ABOUT THE CHARACTERISTICS OF A DC CURRENT TRANSDUCER WITH HALL SENSOR

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***Abstract* – In the field of power electronics and other industrial applications sensors for detecting a large DC current have a strong demand. The actual magnetic sensors have the core too large, and too heavy. The size of magnetic core may be reduced by using an adequate magnetic materials and Hall sensors. This paper presents the construction and characteristics of a DC current transducer with Hall sensor that uses a core of a new $Fe_{50}Ni_{50}$ sintered material. It explores ways of increasing the transducer sensitivity.**

***Keywords*:** *current transducer, magnetic circuit, Hall sensor, characteristics.*

1. INTRODUCTION

In many applications - automotive systems, motors, robots, industrial measurement instrumentation, power electronics - the systems must be capable to of operating reliably through high values of DC currents. In order to measure the continuous currents of high values, there may be used external shunts or DC transducers.

The regular shunts, with voltage drop ΔU = 65 mV for the nominal current, used for measuring the high currents (I >10^2A) have the disadvantage of relatively high power losses on the resistance of the shunt.

The current transducer with Hall sensor allows the measurement of the continuous currents within a wide range of values. Comparatively to the shunt, this transducer displays the following advantages:

- more reduced voltage drop than in the case of a shunt;
- galvanic insulation between the circuits (the current to be measured and the measuring part);
- possibility to change the field of measurement through the modification of the number of turns or through the adjustment of the command current of the sensor.

In this paper a new DC current transducer with Hall sensor is proposed.

2. OPERATING PRINCIPLE OF THE CURRENT TRANSDUCER

The sensors based on the Hall effect are realized out of semi-conductive materials [1]-[3].

The sensor is provided with four electrodes, two used for the introduction within the circuit of the current source I_s and the other two for the collection of the voltage U_H (see Fig. 1).

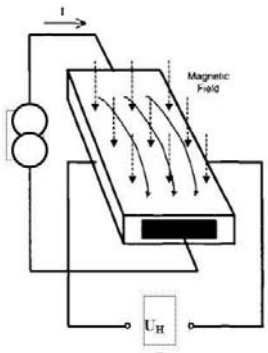

Figure 1: The structure and connection of a Hall sensor.

The Hall voltage U_H is given by the relation:

$$U_H = k_H B \cdot I_c \qquad (1)$$

where:

k_H – constant that depends on the material and on the technology of the sensor,

I_c – control current of the sensor.

If the control current I_c is maintained constant (generator of constant current) the voltage depends on the magnetic induction B that, in its turn, depends on the current to be measured I_x.

The rise in sensitivity of the Hall sensor may be obtained through the introduction of the sensing element within the air gap of a ring built of the ferromagnetic material with high magnetic permeability [4], [5].

The recent magnetic nano-materials have had a strong attention for constituting high-performance sensors and transducers, due to their characteristics: quick response with the variation of the measurement signal, robustness and insensitivity against mechanical vibration, high signal-to-noise ratio [6], [7].

The amorphous alloys [8], [9] suitable may be (see Table 1):

- Fe based alloys with high saturation polarization,

- Fe-Ni based alloys, with intermediate saturation polarization and excellent soft magnetic material properties,
- Co based alloys, with near-zero magnetostriction, excellent soft magnetic material properties and insensitivity to mechanical stresses.

Alloy	J_s, T	H_c, A/m	$\mu_{r\,I}$, 10^5	$\mu_{r\,max}$, 10^5
$Fe_{80}B_{20}$	1.6	3.2	1	3.2
$Fe_{81}Si_{3.5}B_{13.5}C_2$	1.61	3.5	1	2.6
$Fe_{40}Ni_{40}P_{14}B_6$	0.75	0.6	1.5	4.0
$Fe_{40}Ni_{40}Mo_4B_{18}$	0.88	1-4	1.5	2.0
$Co_{58}Ni_{10}Fe_5(SiB)_{27}$	0.55	1.0	1	2.0
$Co_{66}Fe_4(MoSiB)_{30}$	0.55	0.3	1	3.0

Table 1: Magnetic characteristics of some magnetic alloys.

The magnetic field $H(I_x)$ is obtained through the passage of the current to be measured I_x through the winding, consisting in w turns, disposed on the ferromagnetic core of toroidal shape (see Fig. 2).

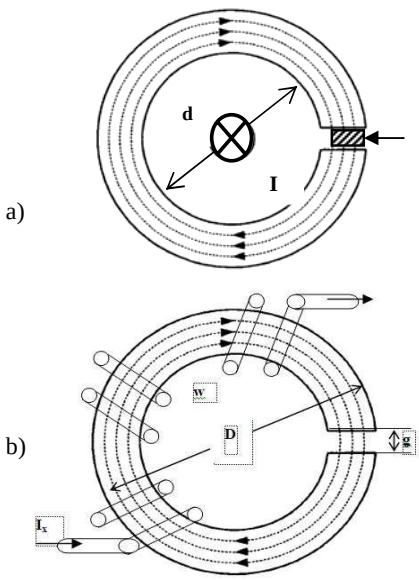

Figure 2: Magnetic circuit of the current transducer: a) w=1, b) w>1.

