Optimized Second-Order Dynamical Systems and Their RLC Circuit Models with PWL Controlled Sources

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Abstract. *Complementary active RLC circuit models with a voltage-controlled voltage source (VCVS) and a current-controlled current source (CCCS) for the second-order autonomous dynamical system realization are proposed. The main advantage of these equivalent circuits is the simple relation between the state model parameters and their corresponding circuit parameters, which leads also to simple design formulas.*

Keywords

Dynamical systems, second-order systems, state models, active equivalent circuits, PWL controlled sources, optimized design formulas.

1. Introduction

Autonomous piecewise-linear (PWL) systems of class C can be described by the general state matrix form [3], [4]

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}\, h\,(\mathbf{w}^{\mathrm{T}}\mathbf{x}) \;; \tag{1}$$

the normalized elementary PWL feedback function (Fig. 1)

$$h\left(\mathbf{w}^{\mathrm{T}}\mathbf{x}\right) = \frac{1}{2}\left(\left|\mathbf{w}^{\mathrm{T}}\mathbf{x}+1\right| - \left|\mathbf{w}^{\mathrm{T}}\mathbf{x}-1\right|\right) \tag{2}$$

contains the regions D_0 and D_{+1} (D_{-1}). The dynamical behavior of the system is determined by two characteristic polynomials related to these individual regions [3]. All the systems of Class *C* having the same characteristic polynomials are qualitatively equivalent and they are related by linear topological conjugacy [4]. Typical systems of this class are the Chua's model, both its canonical forms [3], and also the recently derived optimized state model having the minimum sum of relative eigenvalue sensitivity squares with respect to a change of the individual state matrix parameters [7]. Just this low-sensitivity model is very useful as a prototype for the practical chaotic system realization in a form of electronic circuit. It provides the possibility to utilize a block-decomposed form of the state matrix so that the design procedure can be started from the optimized second-order system and then extended by a simple way to the optimized higher-order case [7], [9].

The state model can be used as a mathematical tool for the numerical simulation of dynamical system behavior as well as a prototype for the electronic circuit realization using available circuit technique. From the complete state equations either the general integrator-based circuit block-diagram (typical for both canonical forms) or the corresponding RLC active circuit (typical for Chua's oscillator) can directly be derived. In both cases only a single PWL network element is used utilizing various types of active electronic blocks operating in both voltage and current modes (op-amps, current conveyors, trans-impedance amplifiers, etc.).

For the optimized low-sensitivity model first the corresponding integrator-based block diagram has been derived for both the second- and the third-order cases [9]. Intention of the paper is to propose the corresponding RLC active circuits where, unlike the Chua's model, the circuit parameters have direct relations to the model parameters.

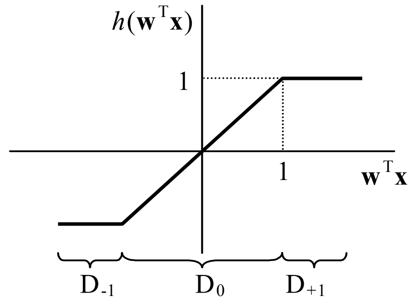

Fig. 1. Simple memoryless PWL feedback function.

2. Second-Order State Models with Optimized Eigenvalue Sensitivities

The most frequently occurring autonomous dynamical systems have their complex conjugate eigenvalues in both regions of PWL function (Fig. 1), i.e. for the inner region (D_0) it is ($\mu_{1,2} = \mu' \pm j\mu''$) and for the outer regions (D_{-1}, D_{+1}) it is ($\nu_{1,2} = \nu' \pm j\nu''$). Then the associated characteristic polynomials are defined as follows

$$(D_0):\quad \mathrm{P}(s) = (s-\mu_1)(s-\mu_2) = \det\,(s\mathbf{1}-\mathbf{A}_0)\;, \tag{3a}$$

$$(D_{-1}, D_{+1}):\quad \mathrm{Q}(s) = (s-\nu_1)(s-\nu_2) = \det\,(s\mathbf{1}-\mathbf{A})\;, \tag{3b}$$

where relation between state matrices can be expressed [3]

