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A CONTACTLESS TWO-SENSOR DC TRANSDUCER – TRANSDUCTION FUNCTION ANALYSIS

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Abstract − In the paper the design and operation principle of a contactless two-sensor DC transducer is presented. The operation of the transducer makes use of the signal yielded by two fluxgate sensors based DC transducer situated at a certain distance from the wire traversed by the current to be measured. The proposed geometrical arrangement of the sensor makes the transduction accuracy less sensitive to inaccurate keeping the distance between the sensor and the wire flowed through by the current to be measured.

Keywords: contactless DC transducer, fluxgate sensor

1. INTRODUCTION

In papers [1] transductor-based magnetic field sensors used in contactless DC transducers not embracing the current-carrying wire have been presented.

The starting point for constructing the sensors was the experience gained while testing a contactless transducer for high DC magnitudes that is based on a sensor, which utilises a specially designed permalloy-made core [2]. The most obvious limitation of the transducer mentioned in [1] is that the transduction accuracy is strongly dependent on how the transducer is arranged geometrically in relation to the wire flowed through by the current to be measured. The following two parameters play a crucial part in transduction: the distance between the sensor and the wire axis, and the length of the current-carrying wire.

The influence of the latter factor decreases as the wire length increases, and the distance between the transducer and the wire decreases. In addition, the transducer accuracy depends on the geometry of the sensor core, and more precisely, on the ratio between the sensor's dimensions and the wire length. To make this factor less influential the dimensions of the sensor should be made smaller. This can be achieved by employing only a fragment of the moulding shown in [2].

The second factor, which exerts influence upon transduction accuracy, is the distance between the sensor and the current-carrying wire axis. The distance can be taken into account when calibrating the transducer and made fixed by employing appropriate distance elements. However, this can be done accurately only if the wire diameter is known, as the distance is reckoned from the wire axis. In case of wires having a different diameter than that assumed, a substantial measurement error may occur.

In [3] a measurement method has been presented that is free from the above-mentioned limitations (Fig. 1).

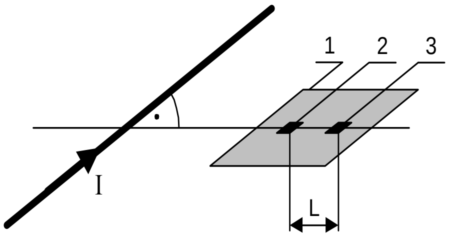

Fig.1. Current measuring using two Hall generators [3].
1 – linking element; 2, 3 – Hall generators

In this approach two Hall generators have been used that are positioned at a strictly defined distance one from the other along a straight line being perpendicular to the wire. The Hall generators must be situated in the same measurement plane as the wire axis does. These requirements are hard to be met in measurement practice. The method requires employing an appropriate computing system, since the current flow in the wire is given by the following relationship [3]

$$I = c \cdot \frac{2\pi L U_3}{\mu_o \left[1 - \frac{U_3}{U_2} \right]} \tag{1}$$

where L is the distance between the Hall generators, and U_2, U_3 are Hall voltages.

2. TWO FLUXGATE SENSORS BASED CONTACTLESS DC TRANSDUCER

Another approach to reduce the effect the sensor-wire distance exerts on the transducing accuracy is to employ two arbitrary magnetic field sensors arranged in another way than that shown in [3]. In the paper an analysis of such measuring systems for fluxgate based sensors has been carried out.

