 2)}, \qquad (6)$$

where I_u – measured direct current; D_c – diameter of the center axial line of the split closed magnetic core; β – coefficient characterizing the magnetic voltage loss in the magnetic circuit; C_v, C_{mv} – coefficients that take into account the geometric dimensions of the split closed magnetic core and the grade of steel used in the magnetic core.

Denoting $C_1 \frac{C_2}{C_3} = C$, we rewrite (4) as

$$E_X = a_X \frac{C_3}{C_2}(CthH_x + H). \qquad (7)$$

Denoting in (7) $a_X \frac{C_2}{C_3} = E_{XB}$, we obtain the expression of the static characteristic of the GNC in relative units in the following form

$$E_X^* = \frac{E_X}{E_{XB}} = CthH_x + H_x. \qquad (8)$$

Figure 2 shows theoretically (solid curve) and experimentally (dashed curve) obtained plots of the static characteristic of the GNC. The use of the intermediate variable H_x as a transformed value is justified by the fact that the output EMF of the GNC is an unambiguous function of H_x, and, on the other hand, H_x carries complete information about the value of transformed current I and the type of steel used in the magnetic core.

The experiments showed that the discrepancy between the experimental and theoretically obtained static characteristics of the GNCs does not exceed 3 percent.

Consider the sensitivity of the GNC shown in Figure 1.

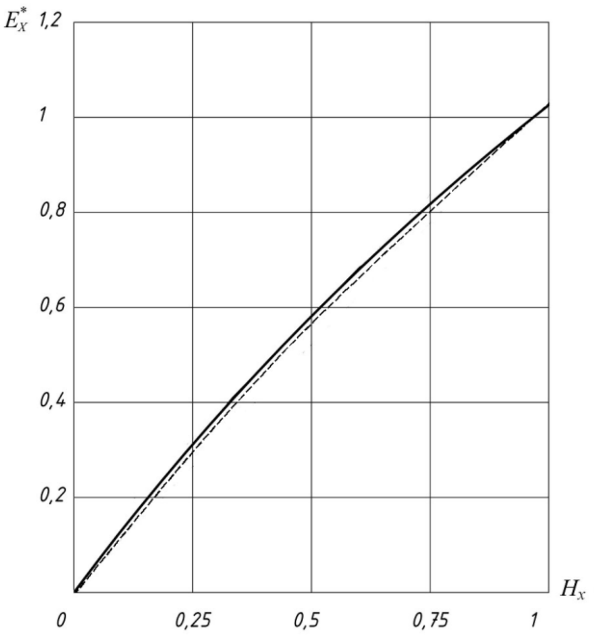

Figure 2. Static characteristic of the GNC

To analyze the GNC sensitivity, we will use the expression of its static characteristic (8).

Dividing (8) by H_x, we obtain an expression for the average sensitivity of the GNC in the following form

$$S_{cp} = \frac{E_X^*}{H_x} = C\frac{thH_x}{H_x} + 1. \tag{9}$$

The results of calculating the average GNC sensitivity according to (9) are shown in Figure 3.

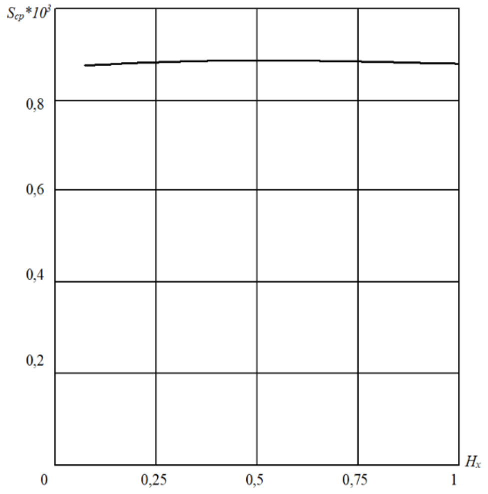

Figure 3. Graph of the dependence of the average GNC sensitivity on the magnetic field strength

The derivative of the output quantity (8) by the measured quantity H_x is the current sensitivity S_t of the GNC. The current sensitivity of the GNC is determined from the expression

$$S_t = \frac{dE_X^*}{dH_x} = \frac{C}{ch^2H_x} + 1. \tag{10}$$

Figure 3 shows graphically the dependence $S_t = f(H_x)$, calculated by (10).

The graphs in Figures 3 and 4 show that the average and current sensitivities of GNCs over the entire range of the converted current are almost constant in magnitude.

