# Study of Tunnel Diodes and Design of Simulink Diagrams

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***ABSTRACT:*** *The study of Tunnel diodes with visualization is presented in this work. We have designed an electrical circuit and presented it with elegance. Further, we have developed the study of Simulink diagrams. This process has helped to understand the links between the cascades and electrical circuits.*

**Keywords:** Cascade systems, Chaos, Bifurcation, Bond graphs, Bondsim library

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## 1. Introduction

The appearance of chaos was discerned in practically realized cascade systems before the exact theory of chaos had appeared. In the cascade systems, at great amplifications and the presence of certain nonlinearity, the existence of some motion was noticed. These motions are known as deterministic chaos, and they could not be classified as classically defined motions. As it is well known, deterministic chaos originates as a consequence of bifurcation in nonlinear system at certain values of parameters, [1, 2]. In this case those are system amplifications.

The chaotic motion was analyzed for discrete nonlinear systems firstly, i.e., for the iterative processes of the following type:

$$\mathbf{x_{k+1}} = f(r, \mathbf{x_k}) \qquad (1)$$

where $r$ is the control parameter, $x_k$ is the state vector. At certain value of parameter $r$, bifurcation appears. If that parameter becomes large enough, chaotic motion (depending on function $f$) appears. In the case of Eq. (1) the discrete system is analyzed, where $k$ is discrete time. In this case iteration is running through time.

The theory of deterministic chaos, developed for these systems, can be applied to the cascade connected systems, too, [3, 4]. In this case the iteration is spacious, i.e., each cascade in system presents iteration. While in the case of Eq. (1), iteration repeats in the same system, in the cascade system, the passing of the signal through the line of the cascade connected nonlinear subsystems, of the same structure, presents the iterative process. In that way the same theory, developed for the systems given by Eq. (1), can be applied to the cascade-connected systems analysis.

The trajectories in the cascade connected continuous systems can be very complex, because, besides the iterative processes appearing during the signal passing through the cascades, each system has its own dynamics, which presents more complex case than the system given by Eq. (1).

There are different approaches for deriving mathematical models of cascade connected systems. The one of them is using bond graphs [5-8]. The fundamental advantage of this modeling is that it is based on the central physics concept - energy. Bond graph consists of components which exchange energy or power using connections called bonds. The power is product of two variables: the effort e and the flow *f*. The effort (for example: voltage, force, pressure, etc.) and the flow (for example: current, velocity, volume flow rate, etc.) are generalization of similar phenomenon of physics. Therefore, the second advantage is that bond graphs can be used for the different types of systems (electrical, mechanical, hydraulic systems, etc.) and for their combinations (electro - mechanical, mechanical - hydraulic systems, etc.). The third advantage is that complex systems can be divided into simple elements using bond graphs. Bond graphs give the complete description of dynamical systems and the state space equations can be derived easily.

However, there is no need for deriving the state space equations from bond graphs if the Matlab/Simulink library called Bondsim is used, [9 - 12]. This library enables direct drawing of the Simulink block diagrams from the bond graphs and direct modeling and simulation of chaotic dynamic of cascade connected systems.

## 2. Bondsim – Simulink Library

Bondsim - Simulink library contains elements (blocks) which were derived from bond graph elements based on the knowledge of the causality and the appropriate functional relations between inputs and outputs. The elements of this library and their application are described in detail in [9 - 12], while the method for the direct transformation of causal bond graph models into the block diagrams (Fakri transformation) is described in [13].

