Estimation of the error of a magnetic modulation non-contact wide-range device for non-destructive control of high amperage currents

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Abstract. The paper provides information on use of direct current (DC) energy in the electric power supply industry of agriculture and water management, hydraulic engineering construction, metallurgy, irrigation and melioration. The need for non-contact non-destructive control of high amperage DCs of high-capacity electrical installations in irrigation and melioration, hydraulic engineering has been identified. The basic requirements for non-contact transducers and sensors of high amperage DC measurements without circuit breaking are formulated. Identified priority directions in the development of above mentioned transducers. The general construction principles of non-contact ferromagnetic transducers of high amperage DCs and the results of the development of one of the modification of the developed wide-range magneto modulation contactless transducers of high amperage DCs and a device based on it are given. It is shown that the developed transducer and device, as distinct from the known ones, have increased accuracy and sensitivity, technological design and small weight and dimensions with low material consumption and cost. The error estimation of the developed magneto modulation non-contact wide-range device for non-destructive control of high amperage currents is carried out and it’s RMS (root-mean-square) and entropy errors are estimated. It can be widely used in power systems in irrigation and melioration, in water supply system, industry, railway transport, science, technology and for testing power meters at their installation site for contactless control of DC and also ACs (alternative currents).

1. Introduction
Nowadays, the development of the power industry of agriculture, a powerful electric drive of water supply pump stations, irrigation and melioration, electrical industry, metallurgy, railway transport and a number of new industries, science and technology are causing factor for of the ever increasing production and consumption of high amperage DC \([1, 2]\). Currently, about 40% of the generated electricity in Uzbekistan is consumed in the form of DC energy. That is why the transforming and measurement of high amperage DC is one of the important issue of modern information and measurement technology \([3]\). At the same time the need to the circuit breaking for the temporary switching on of current measurement devices, the presence of significant power losses on the shunts,
the undesirability or impossibility under the conditions of the technological process of the circuit breaking, as well as the safety are become clear the use of contactless transducers and DC measurement in chains without circuit breaking them, i.e. without destroying the integrity of the power track (bus bar) [4-6].

As a result of the analysis of the places of non-destructive contactless control of the high amperage DC, the main requirements for the non-contact transducer or non-contact measurement were identified. These include: high accuracy, reliability, sensitivity, low weight, dimensions, material consumption and cost, manufacturability of the design, absence of errors caused by external magnetic fields disturbance, a feedback bus with a current from the center of the integrating circuit, ferromagnetic masses, residual magnetization and from the presence of a variable component in a controlled DC, as well as the absence of a galvanic connection between the measured DC and the measuring circuit and the presence in some cases of the possibility of both fixed regulation of the non-contact transducer (NCT) or non-contact measurement (NCM) sensitivity in a wide range of convertible high amperage DC and the flexibility of the integrating circuit, as well as the design of the NCT and NCM as portable and stationary [7 -11].

Recently, the development of microcomputer monitoring and control systems for various technological and physical processes is characterized by the widespread use of primary transducers or sensors of data collecting and processing, and the constantly increasing requirements for elements and technical means of monitoring and control systems in the power industry and in particular in the power supply of hydraulic engineering, irrigation and melioration, powerful water supply pumping stations cause to develop of energy-saving non-contact wide-range ferromagnetic transducers of high amperage DCs with a detachable integrating circuit, which are the main part of the power supply unit and non-contact measurement and allow without violating the structural and circuit integrity of the device to wrap a conductor with converted current and non-contact control of its value [13 -19].

Despite the large number of individual developments in this area [20 -40], the instrument-making industry, both in Uzbekistan and in the CIS (Commonwealth Independent States) countries, has not yet developed light detachable stationary and portable non-destructive non-contact transducers and measurement devices of high amperage DC [1]. The issue is explained that on the one hand by the lack of a sufficiently approved version of the power supply unit and non-contact measurements, and on the other hand by the rigidity of the requirements imposed on them.

It has been determined that none of the known and considered non-contact transducers and non-contact measurement devices not satisfies the stringent requirements in full. Therefore, the non-contact control of high amperage DC is a focal problem of information-measuring technology [3]. In practice, magneto modulation non-contact ferromagnetic transducers (MMNCTF) of high amperage DCs are currently most widely used for this purpose. However, the known transducers have a number of disadvantages, the main ones of which are: a narrow controlled current range, low accuracy and sensitivity, large dimensions and masses [16-20]. Therefore the elimination of these disadvantages in the developed measuring non-contact ferromagnetic transducers of high amperage DCs with a split integrating circuit is an important issue.

