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Static Characteristics of Magnetic Modulation DC Converters with Analog Filter

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Abstract. The paper examines the most important requirements for current converters, the features of magnetic modulation converters, and identifies their fundamental and design features. The paper considers the principle of constructing converters for contactless DC measurement and their disadvantages of converters, methods of current measurement using magnetic modulation current converters, in which the magnetic permeability of a core made of ferromagnetic material is modulated. The influence of the parameters of the elements of a magnetic modulation current converter with an analog filter on their static characteristics and the influence of modulation on the static characteristics of the sensor have been determined. It has been revealed that the discrete operation of the magneto-modulation DC converter does not affect its static characteristics and the nonlinearity due to the type of modulation also does not affect the static characteristics of the sensor. The most important requirement for the operation of a magneto-modulation DC converter for autonomous power supplies with recharging buffer batteries is the formation of a static characteristic with the specified properties: linearity, sensitivity and the required range of operating currents. An analytical expression for the static characteristic is obtained in the form of the dependence of the output voltage on the values of T_1 and T_2 for the basic version of a magnetic modulation DC converter with an analog low-pass filter. Curves of the static characteristics of the magneto-modulation DC converter have been constructed for different values of the resistance of the ballast resistor R, as well as curves of the static characteristics of the magneto-modulation DC converter for different values of the supply voltage E. Analytical expressions for the static characteristics of a magneto-modulation DC converter based on magnetic transistor multivibrators with pulse-width modulation, curves of their characteristics and the output voltage of a magnetic modulation DC converter with a digital output and a discrete filter have been obtained.

Keywords: current converter, magnetic modulation sensor, direct current, non-contact measurement, magnetic permeability, analog filter

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Статические характеристики преобразователей постоянного тока с магнитной модуляцией с аналоговым фильтром

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Реферат. В данной статье рассматриваются важнейшие требования к преобразователям тока, особенности магнитомодуляционных преобразователей и выявлены их принципиальные и конструктивные особенности. Рассмотрены принцип построения преобразователей для бесконтактного измерения постоянного тока и основные недостатки преобразователей, методы измерения тока с помощью магнитомодуляционных преобразователей тока, в которых модулируется магнитная проницаемость сердечника из ферромагнитного материала. Определено влияние параметров элементов магнитомодуляционного преобразователя тока с аналоговым фильтром на их статические характеристики и влияние модуляции на статические характеристики датчика. Выявлено, что дискретность работы магнитомодуляционного преобразователя постоянного тока не оказывает влияния на его статические характеристики и нели-

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нейность, обусловленную видом модуляции, а также не влияет на статические характеристики датчика. Важнейшим требованием к работе магнитомодуляционного преобразователя постоянного тока для автономных источников питания с подзарядом буферной аккумуляторной батарей является формирование статической характеристики с заданными свойствами: линейностью, чувствительностью и требуемым диапазоном рабочих токов. Получено аналитическое выражение статической характеристики в виде зависимости выходного напряжения от величины T_1 и T_2 для базового варианта магнитомодуляционного преобразователя постоянного тока с аналоговым фильтром нижних частот. Построены кривые статических характеристик магнитомодуляционного преобразователя постоянного тока при разных значениях сопротивления балластного резистора *R*, а также кривые статических характеристик магнитомодуляционного преобразователя постоянного тока при разных значениях напряжения питания *E*. Получены аналитические выражения статических характеристик магнитомодуляционного преобразователя постоянного тока на основе магнитно-транзисторных мультивибраторов с широтно-импульсной модуляцией, кривые их характеристик, выходное напряжение магнитомодуляционного преобразователя постоянного тока с цифровым выходом и с дискретным фильтром.

Ключевые слова: преобразователь тока, магнитомодуляционный датчик, постоянный ток, бесконтактное измерение, магнитная проницаемость, аналоговый фильтр

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Introduction

Magnetic modulation converters are named, the action of which is based on a change in the magnetic state of a ferromagnetic material with simultaneous magnetization in constant and alternating fields. Flux modulation is possible due to the non-linear properties of the magnetic circuit [1].

Currently, a large number of converters are known and this creates certain difficulties in choosing the required type, specific design of these converters [2]. In this regard, it is advisable to classify the converters, which will reveal their fundamental and design features.

The currently existing converters are divided into two large groups according to the way they are included in the measured circuit [3]:

1) contact transducers based on measuring the voltage drop across a resistor included in the circuit of the measured current;

2) non-contact transducers based on the measurement of the magnetic field created by the measured current.

Converters of the first group contain, as a rule, a certain set of elements – a shunt, a modulator, a transformer, a demodulator, a low-pass filter, in a large number of variants of such converters [4]. These elements are only supplemented by new ones that contribute to some improvement in their characteristics. Therefore, it would be expedient to select transducers of the second group only.

