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Electronic neuron-like generator with excitable and self-oscillating modes on the basis of phase-locked loop

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Experimental implementation of neuron-like generator on the basis of phase-locked loop (PLL) with band-pass filter is proposed. The generator is able to generate oscillations that are typical for neuronal dynamics like spikes and bursts, both regular and chaotic, and demonstrate excitable (non-oscillating) behavior. Excitable mode is typical for the most of brain neurons that remains silent until activated by external signal. Previous PLL-based neuron-like models couldn't demonstrate excitable dynamics. Therefore, the proposed neuron-like generator could be a basic block for electronic spiking neural networks to mimic brain neural networks.

Keywords: electronic neuron, generator, excitation of oscillations, phase-locked loop.

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At present one of the most urgent tasks of interdisciplinary science is the design and research of neuromorphic devices [1]. Such devices are most often used to create systems for processing various kinds of information with algorithms similar to the data processing algorithms of the human brain or the brain of animals. The development of such neuromorphic electronics will allow computing devices and information processing systems to be built based on new principles and with a high level of parallelism [2]. Neuromorphic devices require the development of electronic components: neurons and synapses. Many papers have been devoted in recent years to the creation and research of such systems [1,3–7].

The paper [8] proposed a phase-locked loop system with a bandpass filter in the control circuit. A more detailed study of the mathematical model of such a system has shown missing equilibrium states corresponding to the synchronization mode of the phase-locked loop system, but there are self-oscillating modes of varying complexity [9]:

$$\frac{d\varphi}{d\tau} = y, \qquad \frac{dy}{d\tau} = z,$$

$$\varepsilon_1\varepsilon_2\frac{dz}{d\tau} = \gamma - (\varepsilon_1 + \varepsilon_2)z - \big(1 + \varepsilon_1\cos\varphi\big)y. \qquad (1)$$

Self-oscillations observed in such system for the variable y are reliably similar to spike and burst oscillation of the neuron's membrane potential. Parameters of filter inertia in a control loop ε_1 and ε_2 make it possible to set the necessary dynamic mode, and γ provides effect similar to exposure to external current. The space of parameters was divided into areas of existence of various dynamic modes.

Hardware implementation [10] of the considered neuron like generator in the form of an electronic device demonstrated the possibility of reproducing the same dynamic modes as in the mathematical model (1) [11]. System (1) is invariant with respect to the transformation (γ, φ, y, z)–$(-\gamma, -\varphi, -y, -z)$, so all the observed dynamic modes obtained under the condition $\gamma > 0$, are also observed under $\gamma < 0$, but in „inverted" form. This implies a fundamental disadvantage of the proposed model (1) and its experimental implementation — the absence of an excitable mode (by excitable we mean a dynamic system with a stable equilibrium state and a periodic pseudorbit of large amplitude, passing in the vicinity of the equilibrium state [12]), when pulse generation would only respond to external disturbance. At the same time, the vast majority of brain neurons are in the excitable subthreshold mode, and their generation is primarily caused by presence of multiple connections.

The aim of the present paper is to modify the existing model of the neuron-like generator in order to preserve the known dynamics and add a mode of unexcited oscillator.

To eliminate the mentioned disadvantage and to add the excitable mode in the region of parameters $\gamma < 0$ in the neuron like generator circuit between low-frequency and high-frequency parts of a band-pass filter, a switch, activated when the signal exceeds the threshold, was added, which made it possible to keep the known dynamics at $\gamma > 0$ and add the unexcited oscillator mode at $\gamma < 0$.

The functional scheme of the modified generator presented in fig. 1 is based on a phase-locked loop system, which includes a referent generator, RG, a phase detector, PD, and voltage-controlled oscillator, VCO. Elements DA1, DA2, DA3, $F1$ and $F2$ are the elements of original band-pass filter, the elements DA4 and TR1 are the elements of circuit to track the state of the system, and element SA1 — an electronic switch, controlled by the tracking circuit. The operation principle of the modified filter is as follows: a signal from the output of the phase discriminator (PD) arrives at the input, then this signal passes through buffer amplifier DA1, where current decoupling of the PD output from the input of the low-pass filter is performed, which allows to reduce the overall noise level and transient time in the system. From the output of DA1 the signal goes to the input of low-pass filter $F2$, where the high-frequency component of the signal is cut off, and the signal is smoothed. Block $F2$ has the ability to adjust the parameters, which in turn allows you to change the frequency range of the filter and the degree of signal smoothing. From output $F2$ the signal goes to the input of the second buffer amplifier DA2, which is necessary to limit the impact of low-pass filter $F2$ on the high-pass filter $F1$, which in turn makes it possible to prevent the occurrence of the reverse wave due to high output resistance of $F2$ and low input resistance of $F1$ and thereby to increase the overall stability of the circuit during operation. Then the signal from the output DA2 goes to the input of high-pass filter $F1$, as well as in parallel to the control circuit of the electronic switch trigger and input contact group of the electronic switch itself. When the signal passes through $F1$, low-frequency and constant component is cut off, to generate a signal required for the device to operate in the previously known mode of generation of neuron like oscillations of varying complexity, described by equations (1). Control circuit DA4 (inverting repeater) and Schmitt trigger TR1 are built so that Schmitt trigger TR1 compares the signal from $F2$ filter output with the trigger upper threshold chosen to detect a signal that occurs when setting parameter $\gamma < 0$. If the threshold is exceeded, the trigger changes from a state of logical „0“state to logical „1“, thereby closing electronic switch SA1. After closing the switch, the signal from output DA2 passes not only through $F1$ filter, but also bypasses the low and constant components. Therefore, a phase-locked loop system is established with a low-pass filter, capable of providing a synchronization mode, thereby generating a constant signal at the output of the filter in the control circuit. The signal at the output of high-pass filter $F1$ complies with variable y in system (1), which is interpreted as the membrane potential of the neuron. Thus, a non-self-oscillating excitable mode is formed in the neuron like generator based on the phase-locked loop system.

