TOWARD A DYNAMIC THEORY OF THE REGENERATIVE OPTRON

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Abstract

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Academician of the Academy of Sciences of the Uzbek SSR É. I. ADIROVICH,
A. G. VISHNEVETSKII,
P. M. KARAGEORGII-ALKALAEV

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1. The foundations of the stationary theory of the regenerative optron with a photoresistor as the light receiver were developed in works ([1–7]). Nonstationary phenomena are determined by the inertia of the generation-recombination processes in the photoresistor, which is the most inertial element of the optron ([3,4]). Therefore, in formulating the dynamic problem one should modify only the equation of the photoresistor, leaving the description of all the other components and connections in the same form as for the stationary problem. The basic system of equations of the dynamic theory of the regenerative optron with a photoresistor can be written as follows:

$$\begin{gathered} V_{10} = V_1' + V_1; \qquad V_{20} = V_2' + V_2; \qquad B = B(B_1, B'); \\ I = GV_1'; \qquad V_2' = V_2'(I_2); \qquad V_1 = V_1(I_1, V_2); \\ dG/dt = f(G, B); \qquad B_1 = B_1(I_2); \qquad I_2 = I_2(I_1, V_2). \end{gathered} \tag{1}$$

Here $G = G_0 + G_\phi$ is the total conductance of the photoresistor; B is its illumination; B_1 is the brightness of the light-emitting diode; B' is the intensity of external illumination. The remaining notation is clear from Fig. 1. As in work ([7]), we consider an optron in which the input may be either the photoresistor circuit or the light-emitting-diode circuit; moreover, in the photoresistor circuit the input may be both electrical and optical.

Fig. 1. Schematic of a regenerative optron

2. For B independent of G, the equation

$$dG/dt = f(G, B) \tag{2}$$

describes the kinetics of the photoconductivity of a photoresistor under specified illumination conditions. Owing to the system of connections implemented in the optron, the illumination of the photoresistor B, in turn, depends on its conductance G and on the value of the controlling (input) parameter X ($X = V_{10}$ and $X = B'$ for an EO$^+$-optron with electrical and optical input, respectively; $X = V_{20}$ in the case of an electrical input in the light-emitting-diode circuit). Eliminating the intermediate dependences by means of equations (1), we obtain

$$dG/dt = P(G, X), \tag{3}$$

where

$$P(G, X) \equiv f[G, B(G, X)]. \tag{4}$$

The equation $P(G, X) = 0$ expresses the stationary characteristic of the optron $G(V_{10})$, $G(V_{20})$, or $G(B')$, which, with the aid of the same equations (1), is reduced to the current-voltage characteristic (I-V characteristic) for electrical input and to the lux-ampere characteristic (L-A characteristic) for optical input. In the dynamic regime, $P(G, X)$ determines the course of nonstationary processes in the optron. We shall show that, just as in the stationary theory, extensive information on the dynamic properties of regenera-

of the regenerative optocoupler can be obtained in general form without specifying the form of the function $P(G, X)$, i.e., without detailing the characteristics of its components and connections.

3. Let us consider nonstationary processes in the optocoupler for a small signal. Let B_{st} and G_{st} correspond to some stationary state of the optocoupler: $P(G_{\text{st}}, B_{\text{st}}) = 0$. Denote $b = B - B_{\text{st}}$, $g = G - G_{\text{st}}$.

Equation (3) in this case takes the form

$$\frac{dg}{dt} + \frac{g}{\tau} = \frac{\gamma}{\tau}\, b, \tag{5}$$

where

$$\frac{1}{\tau} = -\left.\frac{\partial f}{\partial G}\right|_B, \qquad \gamma = \left.\frac{\partial G}{\partial B}\right|_X = -\,\tau \left.\frac{\partial f}{\partial B}\right|_G, \tag{6}$$

with τ and γ being the differential values of the lifetime and the photoconductivity coefficient.

When the photoresistor is illuminated by an external independent source, the photoconductivity signal $g(t)$ is found from equation (5) and is determined by the form of the light signal $b(t)$. In the optocoupler, equation (5) is complicated owing to the additional relation between B and G. According to (4), it is transformed into

$$\frac{dg}{dt} + \frac{a}{\tau}\, g = \varkappa x, \tag{7}$$

where

$$a = 1 - \gamma\, \frac{\partial B}{\partial G}\bigg|_X, \qquad \varkappa = \frac{\gamma}{\tau}\, \frac{\partial B}{\partial X}\bigg|_G. \tag{8}$$

Noting that

$$\frac{\partial B}{\partial G}\bigg|_X = \frac{\partial B}{\partial B_1} \frac{\partial B_1}{\partial I_2} \frac{\partial I_2}{\partial I_1} \frac{\partial I_1}{\partial G}\bigg|_X,$$

and introducing the differential coefficients of light output of the emitter $\alpha = \partial B_1/\partial I_2$, light transmission of the optical path $\theta = \partial B/\partial B_1$, and current gain of the matching electrical stage $k = \partial I_2/\partial I_1$, as well as calculating

$$\frac{\partial I_1}{\partial G} = \frac{I_1/G}{1 + r_{\text{in}} G}\,{*},$$

we obtain

$$a = 1 - \mu, \tag{9}$$

where

$$\mu = \alpha\gamma\theta k\, \frac{I_1/G}{1 + r_{\text{in}} G} \tag{10}$$

is the regeneration coefficient of the optocoupler (7).