Two principles of construction of converters for non-contact measurement of direct current are possible. One of them consists in the implementation of the first Maxwell equation with the determination of the differential and integral parameters of the magnetic field [5].

Another principle is to implement the third Maxwell equation, which establishes a relationship between the electric induction vector and the charge density, which is related to the measured current. The disadvantage of this method is that in this case it is necessary to take into account the speed of the charge carriers that form the current.

In our case, it is not necessary to determine the integral or differential parameters of the field created by the measured current. Since the current-carrying conductor is motionless, has a constant cross section which is including current density distribution, and enough to measure at any point in space the values of the magnetic field strength *H*, induction *B* or electric field strength *E*, unambiguously associated with the measured current.The simplest magnetometric transducer here will be a freely rotating magnetic needle [6].

Of all the above transducers, transducers with a shunt and an M-DM channel have the most acceptable characteristics [7]. In the simplest case, such a converter consists of a shunt, a modulator that converts a DC signal into an AC signal, an isolation transformer, a demodulator (detector), and low-pass filters.

Materials and methods

The main disadvantage of such converters is the rather high power dissipated in the shunt.

The most promising method for measuring the parameters of a magnetic field is the induction method based on the use of the law of electromagnetic induction [8]:

$$e_{\Sigma} = e_{tr} + e_{mov} = -\left(S\frac{dB}{dt} + \frac{dS}{dt} \right), \qquad (1)$$

where e_{Σ} – total electromotive force; e_{tr} – transformer's electromotive force, the appearance of which is associated with a change in the magnetic field over time; e_{mov} – electromotive force of movement, resulting from a change in the effective area of the contour; B – magnetic induction; S – effective contour area, m^2.

Induction converters are divided into passive (current transformers) and active (magnetic modulation).

To measure the current, the most suitable are magnetic modulation current converters, in which the magnetic permeability of a core made of a ferromagnetic material is modulated [9]. They have the highest sensitivity and are the easiest to be implemented. Current transducers (CT) used in measuring areas are subject to various mechanical stresses, which significantly affects their reliability. Therefore, the use here of magnetic modulation DC converters that are insensitive to mechanical influences becomes the only possible one.

Magnetic modulation converters are widely used in computing technology as logic elements and memory devices. In measuring technology, MMCs are used to measure the strength of a constant magnetic field (ferroprobes), to convert direct current into alternating current with a decrease in the absolute value of the current (measuring direct current transformers), to convert direct current into alternating current with an increase in the absolute value of the current (magnetic amplifiers), to measure the movement of an object to which the moving part of the transducer with carries a permanent magnet, is connected (magnetic modulation transducers of displacement).

The most important requirement for a magnetic modulation current converter (Magnetic modulation converters) for signal systems is the formation of a static characteristic with desired properties: linearity, sensitivity and the required range of operating currents. These properties depend on the values of a number of parameters of the Magnetic modulation converters elements: the resistance values of the resistors in the MCM, the number of turns in the transformer windings, and other values.

In the process of developing an engineering methodology for calculating the parameters of Magnetic modulation converters elements, it is required to obtain analytical expressions for the dependences $U_{out} = f\left(I_x\right)$ for Magnetic modulation converters variants with a pulse-width modulator [10]. Using these expressions, it is necessary to determine the influence of the parameters of the magnetic modulation DC converter elements on their static characteristics.

When analyzing the static characteristics of Magnetic modulation converters with pulse-width modulator, it must be borne in mind that, firstly, the converter under consideration is a discrete link, i. e. the "current-pulse duration" transformation occurs in this case discretely with an interval T (where T is the period of self-oscillations), and secondly, it is a non-linear link, since it contains an element that has a non-linear characteristic – the magnetic circuit of the transformer.

It is known that with an infinitely small bandwidth of the continuous part in a discrete system, the influence of the discreteness of the system operation on the values of the output signal is minimal, i. e. the discrete system in this case is identical in its properties to the continuous one [11]. When analyzing the static characteristics of the Magnetic modulation converters, the bandwidth of the continuous part of the device is taken equal to zero, which, with an infinite observation time t, does not affect the value of the output signal. Therefore, the discreteness of the work of the converter under study in the analysis of its static characteristics in this case will not be taken into account, which will not lead to errors when calculating the dependence $U_{out} = f\left(I_x\right)$.

Since the discreteness of the MCC operation does not affect its static characteristics, the nonlinearity due to the type of modulation also does not affect the static characteristics of the sensor.

Thus, when analyzing the static characteristics of the Magnetic modulation converters with pulse-width modulation, we can assume that this converter is a continuous link with a nonlinear dependence $U_{out} = f\left(I_x\right)$. This non-linearity is mainly due to the non-linearity of the magnetization characteristics of the material of the magnetic core of the converter. The analysis of such links, as a rule, is carried out by compiling and solving a nonlinear differential equation that describes the operation of the sensor under study.