If trigger TR1 was initially in the state of logical „1“, then the inverted signal from the output of buffer amplifier DA2 is compared with the lower switching threshold. The lower switching threshold is chosen so that it is activated when crossing into the region of parameters $\gamma > 0$. When the signal crosses this threshold, trigger TR1 is switched from logical „1“ to logical „0“, the electronic switch opens, and the signal passes only through the high-pass filter circuit $F1$. From the output of filter $F1$ and electronic switch SA1, the signal goes to the equivalent inputs of summation unit SU1, where the final control signal is generated to implement both self-oscillating and excitable modes. From the output of SU1 the signal goes to buffer amplifier DA3, which matches the output of the filtering unit and the control input of the voltage controlled oscillator. From the output of DA3 the control signal through the output of the filtering unit goes to the input of the voltage controlled oscillator (VCO), thereby closing the control loop of the phase-locked loop system.

The operator transmission gain of the proposed filter in the control loop may be represented as follows:

$$
\begin{aligned}
K(p) &= \frac{T_1 p}{1 + (T_1 + T_2)p + T_1 T_2 p^2} + \frac{S}{1 + T_2 p} \\
&= \frac{S + (1 + S)T_1 p}{1 + (T_1 + T_2)p + T_1 T_2 p^2},
\end{aligned}
\tag{2}
$$

where S — state function of TR1 Schmitt trigger, taking values 0 and 1. Given the filter modification in the control circuit and the specified transmission gain, equation (1) can be rewritten as follows:

$$
\begin{cases}
\dfrac{d\varphi}{d\tau} = y, \\
\dfrac{dy}{d\tau} = z, \\
\varepsilon_1 \varepsilon_2 \dfrac{dz}{d\tau} = \gamma - (\varepsilon_1 + \varepsilon_2)z - (1 + \varepsilon_1 \cos\varphi \\
\qquad + S\varepsilon_1 \cos\varphi)y - S\sin\varphi,
\end{cases}
\tag{3}
$$

where

$$
S = \begin{cases}
1 \text{ at } U_{sw} \geqslant U_{thr2} - (U_{thr2} - U_{thr1})S_{old}, \\
0 \text{ at } U_{sw} < U_{thr2} - (U_{thr2} - U_{thr1})S_{old},
\end{cases}
$$

U_{sw} — control voltage at Schmitt trigger TR1, U_{thr1} and U_{thr2} — threshold voltages to switch trigger TR1 to state 0 and 1 respectively. Since the value of subsequent Schmitt trigger state depends on the previous one, let us introduce state function S_{old}, which also takes values 0 or 1. Control voltage U_{sw} is taken from low-pass filter $F2$ (Fig. 1).

The proposed modification of the filter in the control circuit was implemented as an analog circuit and used to modify the previously proposed hardware neuron like generator with spiking and bursting dynamics [10]. To demonstrate presence of self-oscillating and excitable modes of operation, oscillograms of voltage at the output of high0-pass filter $F1$ at the transition from the parameter space $\gamma > 0$ to the area $\gamma < 0$ and back were obtained (Fig. 2).

The oscillogram in Fig. 2 shows disappearance of oscillations and establishment of a constant signal in the transition from the parameter space $\gamma > 0$ to the space $\gamma < 0$, as well as appearance of oscillations in the reverse change of parameters. γ parameter was tuned by changing the frequency of the referent generator in the phase-locked loop system.

