Factors affecting the sensitivity of magnetomodulatory current transducers

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Abstract. The article substantiates the choice of a measuring transducer using the magnetic modulation effect. The factors influencing the intrinsic noise of a magnetomodulatory converter are considered. An assessment of their effect on the threshold sensitivity of the transducer has been carried out. It is revealed that the only source of thermal noise of the magnetomodulation transducers, which can affect their extreme sensitivity, are the thermal noise of the measuring winding or the thermal noise of the input circuit. Analytical expressions have been obtained to determine the metrological characteristics of such transducers.

INTRODUCTION

Currently, electric current measuring instruments have been developed quite fully. However, the development of current converters for automated metering and control of electrical energy (AMCEE) and dispatch control and data acquisition (SCADA) systems remains an urgent task. Moreover, the creation of current measuring transducers with high sensitivity is particularly difficult in solving this problem. Among the many options for solving this problem, it seems advisable to create a similar device based on a magnetomodulatory current transducer (MCT). The low level of intrinsic noise, the ability to dispense with contact electrodes, and the ease of matching the primary converter with the modulator are its obvious advantages compared to known sensors [1-3]. An example of the construction of such a device is proposed in [4]. Obtaining the output signal in the form of a sequence of rectangular pulses modulated by duration allows you to organize the output of information about the measured current in both analog and digital form, and easily interface the measuring transducer with digital devices. When measuring low currents in natural conditions, the pulse representation of the output signal can significantly increase the noise immunity of the signal when it is transmitted via a cable to a monitoring system for recording and processing the information received. This article discusses issues related to the identification of the main factors determining the intrinsic noise of the transducer.

MATERIALS and METHODS

Among the large number of parameters that determine the quality of the converter, a special place is occupied by its threshold sensitivity, which is usually understood as the ratio of the MCT's own noise level to its conversion factor:

$$H_{thr.} = \frac{K(q)\sqrt{\sum U_{ni}^2}}{W_n} \tag{1}$$

where U_{ni} – is the voltage of the i-th noise source in band unit, V/Hz;

W_n – is the conversion coefficient of the MCT;

$K(q)$ – is a coefficient that determines the discrimination procedure with a given accuracy.

The conversion coefficient of the MCT W_n – is considered to be the conversion coefficient of the core current generated by the measured signal into the output EMF. In the case of pulse-width mode of operation of the converter, the coefficient W_n characterizes the conversion of the measured parameter of the electric current into a proportional time interval. However, in this case, the root expression of the numerator in formula (1) should be represented as the sum of *n* – increments of the pulse duration due to the corresponding noise sources.

The whole set of noise in magnetic modulators can be divided into 3 components [5, 6]:

1) the voltage of noise caused by both the disordered thermal motion of electrons in the windings (electrical noise) and the non-repeatable processes of core magnetization reversal (magnetic noise);

2) a noise voltage having the same frequency as the useful signal;

3) the noise voltage, which differs in frequency from the useful input signal.

To eliminate the influence of the third component of the noise voltage, special filters or devices can be used that respond to the amplitude difference of the output voltage, therefore, it can be ignored when evaluating the threshold sensitivity of magnetomodulatory transducers.

The main reasons for interference at the output of the converter with the frequency of the useful signal are: hysteresis of the magnetic material; external magnetic fields; insufficient isolation of the excitation and output circuits.

The interference voltage of converters whose output voltage frequency coincides with the frequency of the excitation signal is mainly due to insufficient isolation of the excitation and output circuits in the absence of an input signal, while the degree of isolation and, accordingly, the level of interference changes with changes in the excitation current, ambient temperature and over time due to changes in the characteristics of individual circuit elements.

If the second harmonic is eliminated in the input excitation current of the frequency-doubling converter, then insufficient isolation of the excitation and output circuits does not lead to interference with the frequency of the useful signal, and the reason for the zero departure of the converter in this case is hysteresis.

It was shown in [7, 8] that with a sufficiently large amplitude of the excitation field, the hysteresis cycle for a constant field is transformed into a one-to-one relationship, the geometric location of the points of which coincides with the average magnetization curve. Since the MCT operation mode with frequency doubling is characterized by the ratio $H_m \gg \frac{B_i}{\mu_0}$, the achievement of an unambiguous dependence in MCT with frequency doubling is possible with the ratio $H_m \geq (3 \div 5)H_s$, where H_m – is the amplitude of the excitation field; H_s – is the saturation field strength.