$$\mathbf{A_0} = \mathbf{A} + \mathbf{b}\mathbf{w}^{\mathrm{T}} \tag{4}$$

and **1** is the unity matrix. The optimized low-sensitivity state model (1) have been chosen in the simplified and decomposed complex form [7], in which the corresponding state matrices are

$$\mathbf{A} = \begin{bmatrix} \nu' & -\nu'' \\ \nu'' & \nu' \end{bmatrix}, \quad \mathbf{A_0} = \begin{bmatrix} \mu' & -\mu'' K \\ \mu'' K^{-1} & \mu' \end{bmatrix}, \tag{5a,b}$$

and the optimizing coefficient K is given as the real root of the quadratic equation

$$K^2 - 2K(M+1) + 1 = 0,$$

i. e. $K = 1 + M \pm \sqrt{M(M+2)}$

where the auxiliary parameter M is

$$M = \frac{(\mu' - \nu')^2 + (\mu'' - \nu'')^2}{2\mu''\nu''} > 0, \ (\mu'', \nu'' \neq 0).$$

In the vectors $\mathbf{b} = [\, b_1, b_2]^{\mathrm{T}}$ and $\mathbf{w} = [\, w_1, w_2]^{\mathrm{T}}$ one of the parameters can be chosen, e.g. w_1=1, while the others are obtained as [9]

$$b_1 = \mu' - \nu', \quad b_2 = \frac{(\mu' - \nu')^2}{\nu'' - \mu'' K}, \quad w_2 = \frac{\nu'' - \mu'' K}{\mu' - \nu'}. \tag{6a,b,c}$$

Then the complete state equations of the optimized second-order PWL autonomous system can be written as

$$\dot{x} = \nu'[x - h(x + w_2 y)] - \nu'' y + \mu' h(x + w_2 y), \tag{7}$$

$$\dot{y} = \nu'' x + \nu' y + b_2 h(x + w_2 y), \tag{8}$$

where the parameters b_2 and w_2 are given by the formulas (6b,c). The corresponding integrator-based circuit block diagram, suitable also as a prototype for practical realization, is shown in [7]. All the sensitivity functions are obtained in a complex form, so that also the sensitivities expressed separately for the eigenvalue real and imaginary parts, can easily be derived. Then the minimum sums of relative eigenvalue sensitivity squares with respect to the change of the individual state matrix parameters can be expressed for both the real and imaginary parts generally as

$$\sum S_r^2(\lambda', a_{ij}) = \sum S_r^2(\lambda'', a_{ij}) = 1/2, \tag{9}$$

where in the outer regions (D_{-1}, D_{+1}) $\lambda = \nu', \lambda'' = \nu'$ and in the inner region (D_0) $\lambda' = \mu', \lambda'' = \mu''$ [8].

3. Third-Order State Models

Utilizing the results for the second-order systems, the third-order model with upper block-triangular state matrix containing complex decomposed second-order submatrix can be derived [3].

Suppose one pair of the complex conjugate eigenvalues and one real eigenvalue in both outer and inner regions, (i.e. $\nu_{1,2} = \nu' \pm j\nu''$, ν_3 - real; $\mu_{1,2} = \mu' \pm j\mu''$, μ_3 - real). Then the state matrix and the vectors have the form

$$\mathbf{A} = \left[\begin{array}{cc|c} \nu' & -\nu'' & -b_1 \\ \nu'' & \nu' & -b_2 \\ \hline 0 & 0 & \nu_3 \end{array}\right], \quad \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}, \quad \mathbf{w} = \begin{bmatrix} 1 \\ w_2 \\ 1 \end{bmatrix}, \tag{10a}$$

where

$$b_3 = (\mu_3 - \nu_3), \tag{10b}$$

and parameters b_1, b_2, and w_2 are given by (6). Substituting into (4), we can easily derive that the state matrix associated with inner region has the lower block-triangular form

$$\mathbf{A}_0 = \left[\begin{array}{cc|c} \mu' & -\mu'' K & 0 \\ \mu'' K^{-1} & \mu' & 0 \\ \hline b_3 & b_3 w_2 & \mu_3 \end{array}\right], \tag{11}$$

