E3S Web of Conferences **401**, 04015 (2023) https://doi.org/10.1051/e3sconf/202340104015
CONMECHYDRO - 2023

High-current contactless ferromagnetic converters for multi-profile monitoring and control systems

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Abstract. The article shows that the undesirability of breaking the current circuit for the temporary inclusion of electrical measuring devices, the presence of large power losses on shunts, the impossibility of breaking the circuit under the conditions of the technological process, as well as safety requirements caused contactless conversion and measurement of large DC currents in circuits without breaking them in metallurgy, electrochemical industry, railway transport, in laser technology, renewable energy sources, land reclamation, irrigation and in general in agriculture. Lightweight detachable wide-band stationary and portable non-destructive contactless converters and meters of large direct currents are not yet mass-produced worldwide. Therefore, it is very important to develop and study contactless converters and meters of large direct currents, having an extended range of converted currents with small dimensions and weight and increased accuracy and sensitivity, a simplified and technologically advanced design with low material consumption and cost, and the ability to convert both constant and variable high currents and fixed sensitivity control. All these requirements are met by the effective multifunctional magneto-modulating contactless converters of large direct currents developed by us. The results of the development of one of them are given in the work. The issues of its dynamics are considered. The results of his research are shown. It was found that the transition time for him is 0.025 of the period of the industrial frequency. Therefore, it can be considered practically inertia-free. The developed effective multifunctional magneto-modulating contactless converter can be widely used in monitoring and control systems in water supply, land reclamation, and irrigation, industry, railway transport, metallurgy, science, technology for contactless monitoring of constant and alternating currents, as well as for checking electric meters at the place of their installation.

1 INTRODUCTION

In the modern world, powerful electrotechnological installations and electric power systems in the electric power industry, including in land reclamation and irrigation, are

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 https://doi.org/10.1051/e3sconf/202340104015

conventionally considered as an organic unity of powerful high-current and high-voltage power equipment, and it is conventionally called the "primary system". Currently, the possibilities for the long-term development of these systems by increasing the weight and dimensions of the equipment are almost exhausted. To ensure the efficient and high-quality operation of primary systems in the industry, land reclamation, and irrigation, as well as in areas of irrigated agriculture, control, measurement, regulation, management, and relay protection, which are called secondary electric power systems, are becoming increasingly important [1].

It should be noted that being relatively inexpensive, they allow not only to avoid the high costs necessary to create certain stocks in the expensive main equipment of primary systems but also to solve many new problems of efficient use of energy resources and electrical devices [2].

It should be noted that the primary and secondary systems are interconnected by paths for receiving, processing, and transmitting information built on measuring converters of electrical quantities, particularly large direct currents (LDC) [2]. The need to convert high currents in various sectors of the national economy, in particular, in land reclamation, irrigation, and in general in agriculture, arises when monitoring and controlling the operating modes of powerful electric motors of powerful main pumping stations, rectifier substations and various consumers, where measuring converters of LDC (MCDC) are used [3].

In practice, the requirements of frequent breaking of the current circuit for temporary switching on of electrical measuring devices, large power losses on shunts and in current measuring transformers, as well as the impossibility of breaking the circuit under the conditions of the technological process, led to contactless conversion and measurement of large DC currents in circuits without breaking them, i.e., leaving the bus with currents intact [4].

As a result of the analysis of the conversion of large direct currents in electric power systems and electrotechnological installations, it was revealed that one of the reasons for their low efficiency is the unsatisfactory technical characteristics of their control systems and control modes of operation of electric power systems and electro technological installations and, in particular, the MCDC used in them. Therefore, MCDCS used in secondary systems of electric power systems and installations should have an adjustable conversion range, better dynamic properties in transient operating modes of these systems and installations, and stability of characteristics under extreme operating conditions [5].

In the study of places of multidisciplinary contactless control of LDC, the following general basic requirements for MCDC were clarified: high accuracy, sensitivity and reliability, small mass-dimensional indicators, material consumption, and cost, manufacturability of the design, absence of errors from the influence of external magnetic fields, reverse bus and adjacent current slots, displacement of the current line from the center of the integrating circuit, ferromagnetic masses, the absence of a galvanic connection between the circuit with the converted current and the measuring circuit, in some cases, it is possible to fixedly adjust the sensitivity of the MCDC in a wide range of converted large converted and alternating currents and the execution of the MCDC both portable and stationary. Therefore, it is very important to develop and study such MCDCS that would have increased efficiency (an extended range of converted LDC with small dimensions and weight and increased accuracy, a simplified and technologically advanced design with low material consumption and cost) and expanded functionality (the ability to convert large both direct and alternating currents) [6].