When using alloys of high magnetic permeability (79HM, 79HMA, 80HXC) in the converter, zero loss due to the phenomenon of hysteresis has little effect, and the use of closed toroidal cores leads to a significant reduction in the noise level of the converter [9, 10].

Transducers designed to register small constant signals, in addition to being sensitive to the measured effects, also respond to constant external magnetic fields. To weaken the influence of homogeneous magnetic fields, toroidal cores with evenly spaced output windings are used around their entire circumference. In this design, the EMF of the second harmonic, induced by an external field in one part of the winding, is compensated by the EMF of the opposite direction, which occurs in the other part, regardless of the orientation of the external field. The compensation level is determined by the uniformity of the winding, the uniformity of the magnetic properties of the material and the immutability of the core cross-section.

In frequency doubling transducers, the influence of these noise sources can be completely eliminated or reduced to a level where, for a limited period of time, the threshold sensitivity is determined primarily by the action of electrical and magnetic noise. The occurrence of magnetic noise is due to the fact that with repeated remagnetization of the converter core, the processes of changing the magnetization of individual domains and micro-regions occur differently, that is, Barkhausen jumps for different cycles do not coincide. This causes the appearance of a magnetic induction component with a continuous spectrum (magnetic noise) superimposed on a signal with a discrete spectrum.

Consequently, an EMF of noise caused by a signal with a continuous spectrum of magnetic induction will be induced in the output winding of the converter with a doubling of the frequency. In [11, 12], it was experimentally established that there is a relationship between the parameters of the hysteresis loop and the number of Barkhausen jumps. Since the contribution of the Barkhausen effect to magnetic noise is predominant, it is obvious that the hysteresis loop may contain information about its threshold sensitivity. The advantages of this approach are as follows:

- despite the fact that the determination of the hysteresis loop and its parameters is not difficult, in the laboratory, the study of magnetic noise is a difficult practical task;
- the hysteresis loop is being studied on samples of modern core materials with improved characteristics, and when studying magnetic noise, it requires the construction of a converter in conjunction with an instrument channel;
- hysteresis, as a physical phenomenon, is studied much more fully and widely than magnetic noise.

Therefore, the task of analyzing the hysteresis cycle in order to find individual factors in it that determine the noise properties of the converter is relevant.

RESULTS

As is known, when deriving the expression of the output EMF of a converter, a hysteresis-free approximation of the loop [13] is used, called the average magnetization curve. The use of this method, despite the simplification of the analysis, is accompanied by the loss of significant information about the role of individual components of magnetic permeability and their involvement in the occurrence of noise. Having formally represented a ferromagnet as a mixture of two media: a hysteresis medium for which the reversible part of the magnetic susceptibility is zero, and a hysteresis-free medium with only reversible magnetic susceptibility, let us consider the microscopic structure of the hysteresis loop (Fig. 1), which is an alternation of Barkhausen jumps and areas of reversible induction variation.

Then the induction at any point of the hysteresis loop can be represented as a sum [14-16]:

$$B(H) = B_r(H) + B_b(H), \tag{2}$$

where $B_r(H)$ – is the induction resulting from the summation of reversible increments $B_r(H) = \sum \Delta B_{ri}(H)$; $B_b(H)$ - the induction resulting from the summation of all Barkhausen jumps, $B_b(H) = \sum \Delta B_{bi}(H)$.

Two components can be distinguished from dependence (2): the graph of a purely discontinuous change in induction is the "Barkhausen cycle", and the graph of a reversible change in induction is the "reversible cycle". Since the hysteresis effect is insignificant in the reversible cycle, this dependence can be considered almost unambiguous. Figure 2 shows all three cycles of the process. Taking into account the above assumptions, the Barkhausen cycle can be represented as:

$$B_b(H) = \overline{B_b(H)} + \delta B_b(H), \tag{3}$$

where $\overline{B_b(H)}$ – is the mathematical liquefaction, i.e. the deterministic part of the Barkhausen cycle; $\delta B_b(H)$ – is a centered random function.

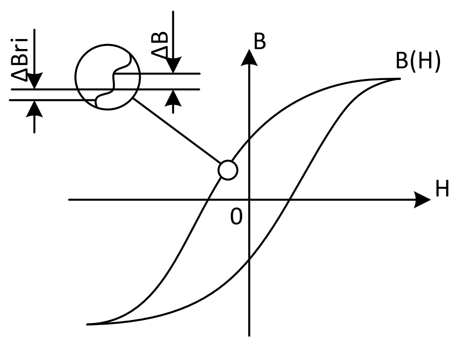

FIGURE 1. Microscopic structure of the hysteresis loop.