2.1. A fluxgate sensor: design and mode of operation

Figure 2 shows diagrammatically a fluxgate based magnetic field sensor [1] and its arrangement in relation to

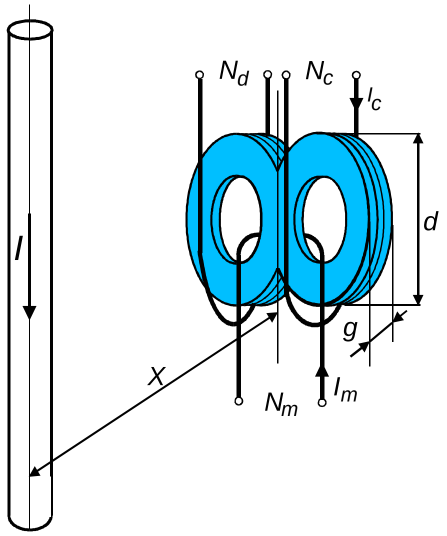

Fig. 2. Diagram of the fluxgate magnetic field sensor and its arrangement in relation to the wire flowed through by the current to be measured

the wire traversed by the current to be measured. The sensor core is composed of two moulding permalloy elements assembled [2]. The magnetizing winding N_m has been threaded through the core holes, and then the following windings have been applied throughout the core length, namely the detecting N_d and the compensating N_c ones.

The transducer co-operates with a typical automatic DC comparator [4], which consists of a magnetizing current generator. The block diagram of the transducer is shown in Fig. 3.

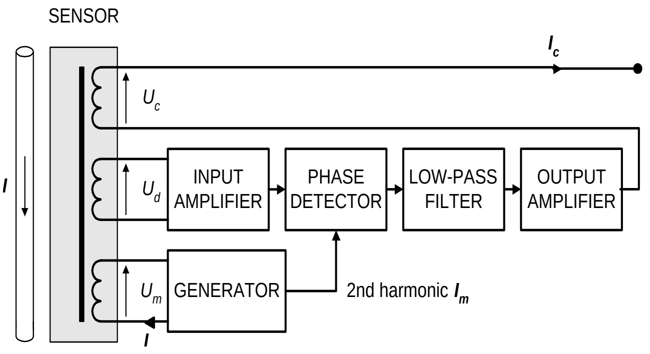

Fig. 3. Block diagram of the contactless DC transducer

The operation principle of the transducer is the following. A long wire is traversed by the current I to be measured, which creates a magnetic field. The intensity of the field H at a point being at a distance X from the wire axis, hence in the sensor's plane, may be given as

$$H = \frac{I}{2\pi X} . \qquad (2)$$

The sinusoidal magnetizing current I_m brings into saturation that part of the core, which bears the magnetizing winding N_m. Because of saturation, the magnetic field of intensity H given by (2), which threads the core, does not affect the core flux. However, when the core is not saturated, i.e. in the magnetizing current zero-crossing area, the core flux generated by the external field does increase. This results in inducing an U_d voltage, in which second harmonic of the magnetizing current is dominant, in the detecting winding N_d. After having been amplified U_d is passed to a phase-sensitive detector driven by the second harmonics of the magnetizing voltage. The detector output voltage, after averaging, drives the output amplifier, which forces in the compensating winding N_c a current flow I_c such that the voltage across the detecting winding N_d be equal zero.

The sensor shown in Fig. 2 is a compensating one. The external magnetic field is being compensated by a field produced by the compensating current flow I_c, through the compensating winding N_c.

Taking into account the geometrical arrangement of the sensor and the current- carrying wire (Fig. 2), at the state of compensated fluxes in the sensor's core, the current to be measured I and the output compensating current I_c, are interrelated approximately by

$$I_c = \frac{k\,\lambda\,d}{\pi\,N_c X}\,I \qquad (3)$$

where:

k – coefficient, which takes care of the arrangement geometry, including the finite current-carrying wire length and influence of the sensor's core on the magnetic field produced by the current-carrying wire;

d – external diameter of the sensor's core element (Fig. 1);

λ – coefficient, which takes care of the compensating flux leakage.

2.2. Two sensors based contactless transducer

To reduce the effect of imprecision in keeping the designed distance between the sensor and the axis of the current-carrying wire one may employ two sensors shown in Fig. 2 geometrically arranged as in Fig. 4.

