01.5

Controllable neuromorphic dynamics of the phase locked loop

© L.A. Tsyrulnikova[1], A.R. Safin[1,2]

[1] National Research University „MPEI“, Moscow, Russia
[2] Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, Russia
E-mail: Hey_Lucy@mail.ru

Received May 31, 2021
Revised July 24, 2021
Accepted July 24, 2021

We consider the neuromorphic dynamics of a filter-free phase locked loop with a phase modulation of a reference oscillator. The transition from pulsed single-spike dynamics to the bursting dynamics can be easily controlled by changing the depth and frequency of phase modulation, as well as the gain factor along the ring of the phase locked loop. The possibility of implementing neuromorphic calculations of the „OR“ type in the scheme of three phase locked loops mutually coupled through a common loop filter (control circuit) is shown. The presented results can be used in designing hardware-implementable neuromorphic networks with increased frequency stability, resistant to noise effects.

Keywords: neuromorphic dynamics, phase locked loop, logical operations.

DOI: 10.21883/TPL.2022.14.52060.18891

At present, hardware implementation of neuromorphic computer systems is rather problematic [1]. In recent years, different versions of practical implementation of artificial neuromorphic systems (ANS) were proposed, which were based on different physical principles, e.g., semiconductor, optical, magnetic, etc. [2]. The advantages of such systems are high-speed operation, low power consumption and small size. However, in addition to the above listed characteristics, a requirement for ensuring the stability is imposed on the ANS construction technology. From this viewpoint, phase systems become attractive for ANS construction since they are able to ensure the necessary stability in a wide locking range. One more reason for using the phase locking loops (PLL) in constructing ANS is the possibility of nanoscale implementation (e g., on the basis of spintronics [3,4] and magnonics [5]) of separate loop components, such as phase detector, controllable oscillator and filter, as well as the possibility of spatial scaling [6]. Hereinafter we regard the „neuromorphic“ dynamics as such a behavior of a dynamic system when it exhibits spike or bursting activity controllable by varying the system parameters [2].

Earlier in paper [7] PLL was offered for using as a basic cell of ANS with a spintronic oscillator as a controllable oscillator for the image recognition tasks. In this case, oscillators themselves do not exhibit neuromorphic behavior, namely, the spike activity, and operate in the self-oscillation mode, while PLL are used to stabilize the oscillator phase. Weighting factors are being set in the neuromorphic processing by the gain factors of the PLL loop filter [8]. The possibility of PLL-generation of the spike and bursting activity was for the first time described in [9,10]. Due to selecting a second-order filter for the PLL loop filter and properly choosing the feedback circuit parameters, the possibility of implementing the neuromorphic dynamics was demonstrated. In order to technically simplify the ANS implementation, in this paper we offer to use a filter-free PLL with the phase-modulated reference oscillator. In this case, generation of the spike activity needs stable work of PLL in the mode close to the threshold of asynchronous oscillations. All the dependences were obtained in this work by numerical simulation.

To describe the PLL neuromorphic behavior, it is necessary to write down a differential equation for the instantaneous phase difference $\phi = \varphi_{\mathrm{VCO}} - \varphi_{\mathrm{RO}}$, where φ_{RO}, φ_{VCO} are the instantaneous phases of the reference oscillator with the preset modulation law and of the voltage-controlled oscillator (Fig. 1, a). At the phase discriminator (PD) output, an error signal $e = E\sin\phi$ is generated, which is proportional to the phase difference ϕ and maximal voltage E generated by PD. The phase of oscillations of the voltage-controlled oscillator is controlled through the loop filter (LF) consisting in a filter with gain factor $K(d/dt)$. The differential equation for the phase difference ϕ in a filter-free PLL with a sinusoidal characteristic of the phase discriminator and phase modulation of the reference oscillator is given by [11,12]:

$$\frac{1}{\Omega}\frac{d\phi}{dt} + \sin\phi = \gamma_0 - \alpha\cos(\omega_M t), \qquad (1)$$

where $\Omega = SE$ is the lock range of the filter-free PLL, S is the slope of the voltage-controlled oscillator control characteristic, $\gamma_0 = (\omega_{\mathrm{VCO}} - \omega_{\mathrm{RO}})/\Omega$ is the relative difference in the frequencies of locked oscillations, ω_M is the modulation frequency, $\alpha = \frac{B\omega_M}{\Omega}$ is the driving force amplitude, B is the phase deviation.