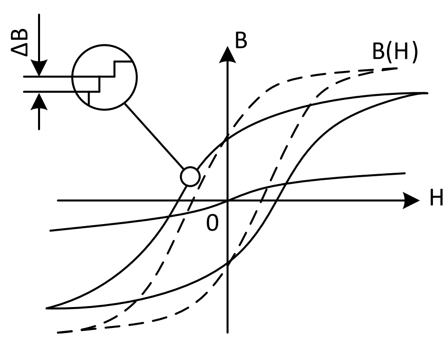

FIGURE 1. Cycles of induction change.

Differentiating the sum (2) taking into account (3), we obtain:

$$\frac{dB}{dH} = \frac{dB_r}{dH} + \frac{\overline{dB_Б}}{dH} + \frac{d}{dH}\delta B_b \tag{4}$$

Thus, the following set of differential permeabilities can be considered: $\mu_d = \frac{1}{\mu_0}\frac{dB}{dH}$, corresponding to the concept of a smoothed averaged loop as a whole; reversible permeability $\mu_r = \frac{1}{\mu_0}\frac{dB_r}{dH}$, characterizing a reversible cycle; Barkhausen permeability $\mu_Б = \frac{1}{\mu_0}\frac{\overline{dB_Б}}{dH}$, corresponding to the concept of about smoothed, averaged Barkhausen; the random component $\delta\mu_Б = \frac{1}{\mu_0}\frac{d}{dH}\delta B_b$, reflecting fluctuations $BB(H)$ relative to the mathematical expectation.

For differential MCT, taking into account the concepts introduced, we write down the expressions of the inductions in the first and second cores of the MCT under the simultaneous action of a strong alternating field of excitation $H_в(t)$ and a weak constant field of the measured signal H_0:

$$B_1 = B_{1b}(H_B + H_0) + B_r(H_B + H_0);$$
$$B_2 = B_{2b}(H_B + H_0) + B_r(H_B + H_0).$$

Decomposing these functions into a Taylor series and leaving, due to the smallness of the remaining terms, only the linear terms of the series, we obtain:

$$B_1 = B_{1b}(H_B) + \frac{dB_{1Б}(H_B)}{dH_В}H_0 + B_r(H_B) + \frac{dB_r(H_B)}{dH_В}H_0 \quad (5)$$

$$B_2 = B_{2b}(-H_B) + \frac{dB_{2Б}(-H_B)}{dH_В}H_0 + B_r(-H_B) + \frac{dB_r(-H_B)}{dH_В}H_0 \quad (6)$$

At the same time $B_{1b}(H_B) = \overline{B_b(H_B)} + \delta B_{1b}(H_B)$; $\frac{dB_{1b}(H_B)}{dH_В} = \frac{d\overline{B_b(H_B)}}{dH_В} + \frac{d}{dH_В}\delta B_{1b}(H_B)$; $\frac{d\overline{B_b(H_B)}}{dH_В} = \frac{d\overline{B_b(-H_B)}}{dH_В} = \mu_0\mu_Б(H_B)$.

Next, consider that random functions

$$\frac{d}{dH_B}\delta B_{1b}(H_B) = \mu_0\delta\mu_{1b}(H_B); \frac{d}{dH_B}\delta B_{2b}(-H_B) = \mu_0\delta\mu_{2b}(-H_B)$$

they are uncorrelated with each other, have zero mathematical expectation and the same statistical characteristics. Then their sum can be represented as a single random process with twice the power density. The same applies to the random functions $\delta B_{1b}(H_B)$ and $\delta B_{2b}(-H_B)$. At the same time

$$\mu_0\delta\mu_{1b}(H_B) + \mu_0\delta\mu_{2b}(-H_B) = \mu_0\delta\sqrt{2}\mu_b(H_B); \quad (7)$$

$$\delta B_{1b}(H_B) + \delta B_{2b}(H_B) = \sqrt{2}B_b(H_B). \quad (8)$$

Taking into account formulas (5-7), we obtain the expression for the total induction in the signal winding of the MCT covering both cores:

$$B_{total} = 2H_0\mu_0\mu_d(H_B) + \sqrt{2}\delta B_b(H_B) + \mu_0 H_0\delta\sqrt{2}\mu_b(H_B). \quad (9)$$

Then the induced EMF in the signal winding is equal to

$$e_{total} = -w_c\frac{d}{dt}(SB_{total}) = -2w_cSH_0\mu_0\frac{d\mu_d}{dt} - \sqrt{2}w_cS\frac{d}{dt}(\delta B_b) - \sqrt{2}w_cSH_0\mu_0\frac{d}{dt}(\delta\mu_b). \quad (10)$$

Consider the components of the output EMF. The first term $e_c = -2w_cSH_0\mu_0\frac{d\mu_d}{dt}$ is the EMF of the useful signal, determined by the measured field and the amplitude of the modulation of the magnetic permeability of the MCT core.