2. Method
On the basis of the MMNCTF of high amperage DCs [11], we have developed an MMNCTF with increased sensitivity and expanded range of converted currents, shown in Figure 1. It contains a detachable magnetic circuit 1, freely wrapping around the bus 2 with a convertible current, consisting of two halves 2 and 3 each of which in turn consists of separate ferromagnetic elements made in the form of trapezoids with equal gaps between them. Each ferromagnetic element has two through holes through each of which a modulating coils (MC) is wound 4. A test coil (TC) is wound over the modulating coil between the through holes 5. All testing coils are connected in series and closed to a measuring device, and the modulating coils are also connected in series and connected to a stable AC source (not shown in Figure 1). The series connection of the modulating coils 2 and 3 with each other in the presence of AC in them and the location of the measuring coils 4 in the gaps between the through holes in the ferromagnetic elements 1 made it possible to modulate the reluctance of the magnetic circuit on the
path of the working flow $F$ created by a controlled direct current, and to direct it in the testing windings 4 electro motive force (EMF) depending on the converted direct current. The developed MMNCFT can also control alternating current. In this case, there should be no AC in sections 2 and 3 of the modulation coil.

Figure 1. Magnetic modulation non-contact wide-range device for non-destructive control of high amperage currents

The expansion of the upper limit of the controlled DC in the developed MMNCFT design is carried out by increasing the length of the working magnetic flux along the steel of the elements of the magnetic circuit and the inclusion of transverse and longitudinal air gaps in its path, i.e. making a split magnetic circuit with longitudinally distributed magnetic parameters.

Figure 2 shows a device consisting of the developed MMNCFT a measuring circuit (MC), a phase-sensitive amplifier (PSA) and an output ammeter. The MC together with a PSA is powered from a driver (D). In this case voltage is supplied to the MC from the stabilizer (St). A standard instrument of class 0.5 is used as an output Ammeter.

3. Results and Discussions

Let us estimate the error of the magnetic modulation non-contact device for non-destructive control of high amperage currents. The estimation of the total error of the device with MMNCFT can be made on the basis of the information theory of measuring devices [41], according to which the error of the measuring device is determined by the value of the entropy error $\Delta$ associated with the RMS error of the non-contact ferromagnetic transducer (NCFT) of high amperage DC through the entropy coefficient $K_e$ in the form:

$$\Delta = K_e G_{NCFT}$$

(1)

and the entropy coefficient depends on the form of the distribution law of the probability density of the errors of the elements. In this case, the value of the total RMS error for a transducer consisting of $n$ elements are determined by the formula
where $\delta_1, \delta_2, ..., \delta_n$ – RMS errors of individual elements.

First, let us highlight the additive and multiplicative components of the error and in accordance with the distribution law find their standard deviations. All calculations are performed in relative reduced values, and during intermediate rounding one extra invalid decimal number is saved in their values.

The MMNCFT has an additive error normalized by the limit value $\gamma_{NCFT} = 0.2\%$, and the measuring circuit MC also has an additive error normalized by the limit value $\gamma_{MC} = 0.1\%$.

In this case, the additive error of the noncontact Ammeter as a whole is due to the additive errors of the MMNCFT, MC, Ammeter, and the multiplicative error is due to the influence of temperature changes on the sensitivity of the MMNCFT, PSA and Ammeter, as well as fluctuations in the supply voltage of the MC and PSA. The distribution law of the MMNCFT error can be taken as normal with an entropy coefficient $K_{NCFT} = 2.08$ [41]. Then the standard deviation will be determined:

$$\sigma_{NCFT} = \frac{\gamma_{NCFT}}{K_{NCFT}} = \frac{0.2}{2.08} = 0.096\%.$$ (3)

Figure 2. Electrical circuit of MMNCFT for high amperage current measurement

As analog, let us define the standard deviation of MC with the normal law of error distribution in the form

$$\sigma_{MC} = \frac{\gamma_{MC}}{K_{MC}} = \frac{0.1}{2.08} = 0.048\%.$$ (4)

