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Nonlinear electronic circuit with neuron like bursting and spiking dynamics

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ABSTRACT

It is difficult to design electronic nonlinear devices capable of reproducing complex oscillations because of the lack of general constructive rules, and because of stability problems related to the dynamical robustness of the circuits. This is particularly true for current analog electronic circuits that implement mathematical models of bursting and spiking neurons. Here we describe a novel, four-dimensional and dynamically robust nonlinear analog electronic circuit that is intrinsic excitable, and that displays frequency adaptation bursting and spiking oscillations. Despite differences from the classical Hodgkin–Huxley (HH) neuron model, its bifurcation sequences and dynamical properties are preserved, validating the circuit as a neuron model. The circuit's performance is based on a nonlinear interaction of fast–slow circuit blocks that can be clearly dissected, elucidating burst's starting, sustaining and stopping mechanisms, which may also operate in real neurons. Our analog circuit unit is easily linked and may be useful in building networks that perform in real-time.

1. Modeling of Biological Bursting Phenomena

Oscillatory electrical activity called bursting is a common feature of single excitable cells in the brain and pancreas, and is thought to underlie some of the normal functions of these organs. Bursting is characterized by quiescent or quasi-stationary states interrupted by episodes of fast spiking activity. Bursting has also been observed in models of artificial neural networks called central patterns generators (Wang and Rinzel, 1995; Coombes and Bressloff, 2005). It is still unknown exactly how bursting is generated, or what causes the frequency adaptation that is seen in inter-spike intervals during a burst. There have been two approaches to analysis of bursting behavior. One is mathematical (Izhikevich, 2000, 2007; Guckenheimer et al., 1997), the other has been the development of analog electronic circuits (Maeda and Makino, 2000; Wijekoon et al., 2008). The advantages of analog circuits are real-time action and connectivity, characteristics that allow large scale neural network building and dynamical modeling (Rabinovich et al., 2006).

Electronic circuits that implement two-dimensional neuron models, such as the integrate-and-fire model and the FitzHugh–Nagumo model (Fitzhugh, 1961; Nagumo et al., 1962), are unable to produce bursting behavior because the models have only one fast timescale closed orbit that simulates the neuron's action potential (AP). In spite of this significant limitation, such circuits are used frequently as building blocks in neural networks. More complex circuits implementing three or higher dimensional models can provide the additional slow timescale variable (Simoni et al., 2004; Le Masson et al., 1999; LaFlaquière et al., 1997) and have been successful in reproducing bursting and frequency adaptation patterns. However, for a long time no one was able to dissect the circuits clearly into their interacting fast and slow parts, and thus understand the transitions between quiescent and oscillatory states through different bifurcation scenarios. The bifurcations are what determine the neuron-computational properties (Izhikevich, 2000). Recently, the bifurcations were geometrically (i.e., mathematically) classified for the Hodgkin–Huxley model (Izhikevich, 2000, 2007). And, we succeeded in reproducing different bifurcation scenarios using Fig. 1 analog circuit (Savino and Formigli, 2007). The Hodgkin and Huxley model (HH) is a multi-dimensional model based on ion channel physiology (Hodgkin and Huxley, 1952).

The goal of this communication is to describe the circuit operation, such as the slow–fast current interaction, voltage-dependence and time-dependence of the intrinsic bursting dynamics, control of its characteristic times, and the effects of external excitations delivered via the input channels. We also present the basic circuit equations for future geometrical analysis and numerical simulation.

2. The Circuit and Its Dynamical Behavior

Our circuit is shown in Fig. 1. The values of the electronic components are given in the legend. The circuit consists of three sections, an input, modulator, and generator. The input section is merely a way to link multiple circuits or to apply external stimuli, and is not necessary for the generation of intrinsic burst dynamics. Details of

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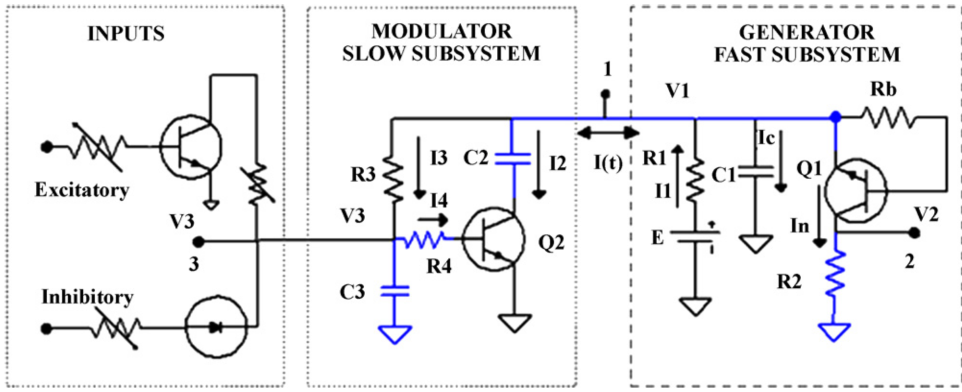

Fig. 1. The bursting and spiking analog circuit. The "frequency adaptation loop" includes $C3$, $R4$, $Q2$ base-collector junction, $C2$, $Q1$ emitter–collector junction and $R2$. Transistors $Q1$ (reverse-biased) and $Q2$ are 2N2222 type, battery $E = 10\,\mathrm{V}$, resistance value in KΩ and capacitances in μF: $R1 = 3.3$, $R2 = 0.1$, $R3 = 100$, $R4 = 1$, $Rb = 50$, $C1 = 1$, $C2 = 10$ $C3 = 2$.

an example of intrinsic bursting behavior exhibited by the circuit is shown in Fig. 2. Bursting is seen at the $V1$ node, $V2$ node, and the $Q2$ collector. The voltage at the $V3$ node displays bursting superimposed on a fluctuating baseline, resulting in a staircase-like pattern. The entire range of bursting behavior possible with the circuit is shown in Fig. 3 with $V2$ and $Q2$ node voltages omitted for clarity. The different dynamics are all produced by changing the variable resistor $R3$, which changes the intensity of the coupling current $I(t)$ between the *generator* and *modulator*. The range of bursting behaviors possible is also summarized in the bifurcation diagram plotted against $R3$ values in Fig. 4. We emphasize here that the role of the coupling current is remarkably non-trivial. It does not merely segment the fast periodic *generator* oscillation into bursts and pauses, but produces variable inter-spike interval sequences and frequency adaptation patterns (Fig. 5) that are similar to those of real neurons.