Cross sections of the parameter space in the electronic neuron like generator were divided into areas with various dynamic behavior, shown in Fig. 3. Designation of areas of various dynamic modes in Fig. 3 corresponds to

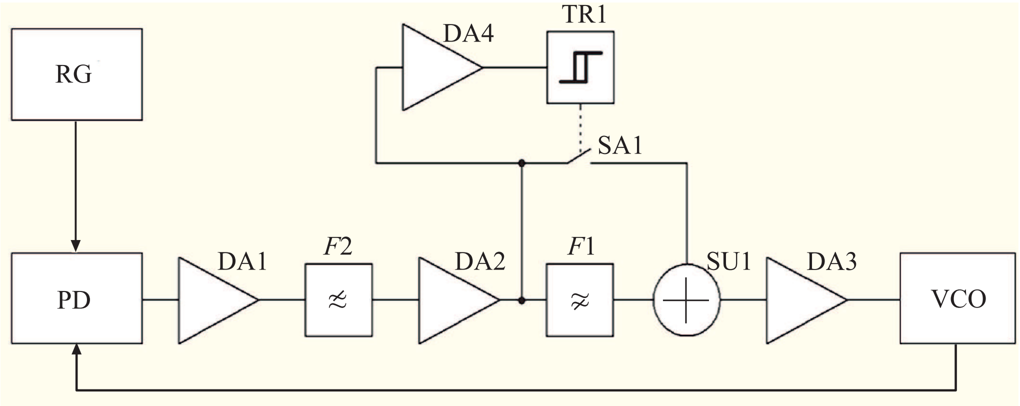

Figure 1. Functional circuit diagram of electronic neuron-like generator with excitable and self-oscillating modes on the basis of phase-locked loop. Explanation in the text.

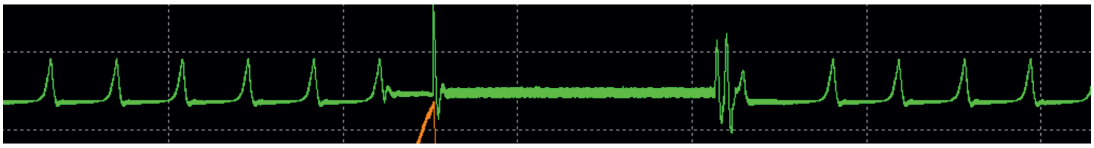

Figure 2. An example of a voltage oscillogram at the output of a high-pass filter when the generator transitions from self-oscillating to excitable mode of operation and back.

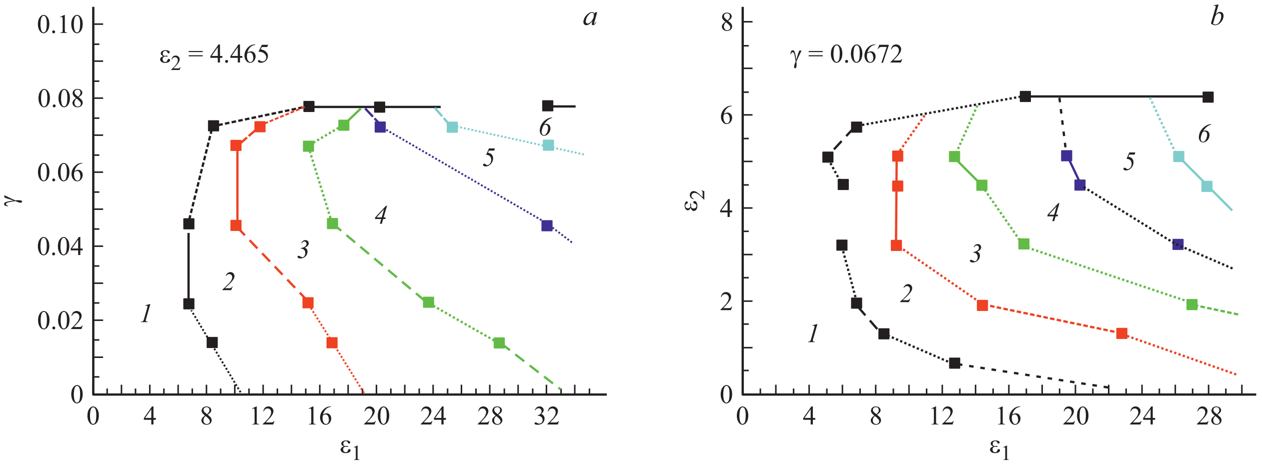

Figure 3. Areas of existence of various dynamic modes in the cross sections of the electronic neuron like generator parameter space with fixed parameters ε_2 (*a*) and γ (*b*).

designations introduced in [9], and reflects the number of pulses in the packet for packet (burst) oscillations.

The resulting separation of parameter space cross sections into regions with various dynamic behavior are qualitatively similar to areas for system (1) in the region of positive γ [9]. With negative γ, a stationary equilibrium mode was implemented in the generator, when a constant signal was observed at the output of the neuron like generator.

Thus, the paper proposes and implements as a radio engineering diagram a modification of the neuron like generator based on the phase-locked loop system with a band-pass filter in the control circuit, which eliminates the basic drawback of the initial model — inability to work in the excitable mode. The new dynamic mode with the absence of self-oscillations in the parameter space $\gamma < 0$ was obtained by introducing an electronically controlled switch between the low- and high-pass filters into the control circuit. The experimental separations of the cross sections of the parameter space in the electronic neuron like generator into regions of existence of various dynamic modes. Along with the existence of a new mode, the existence of previously known self-oscillating modes of varying complexity: spike, burst, and chaotic modes is confirmed.

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Conflict of interest

The authors declare that they have no conflict of interest.

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