Let us consider the system dynamics near the asynchronous oscillations threshold at $\gamma_0 = 0.9$. Fig. 1 presents oscillograms of the PD output voltages $e(t) = E\sin\big(\phi(t)\big)$

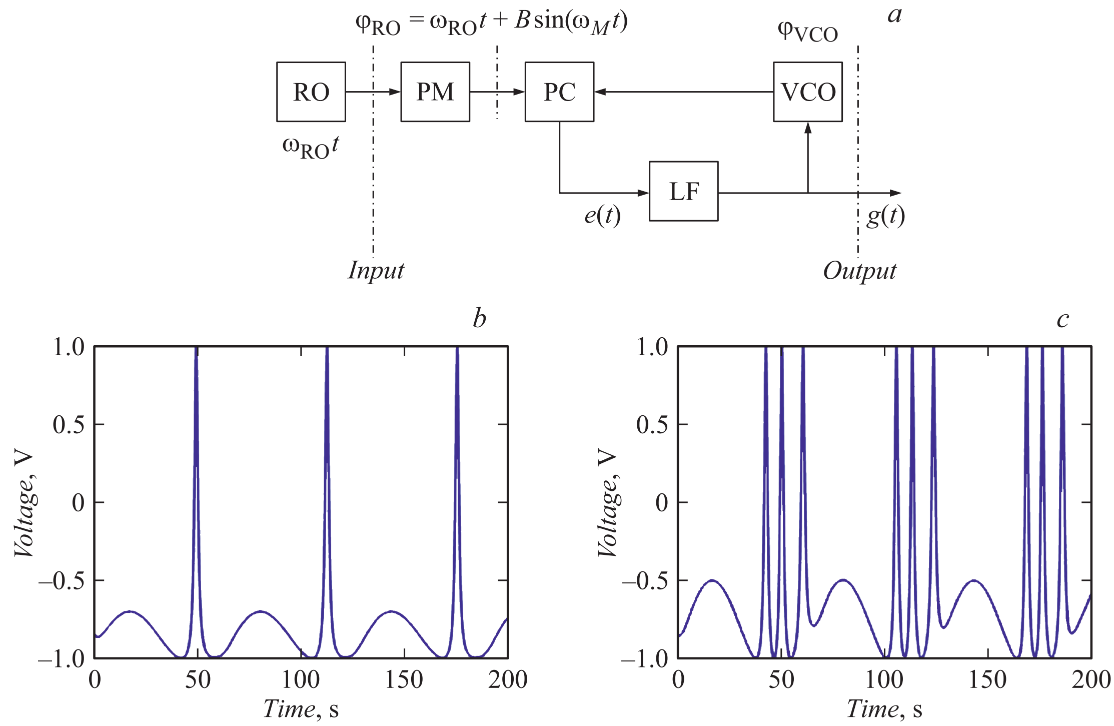

Figure 1. *a* — schematic circuit of PLL with phase modulation of the input signal. RO is the reference oscillator, PM is the phase modulator, PC is the phase discriminator (comparator)— LF is the loop filter, VCO is the voltage-controlled oscillator. *b, c* — voltage oscillograms (numerical simulation) at the loop filter output of the single filter-free PLL at $\Omega = 1$, $\gamma_0 = 0.9$, $\alpha = 0.2$, $\omega_M = 0.1$ (*b*) and $\alpha = 0.4$, $\omega_M = 0.1$ (*c*).

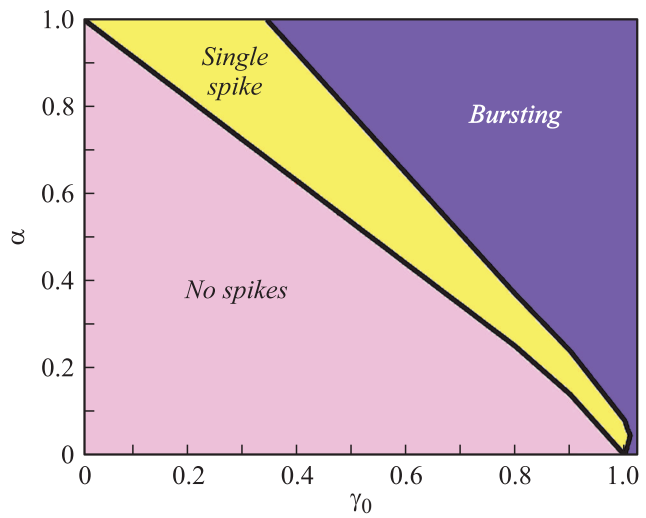

Figure 2. Subdivision of the plane of parameters (γ_0, α) into areas corresponding to the absence of neuromorphic behavior, spike generation and burst generation.

obtained by numerically solving differential equation (1). For instance, for the fixed phase modulation frequency $\omega_M = 0.1$, Fig. 1, *b, c* presents oscillograms for two modulation amplitudes $\alpha = 0.2$ and 0.4 corresponding to the single-spike and bursting activity modes. Fig. 2 demonstrates the subdivision of the parameters (γ_0, α) plane into areas corresponding to the absence of neuromorphic behavior, spike generation and burst generation. Thus, to provide neuromorphic behavior of a single filter-free PLL, it is necessary to fix the initial difference in the locked oscillation frequencies γ_0 near the asynchronous oscillations threshold and the modulation frequency ω_M, and then vary the modulation signal amplitude α, which is technically much easier than to vary the frequency.

