Dynamic characteristics of contactless wide range high current ferromagnetic converters for monitoring and control systems

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Abstract. The article substantiates the need for the use for the needs of industry and metallurgy, hydro-construction, land reclamation, irrigation and, in general, agriculture and water management, contactless conversion and measurement of large direct currents using non-destructive induction wide-range high-current converters of monitoring and control systems - magnetomodulation contactless ferromagnetic converters of increased sensitivity, the results of their constructive development are presented. It is shown that the developed converter, in contrast to the known ones, has increased accuracy and sensitivity, technological design and small weight and dimensions with low material consumption and cost. Its dynamics of work is investigated. The dynamic characteristics of magnetic modulation contactless ferromagnetic converters are considered. The results of their research are presented. It is shown that their transient time is 0.025 of the power frequency period. Therefore, they can be considered practically inertial free. The developed converter can be widely used in electrical systems in hydro-construction, land reclamation and irrigation, in water supply, industry, in railway transport, in science, technology and for checking electric meters at their installation site for contactless control of direct and also alternating currents.

1. Introduction
At many domestic enterprises in the production of sodium, copper, tungsten, molybdenum, zinc, hydrogen, oxygen, phosphorus, when rolling refractory and heat-resistant metals in rolling mills, when receiving products on drawing machines, as well as in monitoring and control systems in railway transport, in land reclamation and irrigation, in laser technology, in the study of plasma physics and others, there is a problem of non-destructive quality control of industrial products and the functioning of technological processes [1].

All these processes of obtaining industrial products and the functioning of technological processes are characterized by the fact that their main parameter of quality control is a large direct current (LDC), by the value of which the quality of industrial products and the functioning of technological processes are judged. Its value is monitored by a number of measuring transducers (MT).

The problem of improving the accuracy, reliability and efficiency of control of these technological processes is urgent, which together will improve the quality and quantity of industrial products and the stability of technological processes (TP) [2].

Despite the presence of a fairly large fleet of LDC measuring instruments, the verification work is poorly organized, since most MTs do not verify. The main reason for this situation is the impossibility of dismantling the verified converters. In some cases, the reasons are the lack of power supplies,
exemplary measuring instruments, and organizational difficulties. There is a great need for portable contactless LDC controls [3 - 6].

It was revealed that the instability of the current control systems, the presence of additional resistances due to the oxidation of contacts lead to a decrease in the productivity of rolling mills, vacuum arc melting furnaces, chemical devices, to downtime, and large voltage drops on the shunts lead to unjustified power losses [6 - 8] ... As a result of the analysis of the conducted studies, an urgent need was revealed at many enterprises of the Republic of Uzbekistan for non-destructive contactless control of LDC with a value from 100A to 30 kA using both portable and stationary MT with an error of 1-3%, using in some cases multi-range, as well as flexible integrating circuit MT non-destructive quality control. It is shown that the main role in creating the optimal design of non-destructive MT non-destructive quality control belongs to a non-contact ferromagnetic converter for non-destructive quality control of industrial products and the functioning of technological processes (NFC) [3].

A review of known works showed that various NFC designs considered by individual authors have large dimensions and weight with a narrow range of controlled LDCs, increased material consumption and low-tech design, errors from the influence of magnetic fields, neighboring buses with currents and residual magnetization, i.e., reduced efficiency, and also do not have the possibility of a fixed regulation of the NFC sensitivity in a wide range of controlled LDCs and have a flexible integrating circuit, i.e., narrow functional capabilities, there are no effective ways to expand the range of controlled LDCs and general principles of NFC construction [9 - 41].

Therefore, the problem of increasing the efficiency and expanding the functionality of non-contact ferromagnetic converters with distributed magnetic parameters and devices for non-destructive quality control of industrial products and the functioning of technological processes for monitoring and control systems is relevant and promising, since the creation of new converters that meet a set of basic requirements for them on the part of monitoring and control systems, will expand their range of controlled LDCs, reduce the weight, dimensions and cost of the structure, increase accuracy, manufacturability and functionality.