According to the standard, the error of electrical measuring instruments must be indicated with an aging margin. Therefore, the error of the Ammeter will be estimated by the value $\gamma_{Ammeter} = 0.84 \gamma_k$, where $\gamma_k$ - is the basic error corresponding to the accuracy class. Then $\gamma_{Ammeter} = 0.84 \cdot 0.5 = -0.42\%$. The error
distribution law of electromechanical instruments is close to trapezoidal with the entropy coefficient \( K_e = 1.9 \). Therefore:

\[
\sigma_{\text{Ammeter}} = \gamma_{\text{Ammeter}} / K_e = 0.42 / 1.9 = 0.22 \%.
\]  

(5)

Three components create the additive error of the device. Therefore, the standard deviation of the error of the MMNCFT will be zero:

\[
\sigma_H = \sqrt{\sigma_{\text{MMNCFT}}^2 + \sigma_{\text{MC}}^2 + \sigma_{\text{Ammeter}}^2} = \sqrt{0.096^2 + 0.048^2 + 0.22^2} = 0.253 \%
\]  

(6)

To determine the entropy coefficient of the sum of these errors, let us turn to the curves of the dependence of the entropy coefficients on the relative weights of the variance given in [41].

The relative weight of the variance of the trapezoidal distribution in the total variance is \( \sigma_{\text{Ammeter}}^2 / \sigma_H^2 = 0.22^2 / 0.253^2 = 0.76 \). With this value of \( P \), the value of \( K_n \) is equal to \( K_n = 2.1 \). Hence, the entropy value of the device zero error is

\[
\gamma_n = K_n \sigma_H = 2.1 \times 0.253 = 0.54 \%.
\]  

(7)

Let us proceed to the summation of the multiplicative errors of the device. In this case, we will assume that the coefficient of temperature influence on the MMNCFT sensitivity is

\[
\Phi_{\text{MMNCFT}} = 0.2\%10^9 \text{K}, \quad \Phi_{\text{Ammeter}} = -0.2\%10^9 \text{K and } \Phi_{\text{PSA}} = 0.15\%10^9 \text{K}.
\]

If the MMNCFT, Ammeter and PSA are located in one housing, they will all be exposed to the same temperature. Therefore, their temperature errors can be considered rigidly correlated with each other and summed up algebraically. Then the resulting temperature influence coefficient will be determined as:

\[
\Phi_\theta = \Phi_{\text{MMNCFT}} + \Phi_{\text{Ammeter}} + \Phi_{\text{PSA}} = 0.2 - 0.2 + 0.15 = 0.15\%10^9 \text{K}
\]  

(8)

If the device is intended for operation in a workshop at temperatures from +5 to + 35 °C, i.e. at a temperature of \((20 \pm 15) \) °C, and all temperature values are equally probable, then the temperature component of the multiplicative error will have a uniform distribution

\[
\gamma_\theta = 0.15 \times 15 / 10 = 0.225 \%.
\]  

(9)

and

\[
\sigma_\theta = \gamma_\theta / K_\theta = 0.225 / 1.73 = 0.13 \%.
\]  

(10)

If the voltage fluctuations of the network from which the device is powered are within ±10% and have a triangular probability distribution law and the MC is powered through a stabilizer with a stabilization coefficient \( K = 20 \), then the supply voltage fluctuations of the MC and the multiplicative error of its output voltage also have triangular distributions within \( \gamma_{\text{MC, M}} = 0.50 \% \) with standard deviation equal to

\[
\sigma_{\text{MC, M}} = \gamma_{\text{MC, M}} \sqrt{6} = 0.5 \times \sqrt{6} = 0.204 \%
\]  

(11)

The PSA is powered by an unsterilized voltage, but due to deep negative feedback, the coefficient of influence of the supply voltage on the gain is reduced to the value

\[
\Phi_{\text{PSA}} = 0.3 / [10(\Delta U / U)] .
\]

Therefore, the multiplicative error of the device caused by random supply voltage fluctuations will also be distributed according to the triangular law within the limits \( \gamma_{\text{PSA, M}} = \pm 0.30 \% \) with standard deviation:

\[
\sigma_{\text{PSA, M}} = \gamma_{\text{PSA, M}} \sqrt{6} = 0.3 \times \sqrt{6} = 0.122 \%
\]  

(12)

Due to the fact that both errors from voltage fluctuations are due to one cause, they are correlated with each other and can be summed up algebraically in the form

\[
\gamma_u = \gamma_{\text{PSA, M}} + \gamma_{\text{MC, M}} = 0.3 + 0.5 = 0.8 \% ,
\]

\[
\sigma_u = \sigma_{\text{PSA, M}} + \sigma_{\text{MC, M}} = 0.122 + 0.204 = 0.326 \%
\]

(13)

(14)

At the same time, the total errors from temperature fluctuations and voltage fluctuations are independent and must be summed up geometrically, i.e. with RMS multiplicative component:
The distribution of the total multiplicative component is a composition of the uniform distribution of the error from temperature fluctuations with \( \sigma_\theta = 0.13\% \) and \( K_\theta = 1.73 \), and triangular distribution of the error from supply voltage fluctuations in the \( \sigma_U = 0.326\% \) and \( K = 2.03 \).

