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SYNTHESIS OF ELEMENTS WITH MANY STABLE STATES ON THE BASIS OF A NONLINEAR FOUR-TERMINAL NETWORK WITH A NONMONOTONIC AMPLITUDE CHARACTERISTIC

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The methods currently used for increasing the number of stable states of storage elements in digital computing machines are reduced, as a rule, to circuit or structural combination of binary elements and, thus, are characterized by a direct dependence of the volume of the equipment used on the number of stable states of the element. At the same time, it is possible to weaken this dependence considerably, and in many cases to eliminate it altogether, if, in implementing multistable elements, nonlinear four-terminal networks with nonmonotonic amplitude characteristics are used, obtained by transforming nonlinear characteristics of various physical nature.

Let there be a four-terminal network whose amplitude characteristic is expressed by a nonmonotonic nonlinear function $U'_{\text{out}} = \varphi(U'_{\text{in}})$. When the input and output of the four-terminal network φ are closed through a feedback circuit β with characteristic $U''_{\text{out}} = \beta(U''_{\text{in}})$, the conditions $U'_{\text{in}} = U''_{\text{out}} = U_1$ and $U'_{\text{out}} = U''_{\text{in}} = U_2$ are imposed on the external voltages (Fig. 1a). The values of the quantities characterizing the equilibrium states are determined by the joint solution of the equations of the four-terminal network and of the feedback circuit. If the feedback circuit is assumed linear, then

$$U_2 = \varphi(U_1), \qquad U_1 = KU_2 - U_0, \tag{1}$$

where K is the gain of the feedback circuit, and U_0 is the constant bias voltage at its output.

Fig. 1. *a*—general block diagram of a multistable element based on a nonlinear four-terminal network; *b*—graphical solution of the system of equations describing the block diagram

In the graphical solution of the system of equations (1), the roots corresponding to the equilibrium states of the system are determined by the points of intersection of the nonlinear characteristic of the four-terminal network with the straight line of feedback (Fig. 1b). In this case, at an equilibrium point two cases may occur:

$$1)\ \frac{\partial\varphi(U_1)}{\partial U_1} < \frac{1}{K}; \qquad 2)\ \frac{\partial\varphi(U_1)}{\partial U_1} > \frac{1}{K}.$$

It can be shown [1] that, under certain conditions, in the first case the equilibrium state is stable, and in the second it is unstable. Obviously, in order that the nonlinear amplitude characteristic intersect the feedback straight line at a certain number of points, it must possess the necessary number of extrema (a ridged characteristic) or have a sufficient number of inflection points (a stepped characteristic).

The number of stable states depends both on the form of the nonlinear characteristic and on the position of the straight feedback line relative to it. The required position of the latter can be ensured by a suitable choice of the quantities K and U_0. The problem of obtaining a nonlinear four-terminal network with an amplitude characteristic of comb-like or step-like type turns out to be more complicated. Simple electrical four-terminal networks with a nonmonotonic amplitude characteristic are absent, while the direct method of enriching characteristics by combining nonlinear elements with simpler characteristics, possessing a single falling segment, leads to a complication of the circuit that is the more considerable, the larger the number of stable states that is required.

The main idea underlying the method considered here for synthesizing multistable elements consists in transforming nonmonotonic dependences between certain quantities x_i into the required amplitude characteristics. Suppose there is a sequence of transformations with the electrical voltages U_{in} and U_{out}, respectively at the input and output:

$$\begin{aligned} U_{\text{out}} &= \varphi_1(x_1), \\ x_1 &= \varphi_2(x_2), \\ &\ldots\ldots\ldots \\ x_{n-1} &= \varphi_n(U_{\text{in}}). \end{aligned} \tag{2}$$

To obtain a nonlinear amplitude characteristic $U_{\text{out}} = \varphi(U_{\text{in}})$, it is necessary that at least one of the transformation characteristics be nonlinear. In practice, two transformation links are most often sufficient, i.e.,

$$\begin{aligned} U_{\text{out}} &= \varphi_1(x), \\ x &= \varphi_2(U_{\text{in}}). \end{aligned} \tag{3}$$

A static or dynamic quantity of any physical nature may serve as the variable x. In this case, the corresponding discrete values of the quantities x and U_{out}

Fig. 2

Figure 1: Fig. 2

act as indications of the stable states.

Of greatest interest is the use of a dynamic transformation, when the intermediate quantity x is, for example, the frequency of harmonic oscillations ω, the duration τ, or the period T of a pulse train. Correspondingly, we obtain the following three groups of multistable elements:

1) frequency-harmonic elements, the dynamic indication of whose states is the frequency of harmonic oscillations ω;
2) time-pulse elements, the dynamic indication of whose states is the duration τ of a periodic sequence of rectangular pulses;
3) frequency-pulse elements, the dynamic indication of whose states is the period T of a pulse train.

Other groups of multistable elements may be formed analogously.