We have developed a number of monitoring complexes [39], including new efficient non-contact ferromagnetic converters of large direct currents with distributed magnetic parameters, for monitoring and control systems of rolling mills, drawing machines, vacuum arc furnaces and regulation of the load current of electrolysis baths, which differ from the known ones in extended controlled range with small dimensions and weight, increased accuracy, simplicity and manufacturability of the design with low material consumption and cost, flexibility of the integrating circuit and multi-range of the converter, as well as the possibility of contactless control of constant rectified, pulsating and impulse currents.

Let’s consider the most typical design of the NFC we have developed - magnetically modulated wide-range NFC (MWNFC), its features and dynamic characteristics.

2. Research methods and results obtained

Figure 1 shows the monitoring and control systems developed by MWNFC. It is developed on the basis of MWNFC [12] and is distinguished by increased sensitivity and an extended range of converted currents. MWNFC contains a split magnetic circuit 1, consisting of two identical halves 2 and 3, each of which, in turn, consists of separate ferromagnetic elements made in the form of trapeziums with the same gaps between them. Each ferromagnetic element has two through holes, through each of which a modulation winding is wound, consisting of sections 4 and 5. Sections 4 and 5 are connected in series and in accordance with. A measuring winding 6 is wound over the modulation winding between the through holes. All measuring windings are connected in series and closed to the measuring device, and the modulation windings are also connected in series and connected to a stable AC source (not shown in Fig. 1). In order to freely grip the bus 8 with controlled current, the closed magnetic circuit 1 is made detachable. Series connection between modulation
windings 2 and 3 in the presence of alternating current in them and the location of the measuring windings 6 in the intervals between the through holes in the ferromagnetic elements allowed

![Figure 1. Magnitomodulation contactless wide-range converter high currents control and management systems](image)

Figure 1. Magnitomodulation contactless wide-range converter high currents control and management systems

to carry out longitudinal modulation of the magnetic resistance of the magnetic circuit on the path of the working flow \( \Phi \), created by a controlled direct current, and induce an EMF in the measuring windings 6, depending on the converted direct current. The developed MWNFC can also control alternating current. In this case, there should be no alternating current in sections 4 and 5 of the modulation winding.

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

To control the LDC, the MWNFC split magnetic circuit covers bus 8. Due to the modulation ampere turns, the split magnetic circuit is in a saturated state during each half-cycle of the supply voltage. In this case, 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 zero, the magnetic core permeability rises to the initial value. Thus, with the stability of the modulation ampere turns, an EMF of double frequency will be induced in the measuring winding, proportional to the controlled current.

With the mutual movement of halves 2 and 3 of the MWNFC detachable magnetic circuit, the size of the gaps between the trapezoids changes, leading to a change in the overall magnetic resistance of the magnetic circuit in the path of the working magnetic flux \( \Phi \) created by a controlled direct current. This leads to a change in the limits of the controlled current, i.e. allows you to make MWNFC multi-limit.

The use of a wide-range MWNFC as a measuring transducer in monitoring and control systems requires a study of its dynamic properties. We investigated the dynamic characteristics of the MWNFC. The study of the dynamic properties of MWNFC is greatly facilitated if we consider the converter as a set of simplest links, each of which is an independent converter of one quantity into another quantity or parameter. All links interconnected in a specific order form a parametric structural
diagram of the MWNFC. In this case, the method of parametric structural diagrams uses a single generalized information model of the converter, which allows one to describe the specific features of the process of obtaining and transforming information, regardless of the physical nature of the phenomenon used for this.

In the process of drawing up the parametric structural diagram of the converter, elementary links are distinguished in it, which have a certain physical nature (for our case, electric "E" and magnetic "μ") and it is assumed that each such link is the reaction of the circuit of the considered physical nature to the impact on this circuit. Since the impact and reaction determine the external properties of the elementary links, therefore we will call them simply quantities. The relationship between the quantities is determined through the chain parameter, which connects the energy spent on the process, with the geometric dimensions of the chain and its physical constants.

