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The measurement of dc magnetic field

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Abstract – The measurement of dc magnetic field, especially for low intensities, returns in actuality. Beyond the importance of measuring the terrestrial magnetic field with his variations, a large amount of new standards concerning generally the electromagnetic compatibility impose as well the measurement of the dc magnetic field. For example, in [1] the dc magnetic field is introduced as the reference magnitude, and in [2] is the reference level established for the magnetic field concerning the surrounding environment, which assures the staff protection.

The paper presents a measurement method of the magnetic field induction based on the Förster probe and the obtained experimental results.

Keywords: measurement of dc magnetic field, Förster probe, nonlinear circuit

I. INTRODUCTION

The dc magnetic field represents a particular form of the electromagnetic field, which can be emphasized nearby the permanent magnets or circuits, where there is a dc current flow through, and which exercise forces and moments upon neighborhood bodies. The ideal medium concerning the magnetic field is the vacuum. Between the magnetic field intensity and the magnetic induction it is possible to write the following relationship:

$$\overline{B} = \mu_0 \cdot \overline{H} \qquad (1)$$

Where: $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ is a universal constant factor of proportionality representing the magnetic permeability of the vacuum.

The measurement of the magnetic field represents a delicate task, because of the field produced by the temporary or permanent magnetization at the interacting bodies level, taking into account the material characteristics. This is the reason, why it is difficult to realize such probes for picking up information concerning this kind of field.

Another problem that appears during the measurement process is the existence of the magnetic terrestrial field, which is, as well, a dc field. That means, when measuring the dc magnetic field, the magnetic terrestrial field value in the measuring point appears like a systematic error related to the measured value. For correcting this error is it necessary to know previously the value of this field, that's why it is necessary measuring it.

In literature [3], there are some measurements methods presented, one of them is the measurement using the Förster probe. As a principle, this type of transducer uses the specific behavior property of ferromagnetic materials taking into accounts a simultaneous magnetization generated by ac and dc fields. In the situation of introducing a magnetized ferromagnetic element in an ac magnetic field, overlapped by a dc magnetic field, this produces a changement of the magnetization behavior on an asymmetric hysteresis cycle, leading into the generation of the harmonic component second order, having a level proportional with the ac signal amplitude and the dc component magnitude of the resulting magnetic field.

II. MEASUREMENT METHOD PRINCIPLE

It is much easier to obtain the second order harmonic component, when the transducer is with two parallel cores – differential variant - having the principle schema presented in fig.1; on each of the two cores we have the same numbers of windings, N1' and N2'', respectively N2' and N2''. Windings N1' and N2'' named, as well as, supplied windings are connected in opposition, so that in every moment

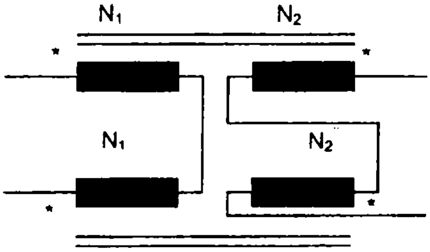

Fig.1. Förster Probe

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the generated ac fluxes generated by these to be equal and of contrary signs.

The measurement windings N1'and N2' are phased series connection; with such a configuration, the odd harmonics will be reciprocally canceled, and the even will add together, which is enhancing the signal to noise ratio, also doubling the probe sensitivity.

If we consider that the dependency between the magnetic induction (for a saturated core, fig. 2) and the magnetic field intensity is:

$$B = a_1 H - a_3 H^3 \qquad (2)$$

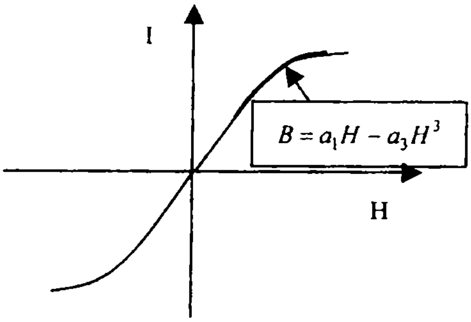

Fig 2. Hysterezis characteristic

Where a_1 and a_2 are parameters with $a_1 > a_3$ and the intensity of magnetic field H comes from a constant field H_0 and a variable field generated by a sinusoidal current $I \sin \omega t$.