The geometrical characteristics of the magnetic core and the placement of the magnetization winding are shown in Figure 2.
In the case of the high currents, the magnetization winding may consist in a single loop (see Fig. 2.a). Within the air gap g ($g << \pi \cdot D$) there will be introduced the Hall sensor.

The value of the magnetic induction B within the magnetic circuit, without air gap that the relative magnetic permeability μ_r=const. may be calculated through the relation:

$$B = \mu_0 \mu_r \cdot \frac{w}{\pi \cdot \frac{D+d}{2}} \cdot I_x \qquad (2)$$

The induction B_a for the magnetic circuit with air gap is calculated through the relation [1]:

$$B_a = \mu_0 \mu_r \cdot \frac{w}{\pi \cdot \frac{D+d}{2} + \mu_r \cdot g} \cdot I_x \qquad (3)$$

When the relative magnetic permeability μ_r is high, about 2-5 10^4 in the case of the sintered material, there being fulfilled the condition $\mu_r \cdot g >> \pi \cdot \frac{D+d}{2}$, the induction B_a may be approximated with the relation:

$$B_a \approx \mu_0 \cdot \frac{w}{g} \cdot I_x \qquad (4)$$

From the relation (4) there may be noted that the induction B_a depends in direct proportion of the number of turns w and the current to be measured I_x that ensures the magnetization and in indirect proportion of the size of the air gap g in which there is introduced the Hall sensor.
It can be noted that the domain of I_x measurement current depends on the magnetisation characteristic *B(H)* of the magnetic core with air gap.
With the rise of the value of the air gap g the domain of linearity of the magnetization characteristic *B(H)* rises in its turn, however because of the diminution of the slope, the sensitivity of the current transducer diminishes [3].

3. EXPERIMENTS, RESULTS AND DISCUSSION

Soft magnetic materials proposed to be used are obtained from a nickel-iron mixture of powders [6].
The samples of ferromagnetic material were obtained through the metallurgy of the powders: obtaining the mixture of ferromagnetic powders, pressing and sintering.
The soft magnetic FeNi rings for DC transducer (Ø44 x Ø30 x 9,5 mm, with equivalent area A=60 mm^2) were prepared by sintering method using fine particles (~ 100 μm) of Fe 50% and Ni 50%.
The 1120°C and 1240°C sintering temperatures and three different pressure values of 600 MPa, 730 MPa and 850 MPa were used.

The structure of the samples was investigated by X-ray diffraction method. The magnetic properties were analyzed.
The thermomagnetic analysis in low and constant magnetic field was performed in order to analyze the magnetic phase homogeneity and to determine the Curie temperature of after sintering procedure.
The minor and major dynamic hysterezis loops in alternative magnetic field with frequency of 50 Hz were measured and analyzed.
The obtained magnetic properties in constant and alternative magnetic field are compared and correlated with the density and structural properties of the samples.
The $Ni_{50}Fe_{50}$ alloy with the sintering parameters of 1240^0C temperatures and the pressure value of 600 MPa shows the highest initial and maximum permeability in low fields $\mu_{rmax} \approx 10^4$ and a good linearity up to B=0.8 T.

For such a sintered torus, there will be practiced en air gap equal to the thickness of the Hall sensor resorted to. In the case of the experiment carried out g=3 mm in order to allow the introduction of a Hall sensor of type βH1.
The command current I_c of the Hall sensor is obtained from *dc* voltage (+V) and with a generator of constant current carried out with the integrated circuit *IC*1 type LM 117 (see Fig. 3).

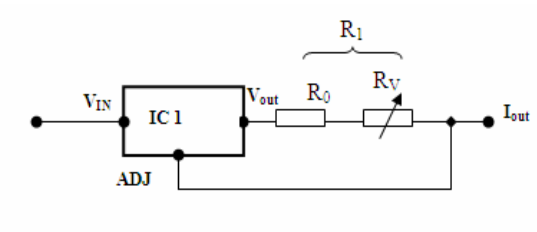

Figure 3: Scheme of the generator of constant current.

The adjustment of the current I_c=I_{out} may be carried out, according to the producer's indications, through the modification of the value of the resistance R_1 ($R_1 = R_0 + R_v$) with the relation:

$$I_c = \frac{V_{ref}}{R_1} = \frac{1.25}{R_1} \qquad (5)$$

The continuous voltage V_{in} from the inlet of the current generator is obtained from the voltage of the network through a low power transformer, a rectifier and a network filter.
The circuit consisting in the resistance R_1 (150 Ω) was calculated in order to obtain a command current I_c=10 mA ±20%.