Despite a large number of individual developments in this field [3-5, 8-30], the instrument-making industry in the Republic of Uzbekistan and in the CIS countries has not yet mass-produced lightweight detachable stationary and portable non-destructive contactless converters and meters of large direct currents. This is due to the lack of a proven version of the MCDC and the rigidity of the requirements imposed on them. Due to the simplicity of manufacturing, the speed of signal processing, and noise immunity, magneto-modulation contactless MCDC made based on converters with distributed parameters are most widely used in practice. The existing magneto-modulating contactless IP have several disadvantages, mainly large weight and dimensions, a narrow range of controlled LDCS, and their low accuracy and sensitivity. Therefore, the development of magneto-modulating contactless MCDC, free from these disadvantages, is an important necessity [31].

2 Materials and Methods

The solution to this problem can be facilitated by developing effective multifunctional magneto-modulating contactless IPPT (MIPPT) for multidisciplinary control and management systems in the electric power industry that meets a set of basic requirements for them [30].

At the same time, the main tasks that need to be solved when designing such MIPPT following modern trends in the development of measuring instruments and DC converters are mainly expanding the range of measured and converted DC values, reducing the overall dimensions of MIPPT and increasing their accuracy and sensitivity [8,10-13]. Most often, these tasks must be solved together for one MIPPT, choosing circuits and designs that simultaneously meet the requirements of a wide range of linearity, low sensitivity threshold, high accuracy, and a wide range of converted DC currents with a small volume of MIPPT. Therefore, special attention should be paid to considering ways and methods by which it is possible to solve the listed tasks and provide the specified metrological and operational characteristics of the MIPPT [31].

It should be noted that one of the effective possibilities of expanding the linearity range of the MIPPT characteristic, reducing the sensitivity threshold, and increasing its accuracy with a wide range of converted DC currents is to increase the length of the MIPPT split magnetic core and its cross–sectional area to the maximum permissible dimensions and the use of longitudinal modulation [32].

3 Results and the Discussions

We have developed several MIPPTs, in which the tasks are solved by using special designs of detachable closed magnetic circuits with transversely and longitudinally distributed magnetic parameters and an increased path length of the working magnetic flux through steel in magneto modulation contactless converters [6,30]. Let us consider the design of the developed high-current wide-range contactless magneto-modulating ferromagnetic converter of large direct currents for multi-profile monitoring and control systems, shown in Fig. 1, and questions of its dynamics of work.

MIPPT is developed based on a converter [33]. It contains a closed magnetic circuit consisting of ferromagnetic elements 1 and 2 with longitudinal and transverse gaps between them. To freely cover the bus 5 with a converted direct current, the magnetic circuit is made detachable. Ferromagnetic elements 2 form a movable ring that can be rotated around its axis. Ferromagnetic elements 1 form a fixed ring. Each ferromagnetic element has two through holes through which the modulating windings 3 are wound. On each ferromagnetic element, a measuring winding 4 is wound between the through holes. All measuring windings are connected to each other in series and closed to the measuring device (not shown in Fig. 1). The modulating windings are also connected in series and connected to a stable AC source. Rotation by a fixed angle of the movable ring along its axis leads to a change in the gaps between the ferromagnetic elements of the movable and fixed rings. This leads to a change in the total magnetic resistance in the path of the working magnetic flux and to a change in the sensitivity of the whole MBIPT, which makes the device multi-limit.

The serial connection of the modulating windings 3 with each other in the presence of alternating current in them and the location of the measuring windings 4 in the intervals between the through holes in the ferromagnetic elements 1 and 2 made it possible to carry out longitudinal modulation of the magnetic resistance of the detachable closed magnetic circuit in the path of the working magnetic flux F, created by a controlled direct current, and to bring in the measuring windings 4 EMF, depending on converted direct current. The developed MIPPT, in the absence of alternating current in the modulating winding 3, can also control alternating current. When monitoring the LDC with a detachable magnetic circuit, IPPT covers bus 5. Due to the modulation amper witches, the magnetic circuit is in a saturated state during each half-life of the supply voltage. At the same time, the permeability of the magnetic circuit for the longitudinal field created by the controlled current decreases sharply. At the moment when the modulation current passes through the zero value, the permeability of the magnetic circuit increases to the initial value. Thus, with the stability of the amperes of the modulation turns in the measuring winding, an EMF will be induced, depending on the controlled current.