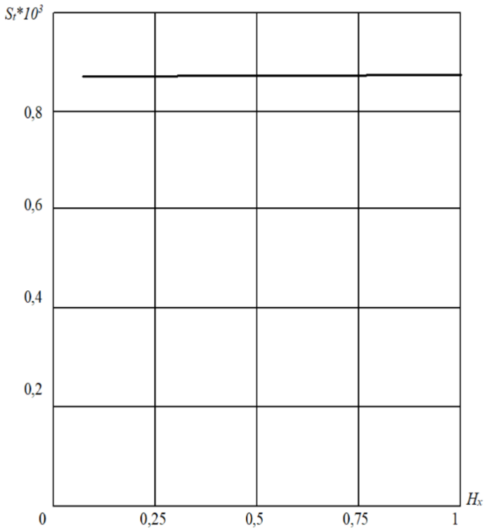

Figure 4. Diagram of the dependence of the current GNC sensitivity on the magnetic field strength of the magnetic field

Let's consider an important characteristic of GNC - the degree of nonlinearity of its static characteristic.

The definition of the degree of nonlinearity of the static characteristic of the transducer is given in (Plakhtiev et al., 2021a). According to this definition, the degree of nonlinearity of the considered section of the GNC static characteristic is the ratio of the maximum deviation of the characteristic ordinate from the straight line approximating it in this section to the whole range of ordinate change in the same section.

To analyze the degree of nonlinearity of the static characteristic of the GBIT we will use the expression of its static characteristic (8).

The degree of nonlinearity of the static characteristic of GNC is determined from the following expression (see Figure 5)

$$\varepsilon, \% = \frac{E\mathrm{x}^* = (H_{xT}) - kH_{xT}}{2E\mathrm{x}^*(H_{xM})} 100, \tag{11}$$

where $E^*(H_{xT}) -$ a value of the output EMF at the point of the static characteristic, where the deviation on the ordinate of the static characteristic from the line approximating it has the maximum value; $E^*(H_{xM}) -$ the maximum value of the GNC output EMF, corresponding to the maximum value of H_{xM}; $E^*_{aP}(H_{xT}) = kH_{xT}$ – equation of the approximating direct static characteristic of GNC; $k = \frac{E^*_{aP}(H_{xT})}{H_{xT}} = \frac{E(H_{xM})}{H_{xM}} = tg\varphi$ – coefficient characterizing the slope angle of the approximating line to the abscissa H_x.

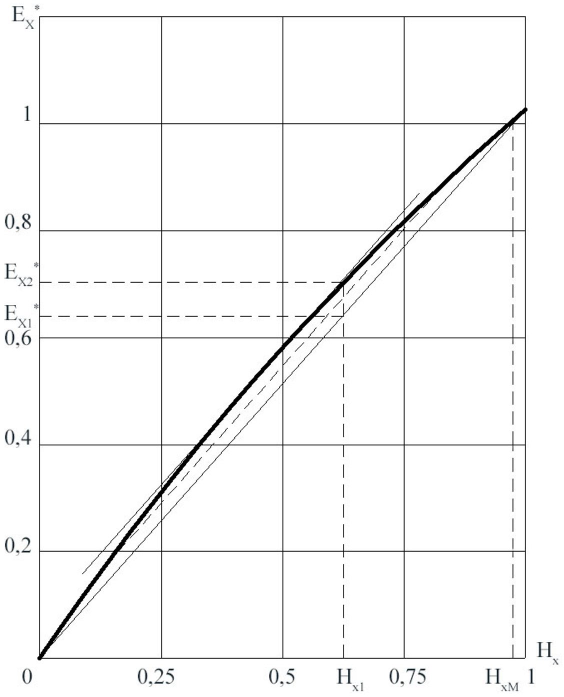

Figure 5. Determination of the degree of nonlinearity of the static characteristic of the developed GNC

The values $E^*(H_{xT})$, $E^*(H_{xM})$, $E^*_{aP}(H_{xT})$ are respectively:

$$E^*(H_{xM}) = CthH_{xM} + H_{xM}, \tag{12}$$

$$E^*_{aP}(H_{xT}) = H_{xT}\frac{E^*(H_{xM})}{H_{xM}} = \frac{H_{xT}}{H_{xM}} =$$

$$= (CthH_{xM} + H_{xM}), \tag{13}$$

$$E^*(H_{xT}) = CthH_{xT} + H_{xT}. \tag{14}$$

Substituting (12) – (14) in (11), we obtain an expression of the degree of nonlinearity of the static characteristic of the GNC in the following form:

$$\varepsilon, \% = 50\left(\frac{CthH_{xT}+H_{xT}}{CthH_{xM}+H_{xM}} - \frac{H_{xT}}{H_{xM}}\right). \tag{15}$$

The coordinate H_{xT}, at which the deviation on the ordinate of the static characteristic from the approximating line has a maximum value, can also be determined graphically, as shown in Figure 5, by drawing a tangent to the curve of the static characteristic at the point H_{x1} parallel to the approximating line.

After substituting the values of H_{xT} and H_{xM} into expression (15), we can obtain the value of the degree of nonlinearity ε, %. For example, for a static characteristic with $H_{x\mathrm{T}} = 0.625$ and $H_{x\mathrm{M}} = 1$, its degree of nonlinearity will be ε = 2.83%, which is acceptable for the GNCs under study.