It results that in the two inductors we will have the following magnetic inductions:

$$\begin{aligned} B_1 &= a_1 (H_0 + N_1' I \sin \omega t) - a_3 (H_0 + N_1' I \sin \omega t)^3 \\ B_2 &= a_1 (H_0 - N_1' I \sin \omega t) - a_3 (H_0 - N_1' I \sin \omega t)^3 \end{aligned} \qquad (3)$$

Because the secondary windings are series in phase, at their inputs, we will obtain the induced voltage having following form:

$$\begin{aligned} u = -\frac{d(\Phi)}{dt} = S\big[&- a_1 \omega (N_1' N_2' - N_1'' N_2'') I \cos \omega t + \\ &+ 3 a_3 \omega H_0^2 (N_1' N_2' - N_1'' N_2'') I \cos \omega t + \\ &+ 6 a_3 \omega H_0 (N_1'^2 N_2' + N_1''^2 N_2'') I^2 \sin \omega t \cos \omega t + \\ &+ 3 a_3 \omega (N'^3{}_1 N_2' - N_1''^3 N_2'') I^3 \sin^2 \omega t \cos \omega t \big] \end{aligned} \qquad (4)$$

Where S is the probe surface.

If the primary and respectively the secondary windings are identical $(N_1' = N_1'' = N_1)$ and $(N_2' = N_2'' = N_2)$ the [illegible]d output voltage becomes:

$$u = 6 a_3 S \omega N_1^2 N_2 I^2 H_0 \sin 2\omega t \qquad (5)$$

It is worth to make some observations concerning relationship (5).

1. The non-symmetries between the winding lead to the fundamental and third order harmonic component appearance that can be eliminated using a band pass filter centered on the second harmonic.
2. The sensitivity of the method is rising with the number of turns belonging to the two inductors, exciting ca signal frequency and amplitude and obviously depends on the used core, taking into account the section S and the coefficient a_3, that characterizes the core saturation.
3. It is known from the electrical transformer theory [4] that the core section can be saturated if it is determinated by the following formula:

$$S < K \sqrt{\frac{P_a}{f}} \qquad (6)$$

Where: P_a is the transformer apparent power, K – constant depending on the construction core material, and f – frequency.

If for a first approximation we are considering that the apparent power is proportional to I^2 and taking into account relationship (6), it results that the obtained output voltage will be:

$$U = k a_3 \sqrt{f} N_1^2 N_2 I^3 H_0 \qquad (7)$$

Where k is a constant.

Finally, it results that for having a raised sensitivity it is necessary to raise:

a) the excitation current or

b) the turns number of the windings, especially the primary winding (otherwise this helps in obtaining a saturated core). The frequency increasement contributes a little in sensitivity increasement and produces as well the leakage in magnetic material increasement.

III. THE MAGNETIC INDUCTION MEASUREMENT PROBE CALIBRATION

Following the upper conclusions, a Förster probe with permaloy core, having a section of approximately 3 mm^2, has been realised.

Measurement schematic of a dc magnetic field is presented in fig. 3. The signal generator SG, delivers a sinusoidal signal with fix or adjustable frequency and is connected to the Förster probe through the capacitor C. It is important that the input probe signal is purely

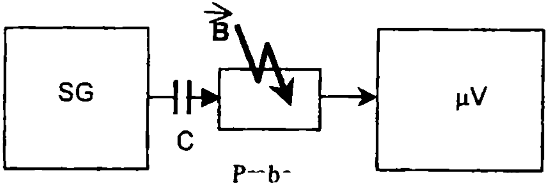

Fig.3 Measuring schematic with selective voltmeter

sinusoidal, without distortions or dc component, because the presence of this dc component could lead to an additionally magnetization of the core and therefore to the appearance of measurement errors.

The selective microvoltmeter μV, has at the signal input a band-pass filter with a rejection factor with respect to the central frequency, that can be adjusted two level, 25 dB respectively 40 dB, concerning the desired selectivity extraction of the measured signal. The input voltmeter signal can be measured directly or passed through the filter that can be adjusted for the desired frequency. As well, at the output of the voltmeter, an oscilloscope can be connected for the visualization of the measured signal.

In this schematic, the selective voltmeter frequency is adjusted to a double frequency in respect to the generator frequency, choosing in this way the measurement of the second order harmonic component.

The measurement schematic calibration has been [illegible] using the Helmholtz inductors; the Förster probe has been placed in the middle of the Helmholtz inductors, with an east-west orientation, so that the dc terrestrial magnetic field that operates upon the probe to be canceled. The Helmholz inductors are supplied by a known dc current, a constant magnetic field will be generated, and the voltmeter tuned on the frequency second order harmonic component, will indicate a proportional value of the measured magnetic field.

In the calibration experiment have been used:

- The magnetic field generator (Helmholtz inductors), [illegible]. k_B = 596 μT/A known with an error δ= ± 0,5%.
- Digital multimeter type M3650D, accuracy class 0,5 ± 1 digit
- Selective nanovoltmeter Unipan, type 237, accuracy class 1,5.