The relative weight of the variance of the uniformly distributed component in the total variance and the entropy coefficient of this composition is \( K_M = 2.06 \). Then the entropy value of the multiplicative component of the error is

\[
\gamma_M = K_M \sigma_M = 2.06 \cdot 0.351 = 0.72\%.
\] (16)

As a result, the error of the device at the end of the scale is determined by adding the additive and multiplicative errors according to the rules for summing independent errors in the form

\[
\sigma_K = \sqrt{\sigma_H^2 + \sigma_M^2} = \sqrt{0.253^2 + 0.351^2} = 0.43\%.
\] (17)

Entropy coefficients of the summed errors \( K_U = 2.03 \) and \( K_M = 2.06 \) are large enough, and their standard deviation are close to each other (\( \sigma_H = 0.253\% \) and \( \sigma_m = 0.351\% \)), so the resulting distribution is close enough to normal with \( K = 2.07 \). Hence, the entropy value of the error at the end of the scale of the device is:

\[
\gamma_K = K_H \sigma_K = 2.07 \cdot 0.43 = 0.89
\] (18)

When normalizing the errors of such a device according to the standard, it is necessary to have data on aging of at least 25% of the physical error, and the normalized error values should be selected from a number of preferred numbers provided for by the International standard. For the considered noncontact ammeter, the accuracy class is 1.5%.

This is an example of estimating the error of the MMNCFT in the design of an analog device. In digital devices based on MMNCFT the error is 0.5%.

4. Conclusions

Developed universal multidisciplinary wide-range MMNCFTs of high amperage DC and ACs for modern computer monitoring and control systems in solar and laser technology, renewable energy sources, industry, agro-industrial sector, in GIS technology, and in particular in digital coatings and visualization databases as well as for verification of power meters at the installation site, characterized by an extended controlled range of convertible DC and ACs with small dimensions and weight, increased accuracy and sensitivity, simplicity and manufacturability of the design with low material consumption and cost and the possibility of contactless control of DC and ACs, as shown by the assessment of the error of a MMNCFT for non-destructive testing of high amperage currents, with an error of 1.5%, as well as for monitoring electricity and testing power meters on site their settings.

It was revealed on the basis of the analysis of methods for estimating the errors of MMNCFT for non-destructive testing of high amperage currents that it is most expedient to determine the total error of a non-contact device with an MMNCFT based on the information theory of measuring devices, which takes into account the distribution law of the probability of occurrence of errors, and the root-mean-square error of its individual elements. It is shown that for a MMNCFT for non-destructive testing of high amperage currents, the root mean square error does not exceed 0.43%, and the entropy error is no more than 0.89%.

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References

[1] Kazakov MK 1998 Methods and means of measuring high voltages and high amperage currents
in power engineering Author's abstract, Doctoral Dissertation Thesis 32.

[2] Baratov RJ, Djalilov AU, Chulliyev YE 2019 International Journal of Advanced Research in Science, Engineering and Technology 6(12) 12240 - 12246

[3] Plakhtiev AM 2017 Effective informational noncontact transducers for modern monitoring and control systems in the agro-industrial complex International Scientific and Practical Conference Agrarian science - to agriculture Collection of scientific articles 37-39.

[4] Semenko NG, Gamazov YuA 1984 Measuring transducers of high amperage currents and their metrological support Publishing house of Standards 132.

[5] Mukhamedkhanov UT 2008 Concepts and methods of constructing quality control systems for technological environments of industrial manufacture, Abstract of Doctor of technical science dissertation.

[6] Spektor SA 1988 Measurement of high amperage DC, Energy 136.

[7] Bolotin O, Portnoy G, Razumovsky K 2012 Energy Security and Energy Saving 5 28 - 32.

[8] Danilov A 2004 Modern Electronics 10 38 – 43.

[9] Bolotin O, Portnoy G, Razumovsky K 2016 ISUP 1(61) 18 - 25.