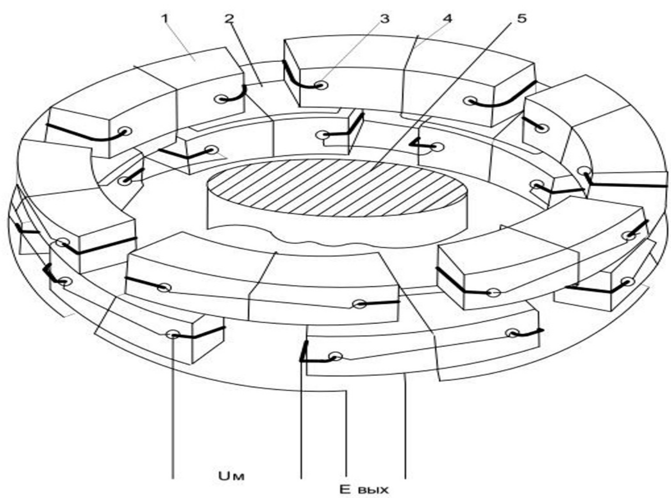

Fig.1. MBIT with longitudinally distributed magnetic parameters

The ability to convert direct and alternating currents, contactlessness, relatively high accuracy, sensitivity, and reliability, a wide range of converted currents, small weight and dimensions, insensitivity to external magnetic fields and ferromagnetic masses, and the absence of errors from the displacement of the bus with current from the geometric center of the integrating circuit – all these are the advantages of the developed MIPPT design.

In connection with the use of MIPPT as a measuring converter in multidisciplinary monitoring and control systems, it is necessary to know the dynamics of its operation. We have investigated the dynamic characteristics of the MPP by the method of parametric structural schemes, which is part of the energy-information method of analysis and synthesis of sensitive elements of control systems [32].

At the same time, we introduce the following designations: the magnitude of the impact is U, the magnitude of the reaction is I, the integral magnitude of the reaction – charge is q, the resistance parameter is R, the inductance parameter is L, the capacitance parameter is C, the conductivity parameter is G = 1 / R, the deductivity parameter is D = 1 / L and the stiffness parameter is W = 1 / G. Note that the determination of the relationship between quantities and parameters within a link of the same physical nature is based on basic and derived criteria.

In Fig. 2, a parametric block diagram of the MEP is compiled based on the above, shown in Fig.1. According to the parametric structural scheme; we will make a mathematical model of the MIPPT to study the dynamics of its operation.

Because the elements of two identical halves 1 and 2 of the closed magnetic circuit MIPPT are in the same conditions, therefore, in the parametric block diagram in Fig. 2, two symmetrical channels are shown for each half. At the same time, the presence of transverse and longitudinal air gaps is considered by equivalent capacities $C_{\mu\,бq}$ and $C_{\mu\,бd}$ [32]. Fig. 3 shows the geometric dimensions of the MIPPT detachable magnetic core.

Based on the parametric block diagram of the MIP and [32,34], we write down the equations describing dynamic processes in it in the following form:

a) the output voltage of each channel

$$U_э(p) = U_{э1}(p) = U_{э2}(p) = K_{I\mu\sum U э}\, p\, C_{\mu\sum} K_{Iэ\text{-}U\mu\text{-}} I_э(p); \tag{1}$$

b) the total voltage at the output of the MIPPT

$$U_{э\sum} = 2\, U_э; \tag{2}$$

c) total equivalent capacity

$$C_{\mu\Sigma} = \frac{1}{W_{\mu\Sigma}} = \frac{1}{W_{\mu б2} + W_{\mu cm}}, \tag{3}$$