For the quantities and parameters, we use the following designations: the magnitude of the impact - \( U \), the magnitude of the reaction - \( I \), the integral value of the reaction - charge - \( q \), the resistance parameter - \( R \), the capacitance parameter - \( C \), the inductance parameter - \( L \), the conductivity parameter - \( G = 1/R \), the stiffness parameter - \( W = 1/G \) and the deductive parameter - \( D = 1/L \).

The definition of the relationship between quantities and parameters within a link of the same physical nature is based on the main and derived criteria.

The ratios of values and parameters that follow from the considered similarity criteria are the basis for constructing parametric structural schemes of MWNFC [43].

Based on the information presented in Fig. 2 the parametric block diagram of MWNFC is drawn (fig. 1).

Using a parametric structural diagram, we will compose a mathematical model of MWNFC to study its dynamics.

As shown in Fig. 1, the elements of the magnetic cores of two identical halves 2 and 3 of MWNFC are in the same conditions. Therefore, in the parametric circuit in Fig. 1 shows two balanced channels for each half. Allowance for transverse and longitudinal air gaps is carried out by the corresponding equivalent capacities \( C_{μq} \) and \( C_{μd} \) [42].

The influence of the reactive parameter \( D_e \) in the structural diagram is taken into account through its real value, for which the resistance \( R_e \) is connected in cascade to it, which affects the dynamics of the process and is taken into account as follows [43]

\[
D_s = \frac{D_{se}}{1 + \frac{D_{se}R_e}{p}}
\]  

(1)

Allowance for transverse and longitudinal air gaps is carried out by the corresponding equivalent capacities \( C_{μq} \) and \( C_{μd} \) [43].

To describe the nature of dynamic processes in MWNFC, we will compose according to Fig. 2 the following equations:

a) total voltage at the output of the converter

\[
U_{Σ\Sigma} = 2 U_s;
\]

(2)

b) the output voltage of each channel

\[
U_s (p) = U_{s1} (p) = U_{s2} (p) = K_{μΣ\Sigma} p C_{μΣ} K_{μs-μq} I_s (p);
\]

(3)

c) total equivalent capacity

\[
C_{μΣ} = \frac{1}{W_{μΣ}} = \frac{1}{W_{μΣ2} + W_{μΣm}},
\]

(4)
Where

\[ W_{\mu cm} = \frac{1}{C_{\mu cm}}; \]  

\[ W_{\mu d^2} = \frac{1}{C_{\mu d}} = \frac{1}{C_{\mu d} + C_{\mu d^2}}; \]  

\[ C_{\mu d} = \frac{\mu_b n (l_\mu - \delta)}{h}; \]  

\[ C_{\mu d^2} = \frac{\mu_b h b}{\delta n}; \]  

d) the modulation effect on the excitation voltage is taken into account in the form

\[ C_{\mu cm} = K_{q\mu - C\mu cm} \left[ C_{\mu - C} + U_{\mu} \right] \cdot \frac{1}{p} \cdot D_{\gamma} \cdot U_{\gamma} \] ...

Solving equations (2) - (4) together, we obtain

\[ U_{\gamma}(p) = \frac{2K_{l_p} U_0 \cdot p \cdot K_{l_p - l_{\mu}} - C_{\mu} - K_{l_p - l_{\mu}} - C_{\mu} - K_{q\mu - C\mu cm} U_\gamma - I_{\gamma}(p)}{R_\gamma + W_{\mu d^2} K_{q\mu - C\mu cm} C_{\mu - C} - K_{l_p - l_{\mu}} - C_{\mu} - K_{l_p - l_{\mu}} - C_{\mu} - K_{q\mu - C\mu cm} U_\gamma \left[ 1 + \frac{p}{D_{\gamma} (R_\gamma + W_{\mu d^2} K_{q\mu - C\mu cm} C_{\mu - C} - K_{l_p - l_{\mu}} - C_{\mu} - K_{l_p - l_{\mu}} - C_{\mu} - K_{q\mu - C\mu cm} U_\gamma \right]} \right] \] 