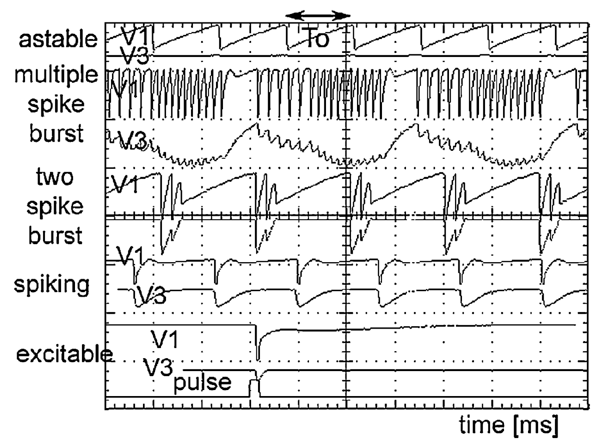

Fig. 3. The range of dynamical behaviors exhibited by the circuit (from top to bottom), as $R3$ is reduced from 400 to 20 KΩ and when $R4 = 10\,\mathrm{K\Omega}$ are shown by the voltage $V1$ at node 1 and voltage $V3$ at node 2, range from astable, to bursting (many to two to single spike), to spiking, to quiescent but excitable. IP indicates the $V3$ voltage inflection in each behavior.

3. The Generator Circuit

When isolated, i.e., when $I(t) = 0$, the *generator* is a classical threshold-negative-resistance oscillator. The negative conductance is implemented by the reverse bias transistor $Q1$ collector–emitter characteristic curve $V_{ec} = V_{ec}(In)$ with an *avalanche* threshold Vth of ≈9.5 V. This is a two-dimensional nonlinear dynamical system in the phase-plane ($V1$, In) with the equations:

$$
\begin{aligned}
L \cdot \frac{dIn}{dt} &= V1 - V_{ec}(In) \\
C1 \cdot \frac{dV1}{dt} &= \left(\frac{E - V1}{R1}\right) - In
\end{aligned}
\qquad (1)
$$

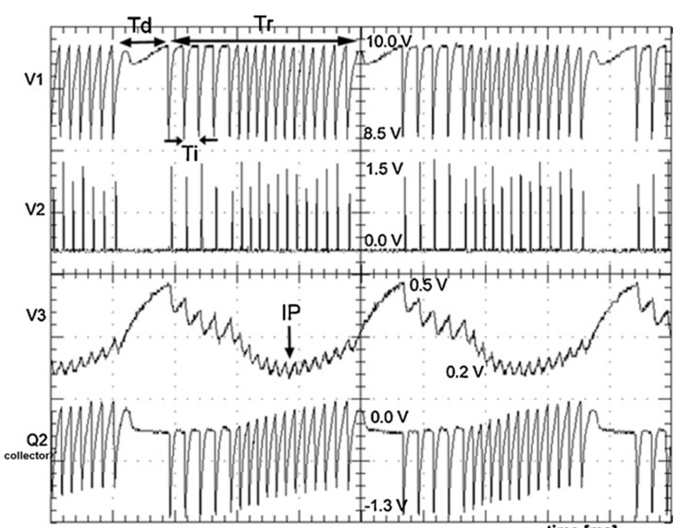

Fig. 2. Typical bursting waveform at nodes 1, 2, 3, and $Q2$ collector. Times T_r and T_d are the durations of the burst and quiescent phases respectively, and T_i is the variable inter-spike interval during a burst. Transistor $Q1$ triggers a pulse or spike each time $V1 > V$th during T_r meanwhile transistor $Q2$ switches between reverse and cutting after the first burst spike and remains saturate ($0.3 < V3 < 0.5\,\mathrm{V}$) during the pause T_d. The staggered voltage $V3$ remains below 0.5 V having the inflection point IP.

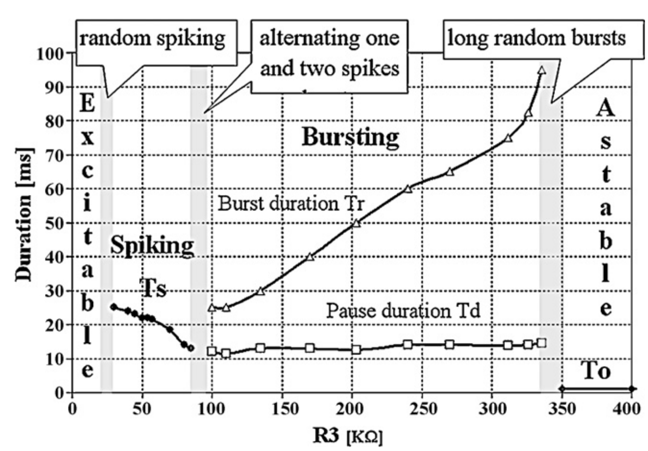

Fig. 4. Codimension-one bifurcation diagram for resistor $R3$ parameter controlling, at the same time, the coupling strength and the burst duration T_r.