Where

$$W_{\mu cm} = \frac{1}{C_{\mu cm}}; \tag{4}$$

$$W_{\mu б2} = \frac{1}{C_{\mu б}} = \frac{1}{C_{\mu бq} + C_{\mu бd}}; \tag{5}$$

$$C_{\mu\delta q} = \frac{\mu_0 bn(l_\mu - \delta)}{h}; \tag{6}$$

$$C_{\mu\delta d} = \frac{\mu_0 h_1 b}{бn}; \tag{7}$$

d) the effect of modulation from the modulation voltage is taken into account in the form of

$$C_{\mu cm} = K_{q\mu\sim C\mu cm} \left| C_{\mu\sim} K_{Iэ\sim U\mu\sim} \frac{1}{p} \cdot D_э \cdot U_{э\sim} \right|, \tag{8}$$

where U_e is a reactive parameter, the influence of which in the block diagram is taken into account through its real value of $D_{эр}$ and the cascaded resistance of $R_э$ connected to it and is written as

$$D_э = \frac{D_{эр}}{1 + \frac{D_{эр} R_э}{p}} \tag{9}$$

Solving equations (1) – (3) together, we obtain

$$U_{э\sum}(p) = \frac{2K_{I\mu\sum Uэ} \cdot p \cdot K_{Iэ-U\mu-} K_{Iэ\sim U\mu\sim} C_{\mu\sim} K_{q\mu\sim C\mu cm} \left|U_{э\sim}\right| \cdot I_э(p)}{R_э + W_{\mu б2} K_{q\mu\sim C\mu cm} C_{\mu\sim} K_{Iэ\sim U\mu\sim} \left|U_{э\sim}\right| \cdot \left[1 + \frac{p}{D_{эр}(R_э + W_{\mu б2} K_{q\mu\sim C\mu cm} C_{\mu\sim} K_{Iэ\sim U\mu\sim} \left|U_{э\sim}\right|)}\right]} \tag{10}$$

Substituting in (10) the values of physical effects, we obtain the following equation

$$U_э(p) = -\frac{w_и p I_э(p)}{\left[W_{\mu\delta 2} + D_{экв2}(U_{э\sim})\right]\left[T_2(U_{э\sim})p + 1\right]} \tag{11}$$

In this equation, D_{qv2} ($U_{e\sim}$), $T_2(U_{e\sim})$, and W_{mcb2} are denoted respectively: equivalent deductivity, time constant, and stiffness of the air gaps between the ferro-elements of the MIPPT.
Substituting the values of physical effects into (11) and converting, we obtain the following expression

$$U_{э\sum}(p) = 2W_и p\, I_э(p) / ([W_{\mu\delta 2} + D_{эКв2}(U_{э\sim})][T_2(U_{э\sim})p + 1]). \tag{12}$$

Here

$$D_{эКв2}(U_{э\sim}) = R_э / ((2/\pi)\, U_{э\sim m} \mu K W_\sim h_1 b / (l_{cp} l_\mu n)) \left[1 - \frac{2}{3}(\cos 2\omega t + \frac{1}{5}\cos 4\omega t)\right]); \tag{13}$$

$$T_2(U_{э\sim}) = (\mu h_1 \Delta W_\sim^2 / l_{cp}) / (R_э + ((2/\pi)\, U_{э\sim m}(\mu W_\sim K h h_1 \delta [1 - \frac{2}{3}(\cos 2\omega t + \frac{1}{5}\cos 4\omega t)]) / (\mu_0 l_{cp} l_\mu [(l_\mu - \delta)\delta n^2 + h h_1])); \tag{14}$$

$$W_{\mu\delta 2} = 1 / (C_{\mu\delta q} + C_{\mu\delta d}) = h\delta n / (\mu_0 b [(l_\mu - \delta)\delta n + h h_1]). \tag{15}$$

Solving equation (13) by the well-known method [14], we obtain

$$P_2(t) = 1/ T_2(U_{э\sim}) = ((2\, U_{э\sim m}\, \mu\, W_\sim K h h_1 \delta / (\pi \mu_0 l_{cp} l_\mu [(l_\mu - \delta)\delta n^2 + + h h_1])) \cdot [1 - \frac{2}{3}(\cos 2\omega t + \frac{1}{5}\cos 4\omega t)]) / ((\mu h_1 \Delta W_\sim^2) / l_{cp}); \tag{16}$$

$$S_2(t) = \int P_2(t)dt = (1/W_\sim \Delta)\{2U_{э\sim m} K h \delta / (\pi \mu_0 l_\mu [(l_\mu - \delta)\delta n^2 + + h h_1]) + R_э l_{cp} / (\mu h_1 W_\sim)\} t -$$

$-(2\ U_{э\sim m}Kh\delta\ /(3\pi\omega\mu_0 l_\mu W_\sim\Delta[(l_\mu-\delta)\delta n^2+hh_1]))\cdot(\sin 2\omega t+0{,}1\ \sin 4\omega t);$ (17)

$$S_2(\varphi)=(1/(W_\sim\Delta))\{2U_{э\sim m}Kh\delta\ /(\ \pi\mu_0 l_\mu[(l_\mu-\delta)\delta n^2++hh_1])+R_э l_{cp}/(\ \mu h_1 W_\sim)\}\ \varphi-$$