As an example, let us present a frequency-pulse multistable element, the block diagram of which is shown in Fig. 2a. It consists of a self-oscillator of relaxation oscillations 1, whose circuit includes elements that make it possible to control the oscillation period T by means of the voltage U_{in}; an oscillatory circuit 2, whose natural frequency ω_k exceeds by several times the frequency $\omega = 2\pi/T$ of the fundamental harmonic of the oscillations of the self-oscillator 1; a detector with smoothing filter 3; and a feedback circuit 4. Thus, the nonlinear four-terminal network φ is formed here by the first three blocks.

Let us first consider the circuit with the feedback circuit disconnected. Suppose the fundamental frequency ω of the oscillations of the self-oscillator depends on the voltage-

···linearly, i.e., $\omega = aU_{\text{in}} + \omega_0$, and the natural frequency ω_k of the oscillatory circuit lies between the frequencies of some two adjacent harmonics of the voltage U_2 at $U_{\text{in}} = 0$, i.e., $i\omega_0 < \omega_k < (i+1)\omega_0$. If the voltage U_{in} is increased, then the frequency ω also increases, as a result of which the oscillations of the i-th harmonic fall within the passband of the circuit, so that

Fig. 2. *a*—block diagram of the frequency-pulse element; *b*—amplitude characteristic of the element

the change in the amplitude of the voltage U_k at its output, and hence of the voltage U_{out} (with "linear" detection), will in character repeat the resonance characteristic of the circuit. With a further increase in the voltage U_{in}, the $(i-1)$-th harmonic falls within the passband of the circuit, and the picture is repeated. Thus, the amplitude characteristic of the nonlinear four-terminal network in this case takes the form shown in Fig. 2b. Since the amplitudes of the

Fig. 3

Figure 2: Fig. 3

harmonic components of the spectrum of oscillations of the relaxation oscillator increase as their numbers decrease, the maxima of the amplitude characteristic also increase with increasing voltage U_{in}. At the same time the differences of the abscissas between two adjacent maxima of the amplitude characteristic also increase.

Fig. 3. Schematic circuit diagram of the frequency-pulse element

The amplitude characteristic of the nonlinear four-terminal network is described by the equation:

$$U_{\text{out}} = \sum_{i=1}^{n} \frac{K_{pK_{dU}} i}{\left\{1 + Q^2 \left[\frac{\omega_k}{i(aU_{\text{in}}+\omega_0)} - \frac{i(aU_{\text{in}}+\omega_0)}{\omega_k}\right]^2\right\}^{1/2}}, \tag{4}$$

where K_p is the resonance transmission coefficient of the circuit, K_d is the transmission coefficient of the detector, U_i is the amplitude of the i-th harmonic of the voltage U_2 at the oscillator output, and Q is the quality factor of the resonant circuit. Together with the feedback equation we obtain a system of equations describing the stationary regime of the frequency-pulse element. An analytical solution of this system is difficult; therefore, as a rule, one resorts to a graphical solution, which for the case of linear feedback is shown in Fig. 2b, where points corresponding to stable equilibrium states are marked. It is not hard to see that the number of possible states increases with increasing ratio ω_k/ω_0. However, since for reliable operation of the element it is necessary that only one harmonic component of the self-oscillator oscillations fall within the passband of the circuit at any one time, it is necessary to ensure a sufficiently high quality factor of the circuit, which limits the value of its maximum permissible frequency ω_k.

Several frequency-pulse multistable elements have been implemented according to the principle described; in these, a sinusoidal-oscillation generator with subsequent limiting, a symmetrical multivibrator, and a blocking oscillator were used as the controlled relaxation generator. Figure 3 shows the schematic diagram of the latter version. The blocking oscillator on transistor T_1 generates pulses, which are taken from resistor R_1, included in the emitter circuit, and are fed to a series resonant circuit consisting of inductance coil L and two series-connected capacitors C_1 and C_2. The voltage from capacitor C_2 is applied to the base of transistor T_2 and is detected by the base–emitter junction. The amplified and filtered voltage is taken from resistor R_2 and enters the control circuit of the blocking oscillator. The dynamic indicator of the stable states (a sequence of pulses of the corresponding frequency) is taken from output A, and the static indicator (a constant voltage) from output B. At $f_k = 480$ kHz, 18 stable states were observed in the device according to the circuit of Fig. 3. In this case, the pulse repetition frequency of the blocking oscillator varied from 25 to 240 kHz, and the output voltage from 0.42 to 3.5 V.

As can be seen from the example considered, the number of stable states is determined by the characteristics of the radio components used and by the operating mode of the circuit. Increasing the number of stable states is not accompanied, within certain limits, by any complication of the circuit and thus does not require additional equipment. This important feature is characteristic in general of multistable elements implemented according to the principle described here.

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CITED LITERATURE

1. M. S. Neiman, *Automatic Processes and Phenomena*, 1958.

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