Inductively coupled burst oscillators in neural network information processing systems

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Abstract. In the current study, we present a self-generating circuit based on an LC oscillatory circuit with a switching element having an S-type current-voltage characteristic. Using the example of a VO₂ switch, we demonstrate that such circuits generate burst oscillations and have a specific mode of bursts synchronization using inductive coupling between generators. Such generators of burst oscillations (of a neural type) can find application in the tasks of cognitive technologies, including the implementation of pulsed neural networks.

1. Introduction
One of the promising fields of electronics is the development and implementation of a new element base of neural network devices, including elements based on physical phenomena and principles that are different from CMOS technologies. Such artificial neurons should, on the one hand, preserve the general principle of generating neural signals, and, on the other hand, have simple circuitry solutions in terms of implementing cognitive technologies, for example, in pulsed neural networks (PNNs) [1]. The development of simple neurodynamic models in circuit design is an important task of modern neuroelectronics and neuroinformatics.

Under the influence of a stimulus (external potential), a neuron passes from the ground state to the excited state, which is observed in the form of a set of spikes - potential bursts [2]. This phenomenon is called the “bursting” effect, and burst-type oscillations are characterized by the alternation of fast oscillations with rest intervals (slow amplitude changes). Burst signals have a higher information capacity compared to regular pulses, and it becomes possible to perform frequency and phase encoding of information not only using a spike sequence, but also burst synchronization.

The phenomenon of electric switching is a sharp, significant and reversible change in the conductivity of the system under the influence of an applied electric field or flowing current. The I–V characteristic of such system contains sections with negative differential resistance (NDR). The existence of NDR is provided by the presence of positive current feedback or voltage feedback [3]. In contrast to electronic devices, this feedback is not created by external circuit elements, for example, as in circuits with operational amplifiers, but this feedback is internal. A classical element with the S-type I–V characteristics and the effect of electric switching is a trigger diode, formed by three consecutive p-n junctions, where the current instability is caused by the avalanche injection of minority carriers through the middle p-n junction [4]. Modern silicon technology allows the creation of dinistor elements with S-type I–V characteristics of a wide range of voltages and currents, characterized by stability and low internal noise.
Among non-silicon materials, in which electric switching takes place, transition metal oxides (TMOs) can be highlighted [5]. At least in two oxides (NbO$_2$ and VO$_2$), electric switching is caused by a metal-insulator phase transition, when heating the material by a flowing current leads (at a certain temperature) to the electronic-structural transition of the oxide from the semiconductor state to the metallic state [6].

In the current study, we present an oscillatory circuit that implements the burst pulse generation based on the LC oscillatory circuit and an element with an S-type I–V characteristic, using the example of a VO$_2$ switch. A specific synchronization mode of burst generators using inductive coupling is reviewed.

2. The simplest RC oscillator based on the S-switch

Figure 1 presents a planar VO$_2$ switch and its I–V characteristic (S-type, without memory effect). Switching has a threshold character with an unstable NDR section, with threshold voltages (currents) of switching on ($U_{th}$, $I_{th}$) and switching off ($U_{h}$, $I_{h}$). The I–V characteristic can intersect with the load curve only on high-resistance (OFF) and low-resistance (ON) branches.

![Optical image of planar VO$_2$ switch](image)

**Figure 1.** Optical image (a) of planar VO$_2$ switch [6] and its experimental and model I–V characteristics (b). Parameters of the I–V characteristics of the VO$_2$ switch: $U_{th}=5.64$ V, $U_{h}=2.12$ V, $U_{cf}=1.754$ V, $R_{off}=10742$ Ω and $R_{on}=276$ Ω (the unstable NDR section is shown by the red dashed line).