[10] Gilardi M 2013 Power Electronics 3 48 - 52.

[11] Kazansky VE 1988 Measuring current transducers in relay protection, Energoatomizdat, Moscow.

[12] Plakhtiev AM, Petrov GP, Minikeev HS 1979 Measurer of high amperage DC USSR Patent N 792152 IIC G01R 19/00 2735180/18 – 21 Bulletin N48.

[13] Gurtovtsev AL 2010 Electrical Engineering News 5 48 -52.

[14] Bolotin O, Portnoy G, Razumovsky K 2012 Energy Security and Energy Saving 5 28 – 32.

[15] Bolotin O, Portnoy G, Razumovsky K 2016 ISUP 1(61) 18 – 25.

[16] Mukhamedkhanov UT 2008 Concepts and methods of constructing quality control systems for technological environments of industrial production, Doctor of Technical Sciences Dissertation.

[17] Borkman D 1997 Hallgeneratoren Elektrie Bd 18 2 46 – 50.

[18] Kramer W 1996 Gleichstrom ETZ-A 18 28 – 33.

[19] Lappe F 1998 Chemi-Ingenier Technick Bd 42 1228 – 1229.

[20] Baratov RJ, Djalilov AU 2018 Journal of Scientific and Engineering Research 5(11) 158-164

[21] Yuki TN 2016 Electromagnetic noncontact measuring apparatus US Patent N234844 IIC G01R 27/04 NKI 324 58.

[22] Nils B 2016 Einrichtung zur Erfassung des Belastungsstromes in Hochstromanlagen Germany Patent N 3148654 IIC 21E36/01.

[23] Eadie EM 2015 Complete specification improvements in multi-range hook-on electrical indication instrument, UK Patent N3966443 IIC G1U.

[24] Standard Telefones & Cables LTD 2016 Current monitoring circuits including hall effect devices UK Patent N 4575111 IIC G01R 19/165 NKI GIU N 4773.

[25] Shibaura T 2017 Transducers UK Patent N 3036894 IIC G01R 19/22 NKI GIU N 4968.

[26] Meierovich EA, Andreevskaya LI 2017 Dispositif pour la mesure de l’intensité du courant, France Patent N 3437944 IIC G01R N2.

[27] Alhadeef BG 2000 Transducteur electrique comportant un moyen de codage d’un parametre du transducteur France Patent N3955731 IIC G01D 18/00 3/04 G01F 25/00 N1.

[28] Ernö R 2018 Elektricky méřič přístroj Czech Republic Patent N 2145015 IIC 21E3601.

[29] Lánzci Z 2015 Aramlo fkést méro műszter, Hungary Patent N2146340, IIC 21E 29-36.

[30] Hitachi Ltd Chiyoda-ku Tokyo 100 (JP) 2017 Magnetoelectrical transducer. Japan Patent N3257766 IIC G01D 5/16 N33.

[31] Brodovsky VN, Korzhanov BM 2017 Current transformer USSR Patent N3592239 IIC 21E3601 Bulletin N4.

[32] Konno Y, Sasaki M 2009 Electric current measure apparatus Japan Patent IIC G01R CN204154795U.

[33] Li Ch 2015 Stripping electrical measuring one meter China Patent IIC G01R CN204154795U.

[34] Lynn M, Shie J 2019 Power amplifier saturation detection Korean Patent IIC G01R US10224917B2.
[35] Jurisch A 1995 Method of measuring current in a conductor in an AC transmission network. Italian Patent IIC G01R WO19945020765A1.
[36] Knoedgen H, Kronmueller F 2019 Highly accurate current measurement European patent office IIC G01R EP2821799A1.
[37] Gati R, Abplanalp M 2008 Configuration of magnetoriesistire sensors for current measurement Spain Patent IIC G01R 07ES2591283T3.
[38] Grieshaber W, Dupraz JP 2011 Method of opening a bypass switch of a high voltage direct current network Canadian Patent IIC G01R CA284893OC.
[39] Plakhtiyev AM, Akhmedov SU 2014 Condition of application and development of contactless ferromagnetic transducers in electrochemistry and metallurgy, *Eighth World Conference on Intelligent Systems for Industrial Automation (WCIS)*, pp 326 - 329.
[40] Plakhtiyev AM, Gaziev GA 2019 *Chemical Technology. Control and Management Journal* 4(90) 25-29.
[41] Yakovlev AG 1997 Errors of instrumentation and sensors Korona Print 268.