$-(2U_{э\sim m}Kh\delta\ /(3\pi\omega\mu_0 l_\mu W_\sim\Delta[(l_\mu-\delta)\delta n^2+hh_1]))\cdot(\sin 2\ \varphi+0{,}1\ \sin 4\ \varphi);$ (18)

$h_2(t-\varphi,\varphi)=(2W_и\ /\ (T_2(U_{э\sim})[W_{\mu\delta 2}+D_{эКв2}(U_{э\sim})]))\cdot[(\mathbf{e}^{S_2(\varphi)}\ /\ \mathbf{e}^{S_2(t)})-1].$ (19)

Substituting the values (13) - (18) into expression (19), we get

$h_2(t-\varphi,\varphi)=M_2(\omega t)\{\exp[S_2(\varphi)-t/T_{эКв2}+V_2(\omega t)]-1\}.$ (20)

Here

$M_2(\omega t)=(2W_и\{R_э+(2U_{э\sim m}\ \mu W_\sim Khh_1\delta\cdot[1-\frac{2}{3}(\cos 2\omega t+\frac{1}{5}\ \cos 4\omega t)]\ /$

$/\ (\pi\ \mu_0\ l_{cp}\ l_\mu[(l_\mu-\delta)\delta n^2+hh_1]))\}\ /\ ((\mu h_1\Delta W_\sim^{\ 2}/l_{cp})\{(h\delta n/(\mu_0 b[(l_\mu-\delta)\delta n^2+hh_1]))+$

$+(\pi R_э l_{cp} l_\mu n/(2\ U_{э\sim m}\mu W_\sim Kh_1 b\cdot[1-\frac{2}{3}(\cos 2\omega t+\frac{1}{5}\cos 4\omega t)]))\});$ (21)

$V_2(\omega t)=(2U_{э\sim m}\ Kh\delta\ /\ (3\pi\omega\mu_0 l_\mu W_\sim\Delta[(l_\mu-\delta)\delta n^2+hh_1]))*(\sin 2\omega t+0{,}1\ \sin 4\omega t);$ (22)

$T_{эКв2}=\mu\mu_0\pi l_\mu h_1\Delta\ W_\sim^{\ 2}\ [(l_\mu-\delta)\delta n^2+hh_1]\ /(2U_{э\sim m}Kh\delta\mu h_1 W_\sim+\pi\mu_0 l_\mu\ R_э l_{cp}[(l_\mu-\delta)\delta n^2+hh_1]);$ (23)

In expression (20), the quantitative side of the transition characteristic of the MIP is shown by two components of the exponent: $S_2(\varphi)$ and $t/T_{экв2}$.

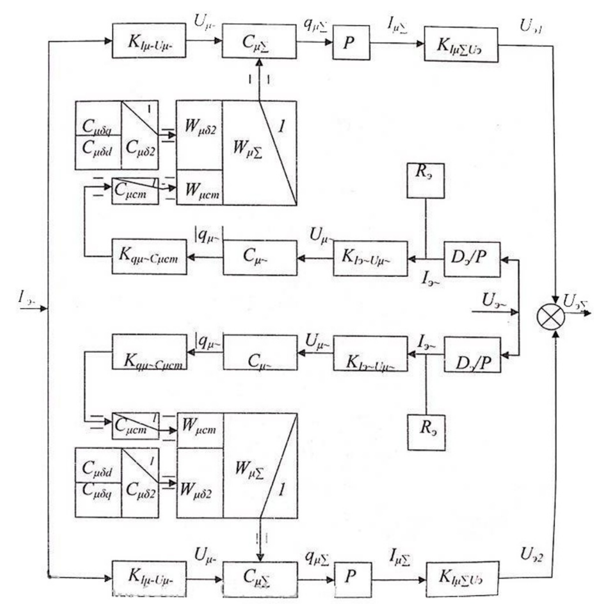

Fig. 2. Parametric block diagram of MIPPT.