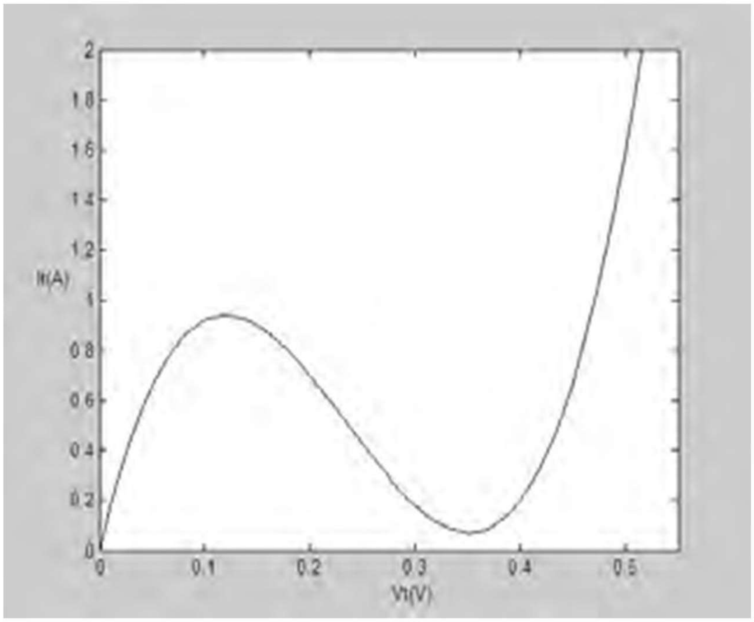


Figure 1. Current – voltage characteristic of tunnel diode

Obtaining the simulation models in the form of block diagrams is done directly from bond graph models. Explicitly written equations are not necessary because the use of Bondsim elements realizes the constitutive relations of the bond graph elements and junctions. Fakri transformation is convenient for direct application of Bondsim elements to optimize Simulink blocks. Using the Bondsim library a visually more distinct simulation model is obtained and it enables simpler manipulation of elements of the simulation model. The application of Bondsim library retained the computational as well as the topological structure of the system.

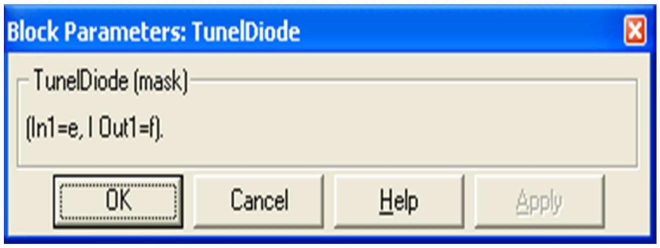
Matlab/Simulink package enables derivation of new elements in the form of blocks. In Section 3 the example of cascade connected electrical circuits is given where the nonlinear element - tunnel diode appears. Bondsim element of tunnel diode is created using the Simulink block Subsystem, i.e., by creating and masking it.

Current – voltage characteristic of tunnel diode is given in Figure 1. From this characteristic can be seen that the voltage – effort is input and the current – flow is output of tunnel diode. Causal Bond graph element of tunnel diode noted as TD is given in Table 1.

Using interpolation the next tunnel diode function, i.e., constitutive relation of the TD bond graph element is obtained:

$$I_t = f(V_t) = 140V_t^3 - 99V_t^2 + 17.7V_t \qquad (2)$$

The equivalent function blocks, Table 1, are derived using the knowledge of causality and relation between input and output of bond graph element TD, Eq. (2). Finally, the Bondsim element of tunnel diode *TD* is formed using Simulink masking option, Table 1, which Dialog box is given in Figure 2. This Dialog box does not require inserting of parameters. It only gives information about input and output of TD element.



Block Parameters: TunelDiode

TunelDiode (mask)

(In1=e, I Out1=f).

Figure 2. The Dialog box of TD Bondsim element

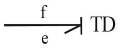
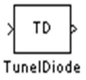
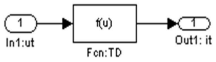
| | |
|---|---|
| Bond graph element |  |
| Bondsim element |  |
| Equivalent functional<br>blocks |  |

Table 1. Bond Graph and Bondsim Element of Tunnel Diode

## 3. CHAOS Modelling

In Figure 3 the system consisting of 30 cascade connected electrical circuits is given. Each cascade has one nonlinear element, tunnel diode.

