SECTION: MECHANICS AND ELECTRICAL ENGINEERING

CALCULATION OF THE INDUCTION MAGNETOMETRIC TRANSDUSER AS PULSE CURRENT METER AND EXPERIMENTAL MEASUREMENT OF PULSE CURRENT AND VOLTAGE IN AN ACCELERATION SYSTEM

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These scientific materials contains information on the basic theoretical provisions of the induction magnetometric transducer (IMT, Rogowski coil), namely its presentation, operating principle, calculation formulas for its main parameters, analysis of the IMT circuit with an integrator [1 – 4]. Also, it contains information on the combined voltage divider, its types, purpose, composition, basic calculation formulas. Also, it contains the stages of obtaining formulas for calculating the elements of the following circuits: voltage, impedance, division ratio.

The induction magnetometric transducer (IMT) is a toroidal multi-turn inductance coil with a load R_k connected to its terminals [1]. The operating principle of the inductive magnetometric transducer is explained in Figure 1.

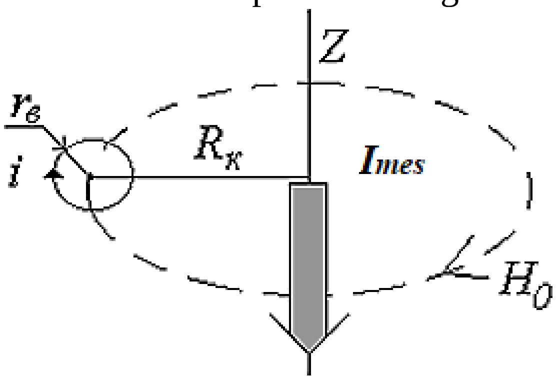


Figure 1 – The operating principle of the induction magnetometric transducer (IMT)

The measured current I_{mes} spreads along the Z-axis and penetrates the inductance coil L_k. The coil radius is denoted as R_k, and the loop radius as r_b. The magnetic field intensity along the axis of the coil loop is given by:

$$H_0 = \frac{I_{mes}}{2 \cdot \pi \cdot R_k}. \tag{1}$$

The directions of the current and magnetic field lines are shown in Figure 1 in accordance with the law of electromagnetic induction. If the coil structure satisfies the condition $R_k >> r_b$, the magnetic field distribution across the plane of the coil loop can be considered constant. Then, the electromotive force (EMF) at the terminals of a single loop is given by:

$$e_b = \int_{S_b} BdS = \pi \cdot r_b^2 \cdot \mu_b \cdot H_0, \tag{2}$$

where S_b – the area of the loop;

μ_b – the magnetic permeability of the medium filling the loop.

For a multi-turn coil, the total EMF is:

$$e_n = \sum_{m=1}^{N} e_{b_m}. \tag{3}$$

Considering equations (1) – (3) and applying Kirchhoff's second law, the voltage equation at the load resistance terminals of an n-turn coil is:

$$e_n = M \cdot \frac{dI_{mes}}{dt} = L_k \cdot \frac{di}{dt} + R_k \cdot i = \frac{L_k}{R_k}\frac{du_h}{dt} + u_h, \tag{4}$$

where M – the mutual inductance between the coil field and the measured current;

u_h – the voltage across the load resistance R_k.

Measurement of Short-Duration Pulse Currents τ_i. For pulse currents of short duration τ_i, the following condition applies:

$$\frac{L_k}{R_k} \gg \tau_i. \tag{5}$$

Neglecting the second term on the right-hand side of equation (4)

$$M \cdot \frac{dI_{mes}}{dt} = \frac{L_k}{R_k} \cdot \frac{du_h}{dt}.$$

The fundamental equation for the sensitivity of the inductive magnetometric transducer (IMT, Rogowski coil) is:

$$u_h = \frac{R_k \cdot I_{mes}}{n}. \tag{6}$$

This equation shows that the sensitivity of the IMT is inversely proportional to the number of coil turns [1 – 4]. The expression (6) is independent of the relative orientation of the current and the coil; it is only important that the loop encloses the entire measured current. If the condition (5) is not met, or the opposite inequality holds $L_k / R_k \le \tau_i$, the IMT differentiates the measured current:

$$u_h = M \cdot \frac{dI_{mes}}{dt}. \tag{7}$$

To obtain an output voltage proportional to the measured current, an integrator is used (Figure 2). The simplest integrating circuit is typically an RC filter.