After the calibration the dc magnetic field measurement constant has been obtained:

$$k_c = \frac{k_B \cdot I}{U} = 0{,}476\ \mu\text{T/mV} \qquad (8)$$

The measurement uncertainty will be equal with [5]:

$$\sigma_B = \sqrt{\left(\frac{I}{U}\cdot\frac{k_B\delta_B}{100\sqrt{3}}\right)^2 + \left(\frac{k_B}{U}\cdot\frac{cl_A I}{100\sqrt{3}}\right)^2 + \left(\frac{k_B I}{U^2}\cdot\frac{cl_V\cdot U}{100\sqrt{3}}\right)^2} = \qquad (9)$$

$$= \frac{k_B I}{U}\frac{1}{100\sqrt{3}}\sqrt{\delta_B^2 + cl_A^2 + cl_V^2} = 0{,}005\ \mu\text{T/mV}$$

That corresponds to an approximately deviation of 1%.

In fig. 4 is represented the dependency between the output voltage and the frequency for a supply current and an external constant induction, revealing the sensitivity dependency with respect to the square root frequency, but if the frequency is large, the sensitivity stay near constant because the loss in magnetic core is grown

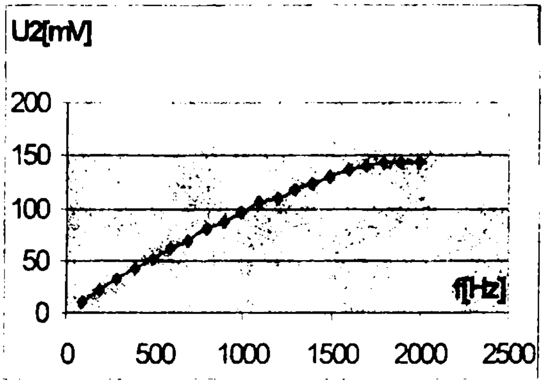

Fig. 4. The dependency between the output voltage and the frequency

In fig. 5 is represented the output voltage dependency with respect to the excitation current.

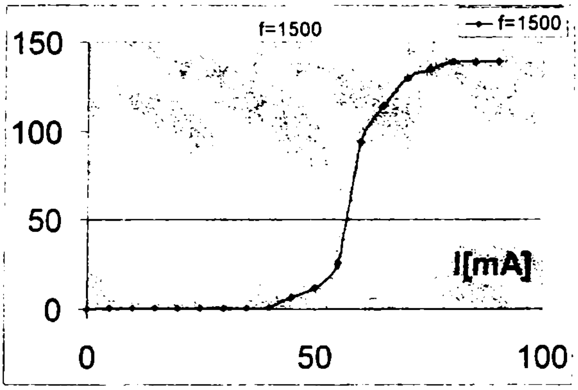

Fig. 5. The dependency between the output voltage and the excitation current

It is possible to observe that around 50 mA, the curve is a third order characteristic and when the current is greater than 50mA the curve becomes saturated.

The explanation of this effect consists of the fact, that at high magnetic field, the core is saturated and the hysterezis curve can be considered like a breaked line. In this case, for a sinusoidal magnetic field, the magnetic induction becomes trapezium.

For a trapezium signal (fig.6), the second harmonic component has the amplitude [6]:

$$U_2 = \frac{A}{2\pi^2}\frac{T_0}{t_c}\sin(2\pi t_c / T_0) \qquad (10)$$

Where, A is the amplitude of the trapezium signal, T_0 – the period of the signal and t_c – rising time.

If we have $t_c \ll T_0$, the sinusoidal function is approximated with its argument and the expression (10) becomes:

$$U_2 = \frac{A}{\pi} \qquad (11)$$

We can see that the second harmonic amplitude is independent of period and rising time.

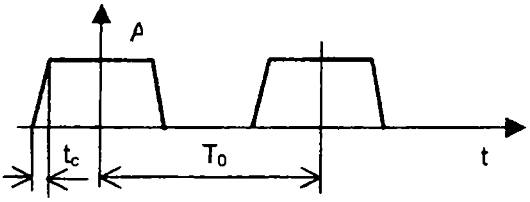

Fig. 6. Trapezium signal

Now, we suppose that we have two complementary trapezium signals, one of them positive and the second one – negative and a delay of $T_0/2$ between them, the first with an amplitude of $A+\Delta$ and the second with an amplitude of $A-\Delta$.

In this case, the amplitude of the second harmonic component will be:

$$U_2' = \frac{2\Delta}{\pi} \tag{12}$$

As a conclusion it can be said that the sinusoidal field applied to the Förster probe is large enough and the output voltage is dependently only on the continuous component.

IV. CONCLUSIONS

The measurement of a dc magnetic field, especially for low intensities, based on the Förster probe is a very sensitive method.

To obtain a large sensitivity and small errors it is necessary that the core of the probe is saturated.

We observe that the frequency of the sinusoidal magnetic field has to be of some kHz, because at larger frequencies, the loss of the magnetic material is bigger.

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