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Abstract

Full Text

ELECTRICAL ENGINEERING

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ON THE THEORY OF THE PHOTOELECTRIC FLUXMETER

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In articles on photoelectric fluxmeters ([1–4]) there is no common point of view on the operating principle of these instruments. In the present work, based on methods of the theory of automatic control and on the use of operational calculus in the interpretation of Heaviside-Mikusinski ([5]), the principal propositions of the theory of the fluxmeter are given, as well as a new method for estimating the accuracy of operation of devices of the photoelectric compensator type, replacing the method of frequency-phase characteristics and being considerably simpler.

Fig. 1. Block diagram of a photoelectric fluxmeter. *G*—galvanometer, *Ph. e.*—photoelectric bridge, *E. a.*—electronic amplifier, *D. e.*—differentiating element

All photoelectric fluxmeters can be represented by a single block diagram (Fig. 1), showing that these instruments in principle do not differ from operational amplifiers and, despite differences in structural design, have a common nature.

A fluxmeter is characterized by the following elements and their transfer functions (initial conditions are equal to zero):

1) Mirror galvanometer (overdamped mode)

$$W_g(s) = \frac{\beta N S_u}{(\tau_1 s + 1)(\tau_2 s + 1)}, \tag{1}$$

where S_u is the sensitivity ($\sim 10^3$ rad/V); τ_1 ($\sim 1 \div 10$ sec.) $> \tau_2$ ($\sim 10^{-2}$ sec.); β is a constant taking into account the load; N (~ 1 lm/rad) determines the luminous flux incident on the photoelements; s is the differentiation operator.

2) Photoelectric bridge (Fig. 2)

$$W_m(s) = \alpha\rho \frac{\tau_4 s + 1}{\tau_3 s + 1}; \tag{2}$$

$\alpha(\sim 10^{-4}$ A/lm) is the sensitivity of the photoelements; $\rho(\sim 10^9\ \Omega)$ is their differential resistance; $\tau_3 = \tau_4 + \tau_5$; $\tau_4 = RC$; $\tau_5 = \rho C$.

3) Direct-current amplifier

$$W_y = K = \text{const}\,(\sim 50). \tag{3}$$

4) Differentiating element

$$W_d(s) = \frac{\tau_d s}{\tau_d s + 1}, \tag{4}$$

$$(\tau_d \sim 10^{-4} \text{ sec.}).$$

The transfer function of the open-loop system is

$$W_0(s) = W_g W_m W_y = K_0 w_0(s), \tag{5}$$

where $K_0 = \alpha\beta\rho N S_u K = \text{const}$ $(\sim 10^8)$, and that of the closed-loop system is

$$(Ws) = \frac{W_0}{1 + W_0 W_d}. \tag{6}$$

It follows from (6) that the value of the output voltage of an ideal integrator is

$$U_{\text{id}} = \frac{1}{\tau_d}\int_0^t U_{\text{in}}\,d\theta = U + Er_1 + Er_2 + Er_3, \tag{7}$$

where U is the output voltage recorded by the recorder;

$$Er_1 = \frac{\int_0^t U\,d\theta}{K_0 \tau_d} \tag{8}$$

"creep" ;

$$Er_2 = \left(\frac{1}{w_0} - 1\right)\frac{\int_0^t U\,d\theta}{K_0 \tau_d} \tag{9}$$

Fig. 2

Figure 2: Fig. 2

frequency-phase distortions;

$$Er_3 = \int_0^t \left(\frac{W_d}{\tau_d} U - U'\right) d\theta \tag{10}$$

the error caused by the error of differentiation in the feedback circuit.

The solution found makes it possible to analyze the errors from the directly observed quantity—the output voltage—and to introduce a correction for the error caused by the form of the signal being measured. The analysis is based on taking into account the enormous magnitude of the circuit gain and on the lemmas:

$$\left|\frac{1}{\tau s + 1} U(t) - U(t)\right| < \tau \max |U'(t)|; \tag{11}$$

$$\left|\frac{1}{\tau s + 1} U(t)\right| < \max |U(t)|. \tag{12}$$

Fig. 2

According to (7)–(10), any stable circuit with large gain and with successive negative feedback through the derivative will integrate with a constant equal, to within the error $\sum Er_i$, to the time constant τ_d of the differentiating element. All instruments are identical with respect to creep (see (8)) and to the dependence of the error on the quality of differentiation (see (10)). The differences are contained in formula (9).

Let us consider two limiting cases:

1) $\tau_1 \sim 1$; $\tau_2 \ll 1$; $\tau_3 < 1$; $\tau_4 \ll 1$. Such fluxmeters will be called fluxmeters of the first group.
2) $\tau_4 \simeq \tau_1$ (the correction principle of S. P. Kapitsa) and $\tau_3 \to \infty$ ($\gg 10$)—the second group.

Representing (9) in the form

$$Er_2 = \frac{1}{K_0 \tau_d} \frac{1}{\tau_4 s + 1} \left(A_1 U'' + A_2 U' + A_3 U\right) \tag{13}$$

$$(A_1 = \tau_1 \tau_2 \tau_3; \quad A_2 = \tau_1 \tau_2 + \tau_2 \tau_3 + \tau_3 \tau_1; \quad A_3 = \tau_1 + \tau_2 + \tau_3)$$

and, applying (11) to (13), we find that for instruments of the first group

$$Er_2 \simeq \frac{1}{K_0 \tau_d} \left(A_1 U'' + A_2 U' + A_3 U \right) \tag{14}$$

with an error not exceeding

$$\Delta Er_2 = \frac{\tau_4}{K_0 \tau_d} \max \left| A_1 U''' + A_2 U'' + A_3 U' \right|, \tag{15}$$

(15) is much smaller than (14); consequently, (14) may be regarded as a correction.

For fluxmeters of the second group,

$$Er_2 = \frac{C_\varphi}{\tau_d} U + \frac{1}{K_0 \tau_d} \left[\frac{1}{\tau_4 s + 1} \left(B_1 U'' + B_2 U' + B_3 U \right) + B_4 U' \right] \tag{16}$$

$(B_1 = \tau_2 \tau_3 (\tau_1 - \tau_4), \quad B_2 = (\tau_2 + \tau_3)(\tau_1 - \tau_4); \quad B_3 = \tau_1 - \tau_4; \quad B_4 = \tau_2 \tau_3; \quad C_\varphi = \tau_3 / K_0$ — the time constant of the fluxmeter without feedback). A formula analogous to (15), because of the large τ_4, does not limit the lower bound of Er_2. In this case there remains an estimate of the error from above on the basis of (12). Since $B_4 \gg A_2$, the error of a fluxmeter of the second group is considerably greater than that of the first.

Taking into account the stability criterion found for both groups in the form

$$\tau_4 > \tau_d, \tag{17}$$

the theory makes it possible to calculate all parameters needed by the designer.

A more detailed theory evaluates the influence of leakages, amplitude distortions, and loads. The method set forth here remains valid.

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Note: Figure translations are in progress. See original paper for figures.