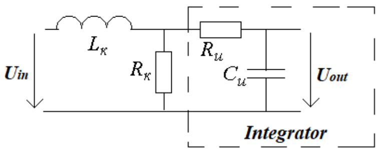


Figure 2 – Rogowski coil circuit with an integrator

The integrator is calculated as follows. Kirchhoff's equation for the second loop of the circuit in Figure 2 is:

$$u_{r_2} = U_{out} + C_u \cdot R_u \cdot \frac{dU_{out}}{dt}. \tag{8}$$

If the time constant $C_u \cdot R_u$ is chosen so that the first term in equation (8) can be neglected:

$$U_{out} \gg C_u \cdot R_u \frac{dU_{out}}{dt}, \tag{9}$$

$$u_{r_2} \approx C_u \cdot R_u \cdot \frac{dU_{out}}{dt}. \tag{10}$$

Considering the condition $u_h = u_{r_2}$ and formula (7), the output voltage becomes:

$$U_{out} \sim I_{mes}. \tag{11}$$

Expression (11) shows that the output voltage of the integrator is proportional to the current being measured. Condition (9) allows us to estimate the integrator parameters. Thus, if we set

$$C_u \cdot R_u = 10 \cdot \tau_u,$$

where τ_u – the duration of the measured current pulse.

From this expression, the values of capacitance C_u and resistance R_u can be determined. The sensitivity ε of the IMT with an integrator is obtained from expressions (7) and (10):

$$U_{out} = \frac{M}{C_u \cdot R_u} \cdot I_{mes} = \frac{L_k}{n \cdot C_u \cdot R_u} \cdot I_{mes}; \tag{12}$$

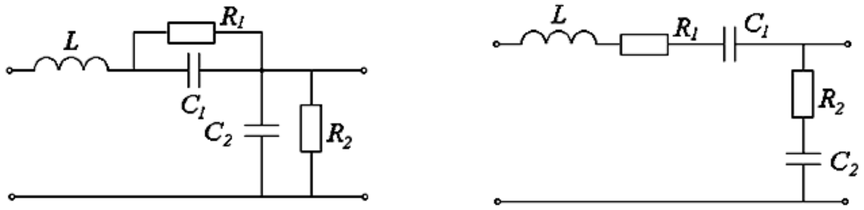
$$\varepsilon = \frac{U_{out}}{I_{mes}} = \frac{L_k}{n \cdot C_u \cdot R_u}. \tag{13}$$

Thus, increasing the time constant reduces sensitivity. Therefore, measuring weak currents while using an integrator requires additional signal amplification. Another way to increase the time constant while maintaining sensitivity is by using an active integrator based on an operational amplifier.

The inductive magnetometric transduser is constructed as a multi-turn toroidal coil wound on a dielectric base. In this design, the converter itself forms a loop in which current can be induced by an external magnetic field. To compensate for the effect of the axial magnetic field, a return conductor is used, connected in series with the coil.

For noise protection, the inductive magnetometric transduser is shielded with a conductive housing. To prevent demagnetization effects, the shield has a longitudinal slit.

Voltage Measurement Using a Combined Divider. To measure high-voltage pulses in acceleration technology, resistive, capacitive, and combined dividers are used [5 – 7] (Figure 3).



a) b)

Figure 3 – Voltage divider circuits

The purpose of voltage dividers is to reduce the measured voltage without significant distortion of the pulse waveform to a level sufficient for its registration by the measuring instrument without the risk of damaging it. The divider consists of two sections: the upper high-voltage section and the lower matching section. To achieve the required electrical strength, the upper section of the divider contains the necessary number of resistors connected in series. In the case of measuring voltages at the megavolt level, cascade connection schemes of dividers may be used. The choice of the divider scheme depends on the characteristics of the output impedance of the voltage source, its size, geometry, and the input impedance of the measuring instrument.

Under ideal conditions, when the voltage source has zero impedance and the input resistance of the measuring instrument is infinite, a resistive divider is used, and the output voltage of the circuit (Figure 3a) is given by:

$$U_2 = \frac{R_2}{R_1 + R_2} \cdot U_1 = K_\partial \cdot U_1, \tag{14}$$

where K_∂ – division coefficient.

As a rule, for high–voltage dividers, the general ratio between the total impedances of the sections is maintained $Z_1 \gg Z_2$. In this case, the division ratio is:

$$K_\partial = \frac{R_2}{R_1}. \tag{15}$$

In real cases, the output and input impedances have a capacitive nature. Additionally, the large geometric dimensions of high-voltage installations require consideration of the inductance of the connection circuit. Therefore, to compensate for the distortion effects of the reactive impedance components, combined resistive-capacitive dividers are used (Figure 3b).

Figure 3a shows a circuit with a parallel combined voltage divider, while Figure 3b presents a circuit with a series combined voltage divider. The condition for the frequency independence of the divider's transfer coefficient is:

$$R_1 \cdot C_1 = R_2 \cdot C_2 . \quad (16)$$

When the given condition is met, expression (14) holds for the division ratio. Additionally, the parameters of the divider must ensure the suppression of the oscillatory transient process caused by the parasitic inductance of the circuit L.