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In expression (20), the quantitative side of the transition characteristic of the MIP is shown by two components of the exponent: Moreover, $S_2(\varphi)$ one component shows a family of transient functions $h(t-\varphi,\varphi)$. In this case, the moments of a single jump signal are characteristic values of the angles. Their values are the largest and smallest values $S_2(\varphi)$. They correspond to the following values of angles φ.

$$\varphi_{\sup} = \frac{\pi}{4}, \quad \varphi_{\inf} = 0$$

Another component $t/T_{экв2}$ shows changes in the envelope of the transition function. This component of the exponent is its main component. It characterizes the quality indicators of the transition characteristic.

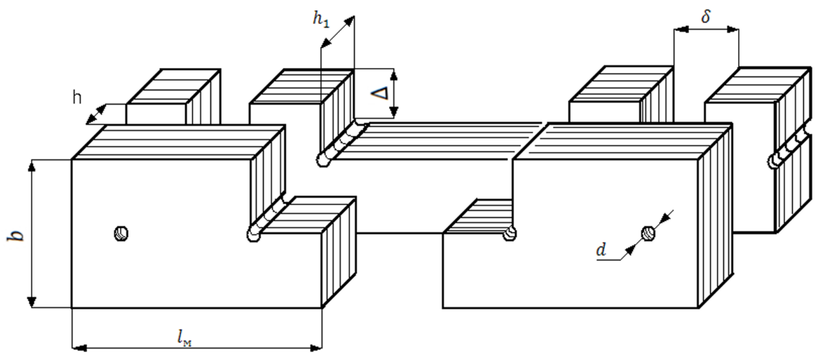

Fig. 3. Geometric dimensions of detachable magnetic circuit MIPPT.

It is important to note here that $\varphi_{\inf}$ when the envelope of the transition function grows exponentially from zero, and when $\varphi_{\sup}$ – from some of its values.

Analyzing the equivalent time constant (23), it can be concluded that the speed of the MIPPT increases the increase in the resistance $R_э$, connected in series with the excitation winding, air gaps δ and h, and a decrease in the lengths of the magnetic circuit elements $l\mu$ and the number of turns $w_{\sim}$.

In the experimental MIPPT (fig.1) with parameters: controlled direct current in the $I_э$ = 10000 A; transverse dimensions of the bus $\alpha \cdot b_1$ = 90·130 mm^2; optimal limit of the controlled value of H_{xn} = 0.71; optimal modulation value of $H_{вм}$ = 1.7; width, length and thickness of the magnetic circuit element b = 15.1 mm, l_μ = 33mm, h_1 = 18 mm; values of air gaps δ = 9.31 mm и h = 4.1 mm; K_δ = 0,85, β = 0.04, n = 22, l_{cp} = 68, $I_{э\sim}W_{\sim}$ = 15A, W_u = 50 rote; the magnetic circuit elements are made of electrotechnical steel E3414 with a sheet thickness of 0.35 mm with parameters $\rho_{\mu min}$ = 110 m/Hn and $\rho_{\mu мax}$ = 550 m/Hn, an equivalent time constant MIPPT equal to T_{ekv2} = 1.271•10^{-4}s was determined by (23).

Summarizing, it can be further noted that in the case of a single jump-like input signal at the most undesirable moment (φ = 0), the transition time will be (3÷4) T_{ekv2}, i.e., t_{per} = 0.5•10-3 s., which means that the transition time will be 0.025 of the period of the industrial frequency. Therefore, it is possible to consider MIPPT practically inertial.

4 Conclusions

High–current contactless ferromagnetic converters have been developed for multi-profile monitoring and control systems that allow contactless monitoring of large both direct and alternating currents in a wide variety of existing monitoring and control systems at many enterprises, in the chemical industry, railway transport, metallurgy, solar and laser technology, renewable energy sources, industry without breaking electrical circuits., irrigation and land reclamation. They are distinguished by a wide range of converted direct currents 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 direct and alternating currents with an error of 1% and also for use for monitoring electricity and checking electric meters at the place of their installation. The dynamics of operation of high-current magneto-modulating contactless ferromagnetic converters is investigated. The results of their research are shown. Their transition time was found to be 0.025 of the periods of the industrial frequency. Therefore, they can be considered practically inertia-free, widely used in multidisciplinary monitoring and control systems, and for checking electric meters at their installation.

Technical characteristics of the MIPPT: the range of converted direct and alternating currents – 0 – 10000 A; sensitivity – 0.2 mV / A; reduced error – 1%; diameter of the inner window of the detachable magnetic circuit – 200 mm; weight – 0.8 kg.

The developed MIPP has been implemented in a small series at several enterprises of the Republic of Uzbekistan and the Russian Federation.

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