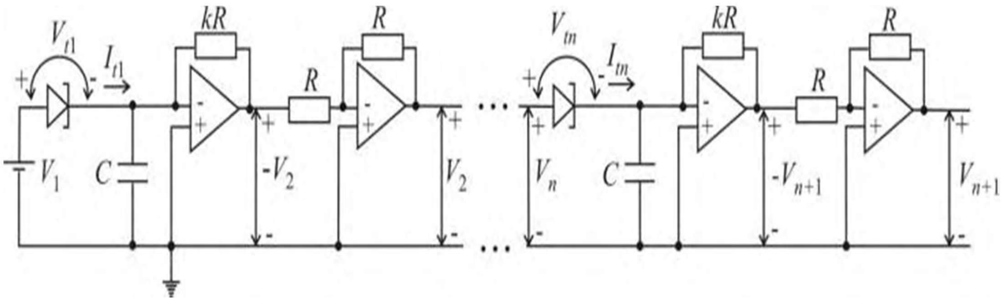


Figure 3. System of 30 cascade connected electrical circuits

For the cascade systems of interest is to consider the following cases:

- The chaotic motion appearing as a result of the complex oscillations in system;
- The chaotic change of quasi steady states in some subsystems.

The second case will be considered further in the paper.

In the quasi steady state all capacitors are open circuits.

Therefore, in the case of the quasi steady state, the system shown in Figure 3 is transformed into the electrical system presented in Figure 4.

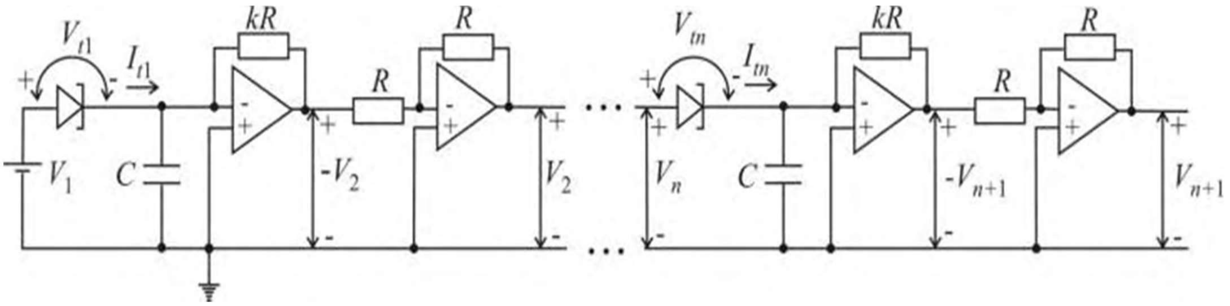


Figure 4. System of 30 cascade connected electrical circuits in the case of the quasi steady state

For each cascade in Figure 4 the next relations hold:

$$\begin{aligned} &V_{ti,s} = V_{i,s} \\ &V_{i+1,s} = k \cdot R \cdot I_{ti,s} \\ &V_{i+1,s} = k \cdot R \cdot f\left(V_{i,s}\right) \\ &i = 1, \ldots, 30 \end{aligned} \tag{3}$$

where *i* is the order of the cascade and k is the control parameter on which value the existence of bifurcation and chaos depends. This equation presents the iterative process of type (1). The iteration is spacious.

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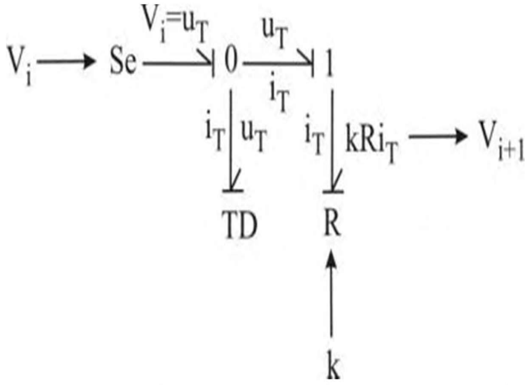

Figure 5. Bond graph model of one cascade

Using the rules for direct transformation of bond graph models into Bondsim models, [10 - 13], Bondsim model of one cascade is obtained and given in Figure 6.