If both branches are approximated by straight lines with resistances $R_{off}$ and $R_{on}$, then the model I–V characteristic (figure 1b) has the form

$$I(U) \approx \begin{cases} U/R_{off}, & \text{state} = \text{OFF} \\ (U-U_{th})/R_{on}, & \text{state} = \text{ON} \end{cases} \quad (1),$$

where $U_{cf}$ is the residual voltage of the low impedance (ON) section. Switching in (1) between OFF and ON states is performed in accordance with the following conditions:

$$\text{state} = \begin{cases} \text{OFF}, & \text{if (state} = \text{ON} \text{) and (} U < U_{h} \text{)} \\ \text{ON}, & \text{if (state} = \text{OFF} \text{) and (} U > U_{th} \text{)} \end{cases} \quad (2).$$
An element with an NDR of S-type can be included in an active RC circuit (figure 2a), provided that the supply current of circuit $I_0$ is in the NDR range:

$$I_{th} < I_0 < I_h$$  \hspace{1cm} (3),

the circuit performs self-oscillations of the relaxation-type. Such RC-oscillators can be connected to a network, which is a variant of the artificial neural network of the oscillatory (self-generating) type, using capacitors and resistors [7]. For the VO$_2$ switch, where the electric switching is caused by the metal-insulator phase transition, a specific version of the coupling between RC oscillators in the form of thermal interaction can be implemented [8].

### 3. Burst generator based on the S-switch.

A modified figure 2 circuit, when a serial $LC_1$ link is connected between the S-switch and the capacitance ($C_0$), is presented in figure 3.

The circuits in figures 3 are modeled by the following 3D-systems of differential equations:

\[
C_0 \frac{dU_0}{dt} = I_0 - I_{sw}(U_0(t) - U_1(t)), \quad C_1 \frac{dU_1}{dt} = I_{sw}(U_0(t) - U_1(t)) - I_L(t), \quad L \frac{dI_L}{dt} = U_1(t)
\]  \hspace{1cm} (4),

where $U_0(t)$ and $U_1(t)$ are the voltages on the capacitors $C_0$ and $C_1$, and $I_{sw}(U)$ is a piecewise linear approximation of the I–V characteristic (1) with the condition (2).
Let us demonstrate the operation of the circuit in figure 3 using the example of a VO₂ switch (figure 1b). As figure 4 demonstrates, the numerical simulation gives burst oscillations of the current $I_{sw}(t)$ and voltage $U_{sw}(t)$ on the switch. The generation of burst oscillations can be explained as follows.

![Figure 4](image.png)

**Figure 4.** Burst oscillations of the current $I_{sw}(t)$ (a) and voltage $U_{sw}(t)$ (b) on the switch and the oscillations of the inductance current $I_{l}(t)$ (c) in the figure 3 circuit. Circuit parameters $L=6\, \text{mH}$, $C_0=5\, \text{nF}$, $C_1=1\, \text{nF}$, $I_0=2.2\, \text{mA}$. The $I-V$ characteristics of the VO₂ switch correspond to figure 1.

The circuit in figure 3a is a parallel oscillatory circuit $LC_0$. To its inductance circuit, an $RC_1$ oscillator with an $S$-switch is connected. Since the parallel circuit has a current resonance at a frequency $\omega_0 \sim 1/\sqrt{LC_0}$, the circuit in figure 3a can be presented as an $RC_1$ oscillator under the influence of a sinusoidal current with a frequency close to $\omega_0$ and an offset of $I_0$ (figure 3b). In this equivalent circuit, the high-frequency relaxation oscillations of the $RC_1$ oscillator are modulated by low-frequency oscillations of the (sinusoidal) supply current. In the time intervals, where the current values of the oscillator fall outside the range (3), these oscillations disappear. The mode of periodically repeating burst generations (switch current spikes) emerges, coupled with the intervals of burst absence (figure 4). The role of the added $LC_0$ link in figure 3a is reduced to low-frequency modulation of the supply current $I_0$ of the $RC_1$ oscillator.