The Figure 4 shows an image of the DC current transducer, realized and tested at values of the measured current I_x <10 A.

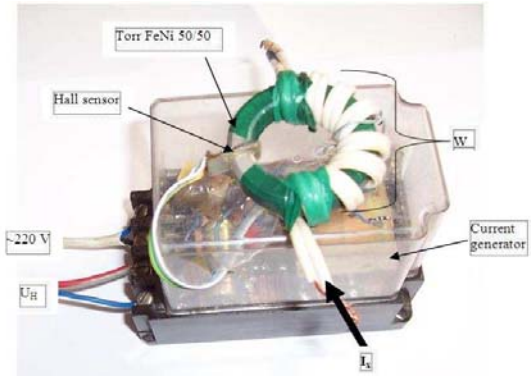

Figure 4: Practical realization of a DC current transducer.

The dependence $U_H(I_{xe})$ of the Hall voltage on the equivalent value of the current to be measured, obtained for w_1=15.5 turns and w_2=30 turns at I_c=9 mA is displayed in Figure 5.

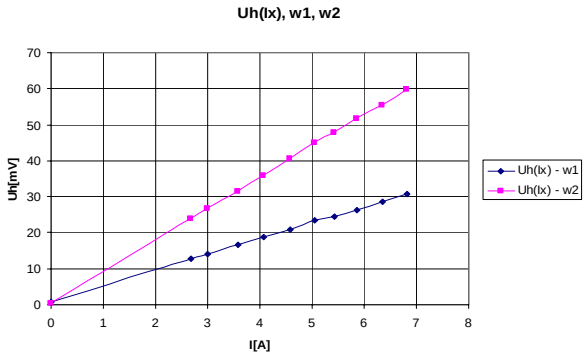

Figure 5: Dependence $U_H(I_{xe})/I_c$=9 mA.

The simulation of the functioning of the transducer at values of the current w-times higher is carried out through the modification of the number of turns w of the magnetization winding.

This way, if there is obtained a value of the voltage U_H for a current I_{x1} that goes through w of the magnetization winding, the same voltage will be obtained for I_{x2}=w I_{x1}, when w=1 (I_{xe}=w I_x).

In Figure 6 there is indicated the dependence of the Hall voltage on the equivalent current for the mentioned number of turns w_1 and w_2.

From the characteristic presented in figure 6 there is noted the linear dependence on the entire variation interval of the current, respectively a direct

proportionality of the generated voltage U_H to the number of turns of the magnetization winding.

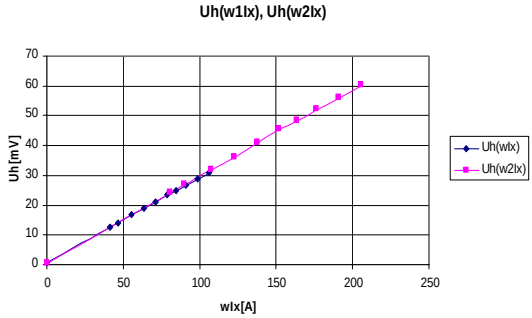

Figure 6: Dependence $U_H(w_1I_{xe})$ and $U_H(w_2I_{xe})$/ I_c=9 mA.

The sensitivity of the current transducer S_I [mV/A] may be determined through the relation:

$$S_I = \frac{\Delta U_{Hall}}{\Delta I} \tag{6}$$

The rise in sensitivity may be obtained through the use of a continuous current amplifier for the voltage of the Hall sensor.

This way, through the introduction of a voltage amplification A_U the sensitivity of the current transducer S_I rises in direct proportion to the value of the amplification.

The working field of the current transducer is set in accordance with the limits within whom the magnetisation characteristic of the magnetic core with air gap is linear.

4. CONCLUSIONS

The current transducer with Hall sensor stands for a manner of measurement of the continuous current within a wide field of values with the mentioned advantages.

The magnetic material of $Ni_{50}Fe_{50}$ alloy used as magnetic core may satisfy the requirements of a DC current transducer.

The precision of the measurement depends on the following factors: linearity of the magnetization characteristic of the core, linearity and stability of the characteristic of the Hall sensor, presence of the perturbing magnetic fields.

Every one of these sources of errors may be analyzed concretely and minimized. This way, the linearity of the characteristic of the sensor and of the magnetization characteristic of the core is improved through the use of Hall sensors and of magnetic materials for whom with air gap there is obtained a linear dependence within a field as great as possible. The attenuation of the perturbing fields may be done through a magnetic screening of the transducer.

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