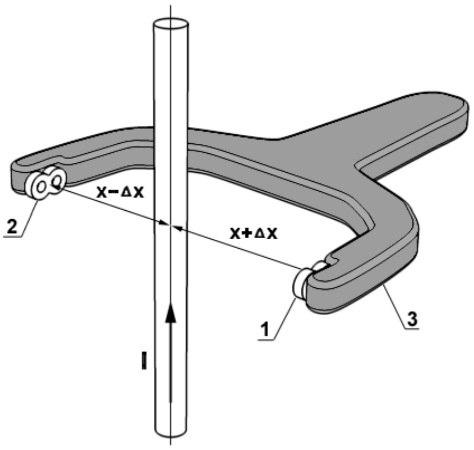

Fig. 4. Geometrical arrangement of the two fluxgate sensor based transducer in relation to current-carrying wire. 1, 2 – sensors, 3 – holder

In this arrangement two fluxgate based sensors are placed on a holder at a distance of $2X_0$ apart and symmetric about the wire flowed through by the current to be measured.

The transducer output signal is a sum of compensating currents delivered by both sensors

$$I_{out} = I_{c1} + I_{c2} \tag{4}$$

Assuming that both sensors are identical and the system is fully symmetrical, (3) can be rewritten in terms of (2) as

$$I_{out} = 2\frac{k\,\lambda\,d}{\pi\; N_c\; X} I \tag{5}$$

As may be seen, the transduction sensitivity is doubled. In practice, the assumption that the system is fully symmetrical is hardly feasible.

Let the initial distance X_0 between the sensors and the current-carrying wire be kept with an accuracy of $\pm \Delta X$

$$X = X_0 \pm \Delta x \tag{6}$$

With this, (3) becomes

$$I_{out} = \frac{k\,\lambda\;d}{\pi\,N_c}\left(\frac{1}{X_0+\Delta x}+\frac{1}{X_0-\Delta x}\right)I \tag{7}$$

Taking into account that in practice $\Delta X << X_o$, after expanding (7) into a series and neglecting the high-power terms we get

$$I_{out} \approx 2\frac{k\,\lambda\,d}{\pi\,N_c\,X_0}\left[1+\left(\frac{\Delta x}{X_0}\right)^2\right]I \tag{8}$$

As may be seen from the approximate transduction function given by (8) the output compensating current is considerably less affected by the imprecision in keeping the designed distance X_o between the sensor and the current-carrying wire axis. In case of the one-sensor transducer, an imprecision in keeping the desgined distance $\Delta X = 0.1\,X_o$ yields a measurement error of 10 %, as follows from (3).

In case of the two-sensor transducer the same level of imprecision will result in a measurement error being by an order of magnitude lower, i.e. 1 %, as follows from (8).

Another factor determining the transduction accuracy is the sensor displacement in relation the axis of the current-carrying wire. Such a displacement usually takes place in actual measurement practice.

Figure 5 shows schematically the geometrical arrangement of the sensors in the case that the axis linking both sensors, which are $2X_0$ apart, is perpendicular to the axis of the current-carrying wire, however without intersecting it. The former axis is shifted in relation to the latter one by the P segment to the nominal axis in relation to which the transducer has been calibrated.

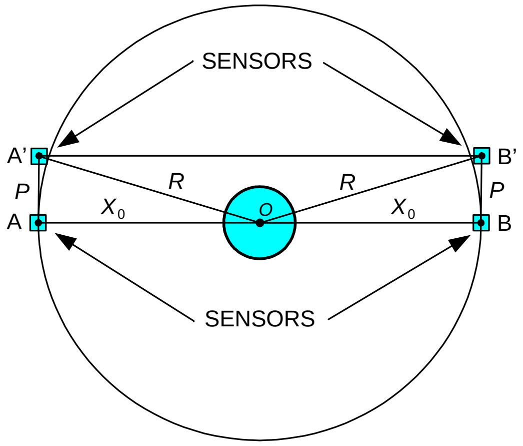

Fig. 5. Geometrical arrangement of the two sensors A, B in situation when they are shifted into A', B' position

From geometrical relationships depicted in Fig. 5 it follows obviously that

$$X_0^{\,2} + P^2 = R^2 \tag{9}$$

where R is the new distance from the sensors to the axis of the current-carrying wire.