We obtain an analytical expression for the static characteristic in the form of a dependence of the output voltage on the values of T_1 and T_2 for the basic version of the Magnetic modulation converters with analog [12]. It is equal to the integral of the difference in voltage drops across the ballast resistors and is determined by the expression:

$$U_{out} = \frac{1}{T_1 + T_2}\left\{\left[\left\{T_1 E_1 - RS_{\mu} W_k k_1 k_2^{'} \int_{-l_2^{'}}^{l_2^{'}} \frac{dl_1}{1 + k_2^{'2} I_1^2}\right] - \left[T_2 E_1 - RS_{\mu} W_k k_1 k_2^{'} \int_{-l_2^{'}}^{l_2^{'}} \frac{dl_1}{1 + k_2^{'2} I_1^2}\right]\right\} =$$

$$= \frac{1}{T_1+T_2}\left\{\left[T_1E_1 - R\frac{S_\mu W_k}{k_1}\left(\operatorname{arctg}\frac{I_2'}{k_2'} + \operatorname{arctg}\frac{I_1'}{k_2'}\right)\right] - \left[T_2E_1 - R\frac{S_\mu W_k}{\alpha_1}\left(\operatorname{arctg}\frac{I_1'}{k_2'} + \operatorname{arctg}\frac{I_2'}{k_2'}\right)\right]\right\} = \frac{T_1-T_2}{T_1+T_2} =$$

$$= E_1 \frac{\left[\frac{k_2'U_{2x}}{R^2+k_2'^2U_{2x}^2} - \frac{k_2'U_{1x}}{R^2+k_2'^2U_{1x}^2}\right]\operatorname{arctg}\left[\frac{2k_2'I_{km}}{1-k_2'I_1'}\right] + \left[\frac{R}{2\left[R^2+k_2'^2U_{1x}^2\right]}\ln\frac{U_{1k}^2\left[1+k_2'^2I_2'\right]}{U_{2k}^2\left[1+k_2'^2I_2'^2\right]} - \right.}{\left[\frac{k_2'U_{2x}}{R^2+k_2'^2U_{2x}^2} - \frac{k_2'U_{1x}}{R^2+k_2'^2U_{1x}^2}\right]\operatorname{arctg}\left[\frac{2k_2'I_{km}}{1-k_2'I_1'}\right] + \left[\frac{R}{2\left[R^2+k_2'^2U_{1x}^2\right]}\ln\frac{U_{1k}^2\left[1+k_2'^2I_2'\right]}{U_{2k}^2\left[1+k_2'^2I_2'^2\right]} - \right.} \to \qquad (2)$$

$$\to \frac{\left. - \frac{R}{2\left[R^2+k_2'^2U_{1x}^2\right]}\ln\frac{U_{1k}^2\left[1+k_2'^2I_2'\right]}{U_{2k}^2\left[1+k_2'^2I_2'^2\right]}\right]}{\left. - \frac{R}{2\left[R^2+k_2'^2U_{1x}^2\right]}\ln\frac{U_{1k}^2\left[1+k_2'^2I_2'\right]}{U_{2k}^2\left[1+k_2'^2I_2'^2\right]}\right]}.$$

Thus, from the last expression it can be seen that the output voltage for all variants of the Magnetic modulation converters with pulse-width modulation is proportional to the ratio ($T_1 - T_2$) to ($T_1 + T_2$), and T_1 and T_2 depend on the measured current I_x.

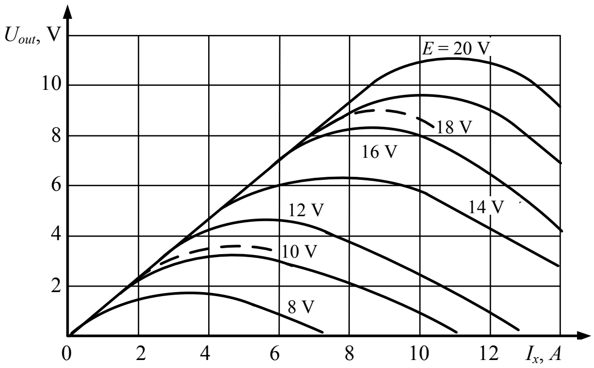

Fig. 1. Curves of static characteristics of MCC at different values of the supply voltage E. Solid curves are calculated, and dotted curves are experimental data