After substitution of the values of physical effects and simple transducers (10) can be rewritten as

\[ U_{\gamma}(p) = 2W_{\gamma p} I_{\gamma}(p) / ([W_{\mu d^2} + D_{xoa}(U_{\gamma})]T_2(U_{\gamma})p + 1), \] 

Where

\[ D_{xoa}(U_{\gamma}) = R_\gamma / ((2/\pi) U_{\gamma - m} \mu KW. h_l b(l_c p l_p n) [l_p - 2 \left( \frac{1}{3} \cos 2\omega t + \frac{1}{5} \cos 4\omega t \right)]; \]  

\[ T_2(U_{\gamma}) = (\mu h_l \Delta W^2/l_c p) / R_\gamma + ((2/\pi) U_{\gamma - m} (\mu W. K hh_i \delta [l_p - 2 \left( \frac{1}{3} \cos 2\omega t + \frac{1}{5} \cos 4\omega t \right)]) / (\mu_l l_c p l_d (l_\mu - \delta) \delta n^2 + \delta n h \delta h_i)); \]  

\[ W_{\mu d^2} = 1 / (C_{\mu d} + C_{\mu d^2}) = h \delta n / (\mu_b [l_\mu - \delta] \delta n + \delta n h \delta h_i). \] 

Solving equation (12) by the known method [44], we obtain

\[ P_\gamma = 1 / T_2(U_{\gamma}) = ((2 U_{\gamma - m} \mu W. K hh_i \delta / (\pi \mu_0 l_c p l_d (l_\mu - \delta) \delta n^2 + \delta n h \delta h_i)) [l_p - 2 \left( \frac{1}{3} \cos 2\omega t + \frac{1}{5} \cos 4\omega t \right)] / ((\mu h_i \Delta W^2/l_c p); \]  

\[ S_\gamma = \int P_\gamma dt = (1/W. \Delta) / (2U_{\gamma - m} K hh_i / (\pi \mu_0 l_c p l_d (l_\mu - \delta) \delta n^2 + \delta n h \delta h_i) + R_\gamma l_c p / (\mu h_i W_\gamma)). \]
\[-2 \frac{U_{\text{m}}}{K_{\Delta}} \frac{W_{\Delta}}{2} \left( \frac{l_{\mu} - \delta}{\mu_{\text{w}}} \delta n^2 + \Delta h \right) \sin(2 \omega t + 0.1 \sin 4 \omega t) \right] \sin 2 \phi + 0.1 \sin 4 \phi; \quad (18)\]

\[h_2(t - \phi, \phi) = \left( 2 \frac{W_{\text{m}}}{T_2(U_{\text{m}})} \left[ W_{\text{m}} \delta^2 + D_{\text{equiv}}(U_{\text{m}}) \right] \right) \left[ (e^{S_2(\phi)} / e^{S_2(\phi)}) - 1 \right]. \quad (19)\]

Substituting values (13) - (19) into (19), we obtain

\[h_2(t - \phi, \phi) = M_2(\omega t) \exp[S_2(\phi) - t/T_{\text{equiv}} + V_2(\omega t)] - 1, \quad (20)\]

Where

![Figure 2. Parametric block diagram of MWNFC](image)
\[ M_2(\omega t) = (2W_{d1}R_s + (2U_{v_m}\mu W_{-\delta}h_1\delta)\left[1 - \frac{2}{3}(\cos 2\omega t + \frac{1}{5}\cos 4\omega t)\right] / (\pi \mu_0 l_s l_p[(l_m - \delta)\delta n^2 + h_1])]) \]

\[ / \cos 2\omega t + 0.1 \cos 4\omega t)\] / \((\mu h_1\Delta W^2/l_{cp})\{(h_\delta n/(\mu h_1(l_m - \delta)\delta n^2 + h_1)) + + (\pi R_{\text{cp}}l_p\mu/(2 U_{v_m}\mu W_{-\delta}h_1\delta)\left[1 - \frac{2}{3}(\cos 2\omega t + \frac{1}{5}\cos 4\omega t)\right])\}; \]