The study of the stability of the stationary state $(B_{\text{st}}, G_{\text{st}})$ reduces to solving equation (7) for $X = 0$. A necessary and sufficient condition for stability is the inequality

$$a \equiv 1 - \mu > 0, \tag{11}$$

as was to be expected, since with the opposite sign of inequality (11) the optocoupler becomes an autonomous element ([8]).

The transient and frequency characteristics

$$g(t) = \frac{\varkappa\tau}{a}\left(1 - e^{-at/\tau}\right); \qquad |g(j\omega)| = \frac{\varkappa\tau/a}{\sqrt{1 + \tau^2\omega^2/a^2}}; \qquad \arg g(j\omega) = -\operatorname{arc\,tg}\frac{\omega\tau}{a}, \tag{12}$$

show that the kinetics of the regenerative optocoupler for a small signal differs from the kinetics of the electronic processes in the photoresistor itself only in that, instead of τ, it contains $\tau_{\text{eff}} \equiv \tau/a > \tau$. The increase in relaxation time is due to partial regeneration, carried out in the optocoupler by positive feedback.

It follows from (12) that comparison of the frequency (or transient) dependences for a small signal in the optocoupler and in the photoresistor can serve

* The calculation method is set forth in (7).

by means of an experimental determination of the regeneration coefficient in any stable stationary state of the optocoupler.

4. Among the nonlinear problems corresponding to large signals, of particular interest are the processes of switching the optocoupler from one stable state to another, caused by the application of a voltage step or a step in the external illumination: $X = X_1$ for $t < 0$; $X = X_2$ for $t \geqslant 0$. In this case the solution is found in quadratures

$$t = \int_{G_1}^{G} \frac{dG}{P(G, X_2)}. \tag{13}$$

Since $P(G_2, X_2) = 0$, it follows from (13) that the slowest portion of the switching process is the neighborhood of the final state G_2. Expanding $P(G_2, X_2)$ in a series in the neighborhood of $G = G_2$ and retaining only the linear term of the expansion, we reduce (13) to the asymptotic formula

$$g = \text{const} \cdot e^{-at/\tau}, \tag{14}$$

from which it follows that the switching time is equal to

$$t_{\text{sw}} \sim \tau/(1 - \mu), \tag{15}$$

where μ is the value of the regeneration coefficient in the final state. From expression (14) it follows, in particular, that the times of the direct and reverse switching of the optocoupler between two states are different, and moreover they can be controlled independently by specifying μ_1 and μ_2.

5. As an example for which the kinetics of optocoupler switching can be represented in elementary functions and studied in detail, let us consider an

optocoupler with constant values of α, γ, θ, and other differential coefficients, for which the stationary problem was solved in ([1,3,4]). $P(G,X)$ in equation (3) for such an optocoupler has the form

$$P(G,U_2) = -\frac{G-G_0}{\tau} + \frac{\alpha\gamma\theta k}{\tau}\left[\frac{U_2 G}{1+rG} - I_{10}\right] \tag{16}$$

and, according to (13), the process of switching from the nonluminous state to the luminous one is described by the formula

$$\frac{G_2-G}{G_2-G_0}\left(\frac{G_0-G_2'}{G-G_2'}\right)^{\mu_2} = e^{-(1-\mu_2)t/\tau}. \tag{17}$$

Here $G_2' = G_0^2/G_2 < G_0$ is the second root of the equation $P(G,U_2)=0$, to which no real state of the optocoupler corresponds, since for $G<G_0$ $\alpha=0$*.

It follows from (17) that the differential values of the relaxation time at the beginning and at the end of the switching of the optocoupler are, respectively,

$$t' \sim \frac{\tau(\mu_2 + G_0/G_2)}{1-\mu_2}; \qquad t'' \sim \frac{\tau}{1-\mu_2}, \tag{18}$$

and for $rG_0 \ll 1$, when the switching of the optocoupler is accompanied by a significant change in current,

$$t' \sim \frac{\tau\mu_2}{1-\mu_2}.$$

Physicotechnical Institute named after S. V. Starodubtsev
Academy of Sciences of the Uzbek SSR

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* See also the note to formula (6) in ([3]).

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