Consider the transfer coefficient of the GNC. The steepness of the GNC characteristic is determined by its sensitivity to a given input signal. It is estimated by the value of the corresponding transfer coefficient (Amirov et al., 2019). Consequently, the transfer coefficient for a GNC is adequate to its current sensitivity and can be determined by an expression similar to (10) in the following form:

$$K = \frac{dE^*_X}{dH_x} = \frac{C}{ch^2H_x} + 1. \tag{16}$$

As a result, it should be noted that the transfer coefficient K of the GNC can be increased by increasing the thickness and width of the ferromagnetic elements of the split magnetic core, the width of the air gap, and reducing the length of these ferromagnetic elements, the number of air gaps between the ferromagnetic elements in the split magnetic core and the specific magnetic resistance of ferromagnetic elements.

We have developed some lightweight, universal, energy-saving galvanomagnetic noncontact large direct current converters (GNC), which allow conversion of both direct and alternating large currents in various control and monitoring systems without breaking the circuit. They use different designs of split closed magnetic cores with transversely and longitudinally distributed magnetic parameters and increased path length of working magnetic flux on steel (Plakhtiev, 2017; Plakhtiev et al., 2020).

3. DISCUSSION

A universal energy-saving galvanomagnetic noncontact converter of large direct currents has been developed, which, unlike the known noncontact converters of large direct currents, has a wide controllable range of currents with small dimensions and mass, a simple and technological design at low material consumption and cost, and can be multireference in a wide controllable range of measured currents with high sensitivity and control DC and AC currents with an error of 1.5%.

The static characteristic of the universal energy-saving galvanomagnetic noncontact converter of large direct currents has been obtained and studied. The discrepancy between the experimentally and theoretically obtained static characteristics of the converter does not exceed 3%.

The average and current sensitivities of the developed galvanomagnetic noncontact converter of large direct currents, which remain practically constant in magnitude over the entire range of the current being converted, were investigated.

An expression for determining the degree of nonlinearity of the static characteristic of a universal energy-saving galvanomagnetic noncontact converter of large direct currents at any point of the static characteristic, depending on the range of the current to be converted, is obtained.

The transfer coefficient of the GNC is considered, which is adequate to its current sensitivity and its value can be increased by increasing the thickness and width of the ferromagnetic elements of the split magnetic core, the width of the air gap, and reducing the length of the ferromagnetic elements of the split magnetic core, the number of air gaps between the ferromagnetic elements in the split magnetic core and the specific magnetic resistance of the ferromagnetic elements.

4. CONCLUSION

Universal multidisciplinary wide-range noncontact galvanomagnetic converters of large direct currents have been developed for modern control and monitoring systems in helio- and laser technology, agricultural sector, and railway transport, characterized by an expanded controllable range of converted direct currents with small dimensions and weight, improved accuracy and sensitivity, simple and manufacturable design at low consumption of materials and costs, the possibility of non-contact control of direct and alternating currents, as well as the fixed sensitivity control in a wide controllable range.

The static characteristic of the universal energy-saving galvanomagnetic contactless converter of large direct currents is obtained and investigated. The discrepancy between the experimentally and theoretically obtained static characteristics of the converter does not exceed 3%.

The developed converter has an increased sensitivity due to the Hall elements evenly distributed along the whole length of the split magnetoconductor on the path of the working magnetic flux. The average and current sensitivity of the developed galvanomagnetic noncontact converter of large direct currents, which practically remain constant in value over the whole range of the transformed current, were investigated.

The expression for determining the degree of nonlinearity of the static characteristic of the universal energy-saving galvanomagnetic noncontact converter of large direct currents in any point of its static characteristic and taking into account the range of the converted current, which value does not exceed 3%, is obtained.

The developed GNC can contactlessly control direct and also alternating currents with an error of 1.5 % in many modern control and monitoring systems in land reclamation, irrigation, solar and laser technology, renewable energy sources, solar power plants, solar power plants, direct conversion of solar energy into electrical energy using photovoltaic and thermoelectric conversions, in renewable energy sources, laser systems, power supply systems for focusing and turning electromagnets of elementary particle gas pedals, at many domestic enterprises in the production of copper, sodium, tungsten, molybdenum, zinc, hydrogen, oxygen, phosphorus and others, rolling of refractory and high-temperature metals in rolling mills, in obtaining products on drawing machines, in monitoring and control systems in non-ferrous metallurgy, in railway transport, irrigation, and land reclamation, as well as in the verification of electric meters at the place of their installation.

The authors plan to organize the future serial production of lightweight multipurpose wide-range noncontact galvanomagnetic converters and meters of large direct and alternating currents.

Acknowledgement: The study was supported by the NRU (TIIAME), and the authors would like to express their deep gratitude to the University administration for their assistance.

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