The second term:

$$e_{shn} = -\sqrt{2}w_cS\frac{d}{dt}\delta B_\delta(H_B), \quad (11)$$

it is a random process caused by periodic changes in induction and independent of the signal field. Let's call it independent magnetic noise. Considering that the exciting field in the general case is a periodic function of time $H_в(t)$, expression (11) can also be represented as: $e_{shn} = -\sqrt{2}w_cS\mu_0\delta\mu_b(H_B)\frac{dH_B}{dt}$. It follows from this expression that independent magnetic noise is formed due to fluctuations in the Barkhausen permeability with their additional modulation by the periodic process of remagnetization. It follows from this expression that independent magnetic noise is formed due to fluctuations in the Barkhausen permeability with their additional modulation by the periodic process of remagnetization.

The third term:

$$e_{shz} = -\sqrt{2}w_cS\mu_0H_0\frac{d}{dt}\delta\mu_b(H_B), \quad (12)$$

it is also a random process, but it already depends on the signal field H_0. Let's call it dependent magnetic noise. However, as the analysis of expression (12) shows, due to the smallness of H_0 at values $H_0 = H_{por}$, the dependent noise can be neglected in comparison with the independent one. Then the total EMF in the signal winding is equal to $e_{total} = e_c + e_{shn}$.

Information about the desired value of the useful signal is determined by the value of the EMF of the second harmonic, which is equal to $e_c = -4w_c S\mu_0\omega_B H_0 \Delta\mu_{д2} cos2\omega_в t$, where $\omega_в$ – is the excitation frequency; $\Delta\mu_{д2}$ – is the amplitude of the second harmonic of the modulation of the differential permeability of the core.

The EMF of independent noises in this case will be a narrow-band random process:

$$e_{shn} = 2\sqrt{2}w_c S\mu_0\omega_B H_m \delta\mu_{b2}(H_B)\cos(2\omega_B t + \psi),$$

where ψ – is a slowly changing random phase; $\delta\mu_{b2}(H_B)$ – is a random function H_B that defines a slowly changing random amplitude. The index 2 indicates the allocation of a signal in a narrow band near the frequency of $2\omega_B$.

Based on the definition of H_{por} [2] as a constant field that creates a second harmonic signal on the signal windings of the MCT with an effective value equal to the effective value of the noise voltage on these windings in the frequency band $\Delta f = 1\ Hz$, we can write $e_{c\ eff}(H_{por}) = \sigma_{shn}$ (13)

where $e_{c\ eff}$ – is the effective value of the EMF of the useful signal at $H_0 = H_{por}$; σ_{shn} – is the RMS value of the EMF of magnetic noise in the 1 *Hz* band at a frequency of $2\omega_B$.

Notation $K = w_c S\mu_0\omega_B = const$, (14)

we get $\sigma_{shn} = 2\sqrt{2}K\sigma_{Mb}H_m$, (15)

where σ_{Mb} – is the standard deviation of the random process $\delta\mu_b(H_b)$.

Taking into account (14), expression (13) will have the form:

$$e_{c\ eff}(H_{por}) = 2\sqrt{2}K\mu_{д2}. \quad (16)$$

Substituting (15) and (16) into (13) and resolving with respect to H_{por}, we obtain

$$H_{por} = H_m \frac{\sigma_{Mb}}{\mu_{д2}} \text{ or } H_{por} = H_m\sigma_{Mb}/(\mu_{b2} + \mu_{r2}) \quad (17)$$

where μ_{b2} – is the amplitude of the second harmonic of the Barkhausen permeability;

μ_{r2} – is the amplitude of the second harmonic of reversible permeability.

Expression (17) illustrates the role of individual components of the permeability of the MCT core in signal generation and the formation of magnetic noise. Thus, the noise generation process is entirely determined by fluctuations in Barkhausen permeability, while in the formation of a useful signal, its contribution is summed up with the contribution of reversible permeability.