4. Oscillations synchronization of two burst generators with inductive coupling

The presence of inductance in the circuit of burst generators in figure 3a makes it possible to organize a magnetic coupling between the generators. Figure 5 demonstrates two oscillator circuits that differ in the capacitance values $C_0$ and have connected circuits with an inductive coupling coefficient $K = M / \sqrt{L_1L_2}$, where $M$ is the mutual induction of the circuits $L_1$ and $L_2$. The coefficient’s value can vary in the range from $-1$ to $1$, with negative values for anti-phase induced currents and positive values for in-phase induced currents, which is determined by two options for winding coils (right-right screw or right-left screw) with respect to each other.

Numerical simulation with the example of a VO₂ switch (figure 6) demonstrates a gradual transition to the burst synchronization mode of two oscillators with an increase of $|K|$. For both anti-phase ($K > 0$) and in-phase ($K < 0$) inductive coupling, synchronization has a similar “scenario”. The nearest bursts of oscillators 1 and 2 “gravitate” to each other with increasing of $|K|$, while the number of oscillations (switching) in the oscillators decrease. For both inductive coupling types, with strong coupling ($|K| = 0.99$), the oscillators generate fully synchronized bursts with a minimum number of switching.
Figure 5. Inductive coupling between burst oscillators with coefficient $K$.

This configuration becomes non-burst, with a regular periodic sequence of pulses, at in-phase mutual inductance ($K = -0.99$). At anti-phase inductance ($K = 0.99$), the burst mode of the signals is preserved.
Figure 6. Burst oscillations of the currents $I_{sw1}(t)$ and $I_{sw2}(t)$ on the switches (1 and 2) in figure 5 circuit for different coupling coefficients $K$. Circuit parameters: $L_1=L_2=6$ mH, $C_{01}=5$ nF, $C_{02}=10$ nF, $C_1=1$ nF, $I_{01}=I_{02}=2.2$ mA. The I–V characteristics of the VO2 switches (1 and 2) are identical and correspond to figure 1.

Table 1 Burst frequencies of oscillators ($F_1$ and $F_2$) depending on the strength of the in-phase ($K<0$) inductive coupling. The oscillators’ parameters correspond to figure 6.

| $K$     | 0   | -0.1 | -0.2 | -0.3 | -0.4 | -0.5 | -0.6 | -0.7 | -0.8 | -0.9 | -0.99 |
|---------|-----|------|------|------|------|------|------|------|------|------|-------|
| $F_1$, kHz | 10.01 | 11.80 | 11.92 | 12.19 | 18.01 | 17.99 | 17.92 | 16.45 | 16.61 | 17.32 | 19.50 |
| $F_2$, kHz | 17.43 | 17.71 | 17.87 | 18.16 | 18.01 | 17.99 | 17.92 | 16.45 | 16.61 | 17.32 | 19.50 |
Quantitatively, the synchronization effect can be determined on the basis of spectral analysis, estimating the frequencies of the first harmonics of the burst signals (by analogy, for example, with a sequence of rectangular pulses). We apply this approach to the case of in-phase ($K<0$) inductive coupling of oscillators.

Table 1 gives the frequencies of the first harmonics of the oscillators’ current signals for different inductive coupling. The main burst frequencies, which initially differ by more than 7 kHz, become equal at the value of $K = -0.4$. Further, the total burst synchronization frequency $F_o= F_1= F_2$ initially decreases with an increase of $|K|$, and then sharply increases for the uttermost value of $K = -0.99$.

5. Conclusion
Recent studies highlighted the interest of VO$_2$ switch applications in the PNN [9] and neural-like circuits [1,10]. The proposed circuit of burst relaxation oscillations based on the VO$_2$ switch has simple design and contains only one switching element without additional feedback and other nonlinear elements (transistors, memristors). In addition, we demonstrated that the presence of inductance in the circuit allows the implementation of a specific synchronization mode of burst generators. This inductive synchronization effect may have practical significance for the introduction of the neurodynamic models in circuit design and brain-machine interface, and requires further, more detailed study.

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