It is assumed here that sensors are relatively small and amount to mass points being R distant from the wire axis. Such an assumtion has also been made while deriving (3). Another assumtion made here is that both sensors are situated symmetrically being R distant from the wire axis.

An increase in the distance between the sensor and the wire axis (Fig. 5) is

$$\Delta X = R - X_0 = \sqrt{X_0^{\,2} + P^2} - X_0 \tag{10}$$

whence, taking into account that

$$P << X_0 \tag{11}$$

usually holds, we get from (10)
Substituting (12) into (5) yields

$$\Delta X \cong \frac{1}{2}\frac{P^2}{X_0} \tag{12}$$

Hence, an increase in the distance between the sensor and the wire axis is directly proportional to the axis displacement P squared and inversely proportional to the distance X_0.

Substituting (12) into (5) yields

$$I_{out} = \frac{2\,k\,\lambda\,d}{\pi\,N_c\left(X_0+\Delta X\right)}I = \frac{2\,k\,\lambda\,d}{\pi\,N_c\left(X_0+\dfrac{P^2}{2X_0}\right)}I \tag{13}$$

whence, after some rearrangements, we obtain

$$I_{out} \approx 2\frac{k\,\lambda\,d}{\pi\,N_c\,X_0}\left[1-\frac{1}{2}\left(\frac{P}{X_0}\right)^2\right]I \tag{14}$$

The expression in square brackets

$$\delta \approx -\frac{1}{2}\left(\frac{P}{X_0}\right)^2 \tag{15}$$

represents a transduction error being dependent on the P/X_0 ratio.

As may be inferred from (15) and its plot shown in Fig. 6, the effect of the transducer axis displacement on the transduction accuracy is insignificant, especially for small values of the P/X_0 ratio. This is attributable to the form the magnetic field takes around the wire carrying the current to be measured. The greater is the initial distance X_0, the smaller is the effect the axis displacement P exerts on the transduction accuracy. Essentially, this effect is negligible for $P/X_0 << 0.1$ assuming the transduction accuracy should be of the order of several percent.

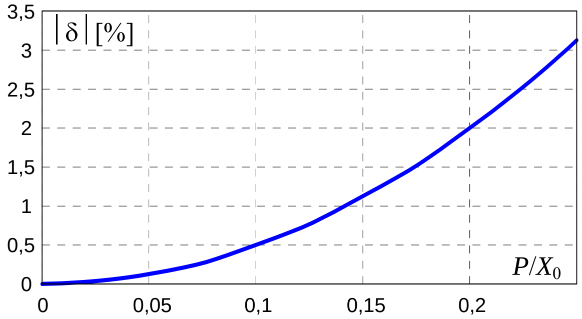

Fig. 6. Transduction error magnitude |δ| vs. P/X_0 ratio

For higher P/X_0 values the relationships given by (14) and (15) are approximate only. This is due to directional characteristics of the sensors [5] and to the fact that sensors have been assumed as being mass points only.

3. CONCLUSIONS

The proposed two-sensor transducer enables one to reduce significantly the effect of imprecision in keeping the designed distance between the sensor and the current-carrying wire on transduction accuracy.

Practically, the effect may be ignored, since transducers of this type deliver results affected by an error of several percent. Although the use of the presented measurement approach requires that two magnetic field sensors and a dualised measurement system should be employed, no computing circuits are needed.

The proposed transducer has been based on fluxgate sensors owing to advantages they offer, viz. high sensitivity and suitability for being employed in compensating transducers. Here the field detection and compensation takes place in the permalloy core of sensors. However, any other magnetic field sensors [6-8] may also be applied to the two-sensor transducer being geometrically arranged as presented above.

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