Now pass to the analysis of possibility to perform neuromorphic computation based on mutually coupled PLL operating in the spike generation mode (Fig. 3, *a*). For this purpose, let us couple through the mutual loop filter two PLLs (phase locked loops) with the third one that will play a role of a resolver. Signals $g_{1,2}(t)$ from the PLL LF outputs are fed to the mutual LF inputs so that output signal $g_{\mathrm{MLF}} = K_1 g_1 + K_2 g_2$ is summed with the output PLL error signal. In this case, the mutual LF is constructed in the form of two multipliers and adder. Let us write down the mathematical model describing the dynamics of the circuit presented in Fig. 3, *a* in the form of a set of differential equations for the phase differences $\phi_{1,2,3}$ of three PLL.

$$\frac{1}{\Omega_1}\frac{d\phi_1}{dt} + \sin\phi_1 = \gamma_{01} - \alpha_1\cos(\omega_M t), \qquad (2)$$

$$\frac{1}{\Omega_2}\frac{d\phi_2}{dt} + \sin\phi_2 = \gamma_{02} - \alpha_2\cos(\omega_M t), \qquad (3)$$

$$\frac{1}{\Omega_3}\frac{d\phi_3}{dt} + \sin\phi_3 + \varepsilon_{13}\sin\phi_1 + \varepsilon_{23}\sin\phi_2 = \gamma_{03}. \qquad (4)$$

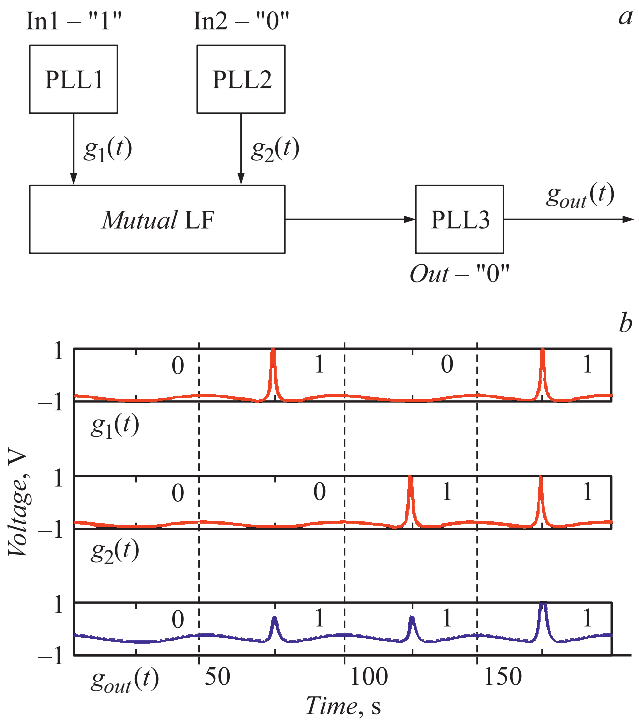

Figure 3. Schematic circuit of two PLL mutually coupled through the common loop filter and operating in the spike generation mode and with the third PLL operating as a resolver (for example, the logical operation „OR") is shown) designed for implementing the neuromorphic computation, and oscillograms (numerical simulation) of volages at the PD output in performing the „OR"operation (*b*). PLL is the phase locked loop, *Mutual* LP is the mutual loop filter. Modeling parameters: $\Omega_j = 1$ $(j = 1, 2, 3)$, $\gamma_{0j} = 0.9$ $(j = 1, 2, 3)$, $\omega_M = 0.1$, $\varepsilon_{13} = \varepsilon_{23} = 0.7$, a $\alpha_{1,2} = 0.1$ and 0.2 corresponds to logical „0" and „1".