Electrical thermal noise caused by the disordered thermal motion of electrons in the MCT windings is a typical white noise with a uniform spectrum. Therefore, the EMF of thermal noise, the expression for which has the form: $E_{sh} = \sqrt{4KTR_a\int_{f_l}^{f_u} df}$, where $K = 1{,}38 \cdot 10^{-6}\ J/°K$ - is the Boltzmann constant, *T* – is the absolute temperature, $°K$, R_a – is the active resistance of the corresponding windings MCT, Ohms; f_l, f_u - the lower and upper limits of the frequency range, *Hz*, can be written as

$$E_{sh} = \sqrt{4KTR_a\Delta f}. \quad (18)$$

The EMF of thermal noise E_{sh} leads to the appearance of noise currents I_{sh} in each of the MCT circuits. These currents, in turn, create the corresponding voltage components in the core. However, the magnitude of the noise current is determined by both the EMF of thermal noise E_{sh} and the load resistance in the corresponding MCT circuit.

So, for example, in the case when the information winding of the MCT is loaded onto the input resistance of the differentiator, which forms transitions through the zero of the output EMF, at $R_a = 20\ Ом, T = 300\ °K, \Delta f = 1000\ Hz, R_{in} = 1мОм$, we will have $I_{sh} = \frac{E_{sh}}{R_{in}} = \frac{\sqrt{1{,}38\cdot10^{-6}\cdot300\cdot20\cdot10^{3}}}{10^{6}} = 5.5 \cdot 10^{-11}$A.

Obviously, for $R_{in} \gg R_a$ thermal noise of the information winding can be ignored.

If we consider the excitation circuit, then the obvious condition for obtaining an undistorted shape of the excitation field is the presence in the excitation circuit (as the last link) of a current source, the internal resistance of which is also very high ($R_{in} \gg R_a$). Therefore, the thermal noise of the excitation winding can also be ignored.

Thus, the only source of thermal noise of the MCT that can affect its extreme sensitivity is the thermal noise of the measuring winding or, if there is none, the thermal noise of the input circuit. Based on expression (19), we can write the expression for the EMF of thermal noise $E_{shin} = \sqrt{4KT(R_{ain} + R_p)\Delta f}$,

where R_{ain} – is the active resistance of the measuring winding;

R_p – is the active component of the spreading resistance of the primary measuring transducer.

Then the noise current in the primary circuit is defined as $I_{shin} = \sqrt{\frac{4KT\Delta f}{R_{ain}+R_p}}$.

Based on the law of total current, neglecting the scattering fluxes, we obtain the magnetic field strength in the core of the MCT created by the current I_{shin}:

$$H_{she} = \frac{I_{shin} W_{in}}{l_{av}} = \sqrt{\frac{4KT\Delta f w_{in}^2}{(R_{ain}+R_p) l_{av}^2}} \quad (19)$$

where W_{in} – is the number of turns of the measuring winding;

l_{av} – is the length of the average power line of the MCT core.

Finally, based on expressions (17) and (19), we obtain an expression for determining the total strength of the magnetic field $H_{shtotal}$:

$$H_{shtotal} = \sqrt{H_{sh\text{м}}^2 + H_{she}^2} = \sqrt{\left(\frac{H_m \sigma_{\text{м}b}}{\mu_{b2}+\mu_{r2}}\right)^2 + \frac{4KT\Delta f w_{in}^2}{(R_{ain}+R_p) l_{av}^2}}. \quad (20)$$

Expression (20) defines the limiting or threshold sensitivity of the MCT to the magnetic field of the core.

CONCLUSION

The analysis made it possible to identify the main factors determining the intrinsic noise of a magnetic current converter operating in frequency doubling mode, which can be used to reduce magnetic noise.

The analysis of the hysteresis cycle of the magnetic converter core showed that a significant part of the magnetic noise is independent noise resulting from permeability fluctuations associated with the Barkhausen effect, which are additionally modulated by the periodic process of remagnetization.

It has been established that the main source of thermal noise in magnetomodulatory transducers, affecting their extreme sensitivity, is the thermal noise of the measuring winding. In the absence of the latter, the thermal noise of the input circuit is crucial. An expression describing the threshold sensitivity of a magnetomodulatory current converter relative to the magnetic field of the core is obtained. In the future, it is planned to analyze the factors affecting the accuracy of converting the MCT signal with pulse width modulation, which will allow you to select the modulation parameters.

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