Measurement of Pulsed Current Using an Inductive Magnetometric Transducer (IMT) [6,8,9]. The IMT is based on Faraday's law of electromagnetic induction:

$$\mathrm{E}(t) = -\frac{d\Phi(t)}{dt}, \quad (17)$$

where $\mathrm{E}(t)$ – electromotive force (EMF) induced in the measurement coil;

$\Phi(t)$ – magnetic flux through the coil.

Since the magnetic flux is related to the current through the law of total current (generalized Ampère's law):

$$\Phi(t) = L_m \cdot I(t), \quad (18)$$

where L_m – the inductance of the magnetic system, we obtain:

$$\mathrm{E}(t) = -L_m \cdot \frac{dI(t)}{dt}. \quad (19)$$

Thus, knowing the signal shape $\mathrm{E}(t)$, the current can be reconstructed as:

$$I(t) = -\frac{1}{L_m} \cdot \int \mathrm{E}(t)\,dt . \quad (20)$$

Measurement of Pulsed Voltage Using an Inductive Magnetometric Transducer (IMT) [6,8,9]. Pulsed voltage $U(t)$ can be measured using high-frequency voltage dividers or capacitive sensors. If a capacitive divider with a division factor k is used:

$$k = \frac{C_1}{C_1 + C_2} . \quad (21)$$

Then the output voltage $U_{out}(t)$ is related to the input voltage $U(t)$ as:

$$U_{out}(t) = k \cdot U(t). \quad (22)$$

From this, the input voltage can be found as:

$$U(t) = \frac{U_{out}(t)}{k}. \quad (23)$$

For a resistive divider:

$$U_{out}(t) = \frac{R_2}{R_1 + R_2} \cdot U(t). \quad (24)$$

Differential methods can also be used, where the derivative of the voltage is measured:

$$E(t) = C \cdot \frac{dU(t)}{dt}, \quad (25)$$

and then is reconstructed by integration.

Reconstruction of Pulsed Voltage via Integration. In some cases, voltage is measured using a differential method, for example, when using capacitive sensors or high-frequency probes. In this case, the output signal of such a sensor represents the derivative of the voltage, equation (25). To reconstruct the voltage , the measured signal must be integrated:

$$U(t) = \frac{1}{C} \cdot \int E(t) dt + U_0, \tag{26}$$

where U_0 – the integration constant, determined from boundary conditions or known initial voltage values.

References

1. Ashish S. Paramane. 2014. Comparative Performance of Conventional Transducers and Rogowski Coil for Relaying Purpose. International Journal of Advanced Research in Electrical and Electronics Engineering, Volume: 1, Issue: 3, pp 93 – 100. ISSN_NO: 2321-4775

2. Ayob Nazmy Nanyan. 2018. The Rogowski Coil Sensor in High Current Application: A Review. IOP Conference Series: Materials Science and Engineering, Volume 318, 10 p. DOI: https://www.doi.org/10.1088/1757-899X/318/1/012054

3. Rudy Fernandez. 2019. Development of rogowski coil sensor for partial discharge detection. IOP Conference Series: Mat. Science and Eng., Volume 602, 6 p. DOI: https://www.doi.org/10.1088/1757-899X/602/1/012031

4. Huan Liu, Xiaobin Wang. 2021. A modular magneto-inductive sensor for low vector magnetic field measurements. Review of Scientific Instruments, Volume 92, 7 p. DOI: https://doi.org/10.48550/arXiv.2007.09893

5. E. Kuffel, W.S. Zaengl, J. Kuffel. 2000. High Voltage Engineering. Fundamentals (Second edition). Butterworth-Heinemann. ISBN 0 7506 3634 3

6. Klaus Schon. 2019. High Voltage Measurement Techniques. Springer Cham. DOI: https://doi.org/10.1007/978-3-030-21770-9 eBook ISBN: 978-3-030-21770-9

7. Y. Anokhin, V. Brzhezytskyi, Ya. Haran, I. Masliuchenko, O. Protsenko, Ye. Trotsenko. 2017. Application of high voltage dividers for power quality indices measurement. Electrical engineering & electromechanics, no.6, pp. 53 – 59. DOI: https://www.doi.org/10.20998/2074-272X.2017.6.08

8. Florian Krismer; Johann W. Kolar. 2010. Accurate Power Loss Model Derivation of a High-Current Dual Active Bridge Converter for an Automotive Application. IEEE Transactions on Industrial Electronics, Volume: 57, Issue: 3, March, pp: 881 – 891. DOI: https://www.doi.org/10.1109/TIE.2009.2025284

9. A. Sovlukov and V. Tereshin. 2003. Determination of liquefied petroleum gas quantity in a reservoir by radlofrequency techniques. Proceedings of the 20th IEEE Instrumentation Technology Conference (Cat. No.03CH37412), pp. 368-373. DOI: https://www.doi.org/10.1109/IMTC.2003.1208182