\[ V_2(\omega t) = (2U_{v_m}K\delta / (3\pi \mu_0 d_\delta W\Delta[(l_m - \delta)\delta n^2 + h_1]) \sin 2\omega t + 0.1 \sin 4\omega t); \]

\[ T_{\text{sup2}} = \mu_0 \pi d_1 h_1 \Delta W^2 [(l_m - \delta)\delta n^2 + h_1] / \]

\[ / (2U_{v_m}K\delta h_1 W_\delta + \pi \mu_0 d_1 R_{\text{cp}}d_1(l_m - \delta)\delta n^2 + h_1)]; \]

In expression (20), the quantitative side of the transient response is determined by two components of the exponent: \( S_2(\varphi) \) and \( t/T_{\text{sup2}} \).

Moreover, the first component of the exponent \( S_2(\varphi) \) characterizes the family of transition functions \( h(t - \varphi, \varphi) \). The most characteristic angles \( \varphi \), determining the moments of supply of a single jump signal, are the largest and smallest values \( S_2(\varphi) \) which correspond

\( \varphi_{\text{sup}} = \frac{\pi}{4}, \quad \varphi_{\text{inf}} = 0. \)

and the second component of the exponent \( t/T_{\text{sup2}} \) shows the nature of changes in the envelope of the transition function. It determines the main indicators of the quality of the transient response and is the main component.

When \( \varphi_{\text{inf}} \), the envelope component begins to increase exponentially from zero, and at \( \varphi_{\text{sup}} \) - from a certain value.

Analysis of the equivalent time constant (23) shows that the performance is influenced by the geometrical dimensions and parameters of the MWNFC. The speed increases with an increase in the air gap \( \delta \), resistance \( R_s \), connected in series with the excitation winding and a decrease in the number of turns \( W_\delta \), and the length of the magnetic circuit element \( l_m \). In addition, in order to increase the performance in this case, it is also necessary to increase the transverse air gap \( h \).

For MWNFC (Fig. 1) with parameters: controlled direct current in the busbar \( I_c = 10000 \text{ A} \); transverse dimensions of the busbar trunking \( a \cdot b_1 = 85 \cdot 120 \text{ mm}^2 \); optimal value of excitation \( H_{\text{min}} \) \( = 1.65 \); the optimal limit of the controlled value \( H_{\text{op}} \) \( = 0.69 \); the size of the air gap \( \delta \) \( = 9.27 \text{ mm} \); the length of the magnetic circuit element \( l_m \) \( = 32.5 \text{ mm} \); \( h_1 = 17.5 \text{ mm} \); values \( K_\beta = 0.8, \beta = 0.04, n = 20, l_{\text{sw}} = 66.4, l_s W_1 = 14.9 \text{ A}, W_1 = 50 \text{ turn} \); the elements of the magnetic circuit are made of a sheet thickness of 0.35 mm with the parameters \( \rho_{\text{min}} = 110 \text{ m/H} \) and \( \rho_{\text{max}} = 550 \text{ m/H} \), the equivalent time constant MWNFC was determined according to (23), equal to \( T_{\text{sup2}} = 1.26 \cdot 10^{-4} \text{ s} \).

In the case of the most unfavorable moment of supplying a single stepwise input signal \( (\varphi = 0) \), the time of the transient process will end in \( (3 \div 4) T_{\text{sup2}}, \) i.e. for \( t_{\text{per}} = 0.5 \cdot 10^{-3} \text{ s} \). Therefore, the transient time is \( 0.025 \text{ of the power frequency period} \) Therefore, MWNFCs can be considered practically inertial-free.

3. Conclusions

The dynamic characteristics of magnetic modulation contactless ferromagnetic converters are considered. The results of their research are presented. It is shown that their transient time is \( 0.025 \text{ of the power frequency period} \). Therefore, they can be considered practically inertial-free.
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