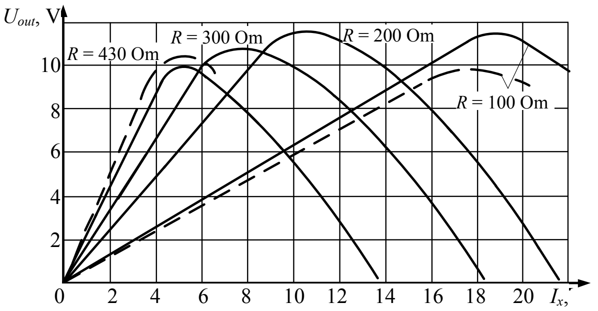

Fig. 2. Curves of static characteristics of MCDC at different values of the resistance of the ballast resistor R. Solid curves are calculated, and dotted curves are experimental data

Results

An analysis of the obtained analytical expressions for the static characteristics of magnetic modulation DC converter with pulse-width modulation and their curves, as well as a comparison of the results of calculation and experiment, allow us to draw the following conclusions:

1. The resulting analytical expressions for the conversion characteristic describe the static mode of operation of the MCC with sufficient accuracy.
2. The static response of the MCC with pulse-width modulation has a high linearity in the initial section.
3. The sensitivity of the MCC is determined to a greater extent by the value of the resistance of the ballast resistor R.

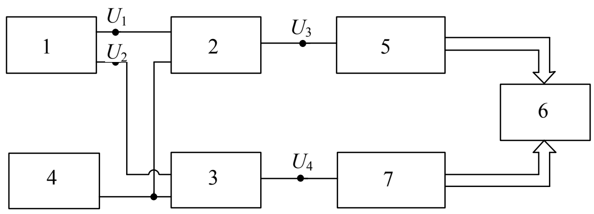

Fig. 3. Functional diagram of the MCC

Fig. 1 shows an Magnetic modulation converters circuit with a digital output that uses low pass filter instead of analog. Let us determine whether such a method of extracting a useful signal affects the shape of the static MCC characteristic. To do this, we will find the dependence $U_{out}\left(I_x\right)$.

Under the action of the current I_x, the duty cycle of the pulses generated by the magneto-transistor multivibrators changes. In this case, the amplitudes of positive and negative pulses on the output winding W_{out} change relative to its midpoint at constant volt-second areas.

When the current I_x changes, the values of U_1 and U_2 change, but their sum and the volt-second area of the pulses remain constant.

That's why:

$$\begin{cases} U_1 = U_2 = \left(E_1 - I_{ks}R\right)\dfrac{W_{out}}{W_k}; \\ U_1T_1 = U_2T_2, \end{cases} \quad (3)$$

where I_{ks} – is the transistor collector current value corresponding to the saturation induction B_s; W_k, W_{out} – the number of turns, respectively, in the collector and output windings.

From equations (3) we find the values U_1 and U_2:

$$\begin{cases} U_1 = \dfrac{2\left(E_1 - I_{ks}R\right)T_2}{T_1 + T_2}\dfrac{W_{out}}{W_k}; \\ U_1 = \dfrac{2\left(E_1 - I_{ks}R\right)T_1}{T_1 + T_2}\dfrac{W_{out}}{W_k}. \end{cases} \quad (4)$$

The output voltage of the MCC with digital output and discrete filter is equal to the voltage difference between U_1 and U_2:

$$U_{out} = U_1 - U_2 = 2\left(E_1 - I_sR\right)\frac{W_{out}}{W_1}\frac{T_1 - T_2}{T_1 + T_2}. \quad (5)$$

It can be seen from expression (1.4) that the shape of the characteristics $U_{out} = f\left(I_x\right)$ for the MCC with a discrete filter is similar to the shape of the dependencies $U_{out}\left(I_x\right)$ according to expressions (1) obtained for the MCC with an analog filter. The dependence according to expression (4) differs only in scale.

CONCLUSION

Thus, the analysis of the expression for the static characteristic of the MCC with a digital output and with a discrete filter shows that the discrete filter does not affect the shape of the static characteristic of the MCC.

An analysis of the static characteristics of the considered magnetic modulation converters on magnetic transistor multivibrators with pulse-width modulation has shown that they have a high linearity in the initial section, and the duration of the linear section of the characteristic depends on the quantities that mainly affect the maximum collector current (I_{MC}): the values of the power supply voltage (E), the resistance of the base resistor (R_b) and the number of turns of the base winding (W_b).

It is established that the static characteristic is linear approximately in the area $(-0,6I_{MC}W_k < I_x < +0,6I_{MC}W_k)$. And also the sensitivity of the MCC is largely determined by the resistance value of the ballast resistor (R), the number of turns of the collector winding (W_k) and it grows with a decrease in W_k and with an increase in R.

An analysis of the expression for the static characteristic of the MCC with a digital output and with a discrete filter has shown that the discrete filter does not affect the shape of the static characteristic of the MCC.

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