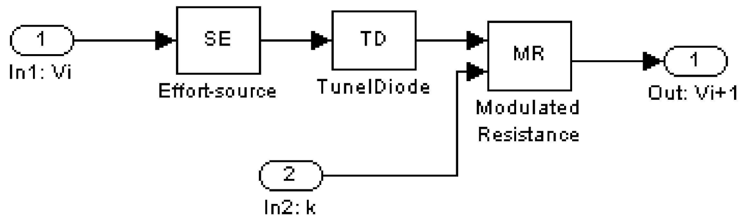

Figure 6. Bondsim model of one cascade

Selecting the Bondsim model in Figure 6 and checking the Simulink option Create subsystem the Simulink block Subsystem of one cascade is fomed, Figure 7.

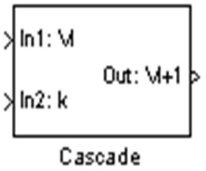

Figure 7. Simulink block Subsystem of one cascade

Bondsim model of system of 30 cascade connected electrical circuits in the case of the quasi steady state, Figure 8, is obtained connecting 30 Subsystems given in Figure 7.

Results of simulation of the oscillatory and chaotic dynamic of cascade systems for $R = 1\Omega$ and input voltage $V_1 = 0.25$V are shown in Figure 9. Figure 9a shows bifurcation diagram, i.e., dependency of the voltages of the cascades $V_{i,s}$ ($i = 1, . . ,31$) in the steady state on the parameter $r$. It can be noted that for a small values of the parameter $r$, the most of cascades have the same output. The first bifurcation appears for $r_1 = 0.2287$, the next one for $r_2 = 0.2897$, and for $r_3 = 0.32$ chaos appears in cascade system.