Here $\varepsilon_{13,23}$ are the normalized factors of the first and second PLL coupling with the third one, respectively, Ω_j and γ_{0j} $(j = 1, 2, 3)$ are the lock ranges and initial PLL frequency mismatch, respectively, $\alpha_{1,2}$ are the modulation signal amplitudes. The remaining parameters of model (1) obtained in (2) additional indices characterizing the PLL under consideration. Notice that the third PLL is free of phase modulation of the reference oscillator. This model of two PLL coupled with the third one playing the role of a resolver is able to perform various logical operations. For instance, Fig. 3, *b* presents oscillograms of voltages at input PLL whose signal level corresponds to logical „0"and „1" and is controlled by varying parameter α at each LPP, as well as at the output LPP that performs the selection operation. In this case, the level of relative mismatch of the oscillation frequencies $\gamma_{0j} = 0.9$ is chosen so that the truth table is realized, which corresponds to logical „OR" at the equal coupling factors $\varepsilon_{13}, \varepsilon_{23} = 0.7$. Other logical operations also may be realized in a similar way, including a great number of inputs and outputs. Analysis of the phase stability of such operations is an acute issue for further investigations.

Thus, neuromorphic dynamics of a filter-free phase lock loop with the phase-modulated reference oscillator has been studied. The transition from the pulsed single-spike dynamics to the bursting one may be controlled by varying the phase modulation depth and frequency, as well as the gain factor along the ring of the phase lock loop. The possibility of performing neuromorphic computations of the „OR" type in the circuit of two phase lock loops mutually coupled through the common loop filter has been shown. The presented results may be utilized in designing hardware-implementable neuromorphic networks characterized by high frequency stability and resistance to noise effects [3,4,7].

Financial support

The study was carried out in the scope of Project „Development of devices for signal formation, reception and processing based on magnetic nanostructures" and was supported by the National Research University „MPEI"grant for implementing research programs „Energetics", „Electronics, Radio Engineering and IT" and „Industry technology 4.0 for industry and Robotics " for 2020–2022.

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] S. Soman, Jayadeva, M. Suri, Big Data Analytics, **1**, 15 (2016). DOI: 10.1186/s41044-016-0013-1

[2] D. Marković, A. Mizrahi, D. Querlioz, J. Grollier, Nature Rev. Phys., **2**, 499 (2020). DOI: 10.1038/s42254-020-0208-2

[3] A. Mitrofanov, A. Safin, N. Udalov, M. Kapranov, J. Appl. Phys., **122**, 123903 (2017). DOI: 10.1063/1.5004117

[4] J. Torrejon, G. Khalsa, J. Torrejon, M. Riou, F.A. Araujo, P. Bortolotti, V. Cros, J. Grollier, S. Tsunegi, K. Yakushiji, A. Fukushima, H. Kubota, S. Yuasa, G. Khalsa, M.D. Stiles, D. Querlioz, Nature, **547**, 428 (2017). DOI: 10.1038/nature23011

[5] A.V. Sadovnikov, A.A. Grachev, S.A. Odintsov, A.A. Martyshkin, V.A. Gubanov, S.E. Sheshykova, S.A. Nikitov, Pis'ma v ZhETF, **108** (5), 332 (2018) (in Russian). DOI: 10.1134/S0370274X1817006X

[6] L.A. Tsyrulnikova, B.P. Sudeev, A.R. Safin, Izv. vuzov Rossii. Radioelektronika, **23** (3), 32 (2020) (in Russian). DOI: 10.32603/1993-8985-2020-23-3-32-40

[7] D.E. Nikonov, G. Csaba, W. Porod, T. Shibata, D. Voils, D. Hammerstrom, I.A. Young, G.I. Bourianoff, IEEE J. Explor. Solid-State Computat. Devices Circuits, **1**, 85 (2015). DOI: 10.1109/JXCDC.2015.2504049

[8] F.C. Hoppensteadt, E.M. Izhikevich, IEEE Trans. Neural Networks, **11** (3), 734 (2000). DOI: 10.1109/72.846744

[9] M.A. Mishchenko, V.D. Shalfeev, V.V. Matrosov, Izv. vuzov. Prikladnaya nelineynaya dinamika, **20** (4), 122 (2012). DOI: 10.18500/0869-6632-2012-20-4-122-130 (in Russian)

[10] V.D. Shalfeev, V.V. Matrosov, *Nelineynaya dinamika sistem fazovoy sinkhronizatsii* (Izd-vo Nizhegorodskogo gosuniversiteta, N. Novgorod, 2013) (in Russian).
[11] V. Lindsey, *Sistemy sinkhronizatsii v cvyazi i upravlenii* (Sov. radio, M., 1978) (in Russian).
[12] *Sistemy fazovoy sinkhronizatsii*, pod red. V.V. Shakhgil'dyana, L.N. Belyustinoy (Radio i svyaz', M., 1982) (in Russian).