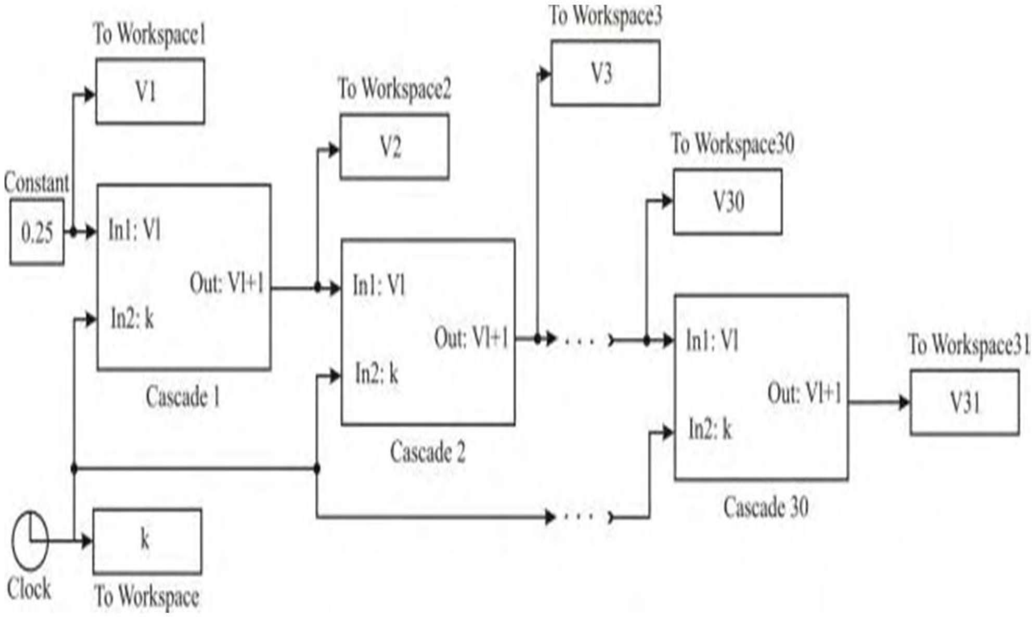

Figure 8. Bondsim model of system given in Figure 4

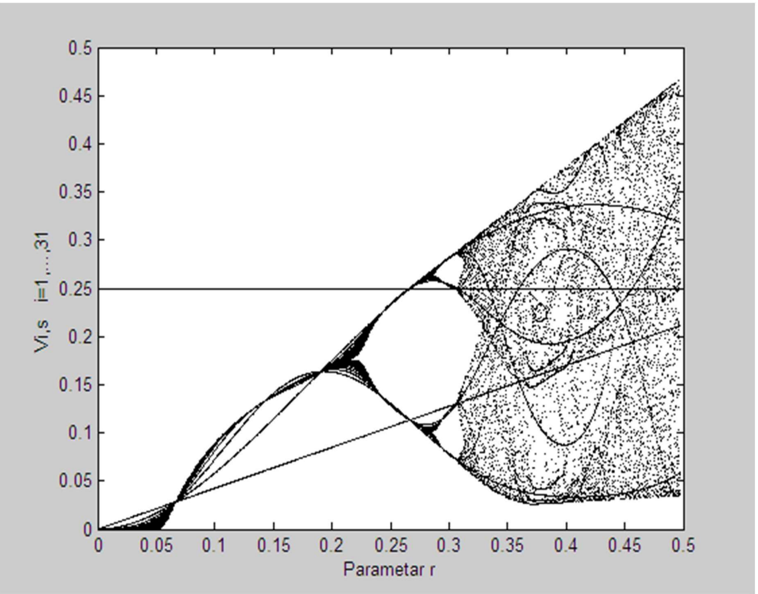

Figure 9a. Bifurcation diagram

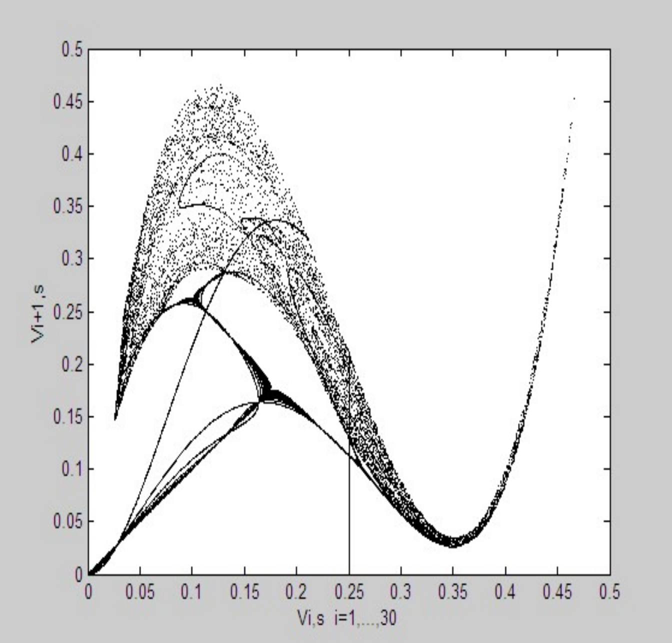

Figure 9b. Dependency of the output of the (*i*+1)-th and the *i*-th cascade on the parameter *k*

Figure 9b shows the phase portrait ($V_{i,s}$ , $V_{i+1+s}$) in function of control parameter *r*. This diagram enabled the analysis of relations between the inputs and outputs of particular pairs of cascades in function of parameter *r*. Also, it enables the determination of optimal value of parameter *r* for the project of cascade systems.

These results are identical with ones given in [4] which were obtained using classical way of modeling, writing *M*-file in Matlab/ Simulink package.

## 4. Conclusion

In cascade systems, the signal passing through the line of cascade connected nonlinear subsystems, of the same structure, presents the iterative process. The trajectories in cascade connected continual systems can be very complex because, besides the iterative process which appears during the passing of the signal through cascades, each system has its own dynamic. For small values of parameter *k*, the outputs of all cascades are nearly same. At great amplification the oscillation appear in the beginning cascades which can cause the appearance of bifurcation and chaos in the next cascades.

Using the nonlinear Bondsim elements a visually more distinct simulation model is obtained and it enables simpler manipulation of nonlinear elements of the simulation model. The application of Bondsim library retained the computational as well as the topological structure of the system. The simple application of proposed method is illustrated using a concrete example of modeling and simulation.

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