so that such a model has very low eigenvalue sensitivities both in outer and inner regions of the PWL feedback function. The complete state equations of the optimized third-order PWL autonomous system can be then rewritten into

$$\begin{aligned} \dot{x}_1 &= \nu'[x_1 + x_3 - h(x_1 + w_2 x_2 + x_3)] - \nu'' x_2 + \\ &+ \mu' [h(x_1 + w_2 x_2 + x_3) - x_3] \end{aligned}, \tag{12}$$

$$\dot{x}_2 = \nu'' x_1 + \nu' x_2 + b_2 [h(x_1 + w_2 x_2 + x_3) - x_3], \tag{13}$$

$$\begin{aligned} \dot{x}_3 &= \nu_3 [x_3 - h(x_1 + w_2 x_2 + x_3)] + \\ &+ \mu_3 h(x_1 + w_2 x_2 + x_3) \end{aligned}, \tag{14}$$

where the basic individual parameters are separated. However, parameters b_2 and w_2 are given by more complex formulas (6b,c) but the final required effect, i.e. the minimum eigenvalue sensitivities, has been achieved by this.

4. Active RLC Circuit Models with PWL Controlled Sources

To obtain general results in circuit model synthesis the second-order system described by the general state matrix equation (1) is considered, i.e.

$$\mathbf{x} = \begin{bmatrix} x \\ y \end{bmatrix}, \ \mathbf{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \ \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}, \ \mathbf{w} = \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}, \tag{15}$$

which evidently includes also the optimized state model introduced in Chapter 2. In the next part two RLC circuit models containing voltage- and current-controlled sources and possessing simple design formulas are shown.

4.1 Circuit Model Utilizing VCVS

Consider the autonomous RLC circuit introduced in Fig. 2 containing voltage-controlled voltage source

(VCVS) with PWL transfer characteristic function $u_0=f(u_1+R_2 i_2)$ having three segments (Fig. 3) expressed as

$$u_0 = A_1\left(u_1 + R_2 i_2\right) + \left(A_0 - A_1\right) h\left(u_1 + R_2 i_2\right) . \qquad (16)$$

Choosing the capacitor voltage u_1 and the inductor current i_2 as the state variables, both Kirchhoff's equations of this circuit can be written in the basic form

$$\frac{u_0 - u_1}{R_1} + i_2 - C_1 \frac{\mathrm{d}u_1}{\mathrm{d}t} - \frac{u_1}{R_3} = 0 \ , \qquad (17a)$$

$$R_4 i_2 + L_2 \frac{\mathrm{d}i_2}{\mathrm{d}t} + R_2 i_2 - \left(u_0 - u_1\right) = 0 \ , \qquad (17b)$$

and then rewritten to the complete (non-normalized) state equation form, i.e.

$$\frac{\mathrm{d}u_1}{\mathrm{d}t} = \frac{A_1 G_1 - \left(G_1 + G_3\right)}{C_1} u_1 + \frac{A_1 G_1 R_2 + 1}{C_1} i_2 + \frac{A_0 - A_1}{C_1 R_1} h\left(u_1 + R_2 i_2\right) , \qquad (18a)$$

$$\frac{\mathrm{d}i_2}{\mathrm{d}t} = \frac{A_1 - 1}{L_2} u_1 + \frac{A_1 R_2 - \left(R_2 + R_4\right)}{L_2} i_2 + \frac{A_0 - A_1}{L_2} h\left(u_1 + R_2 i_2\right) . \qquad (18b)$$

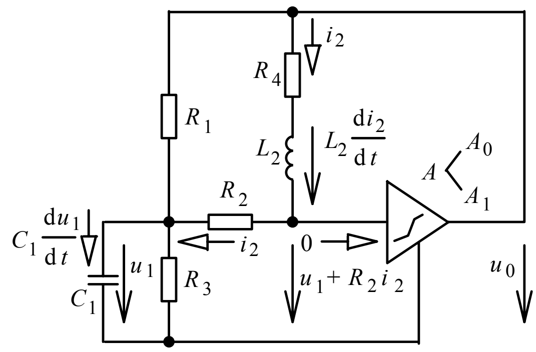

Fig. 2. Second-order autonomous circuit with PWL voltage source.

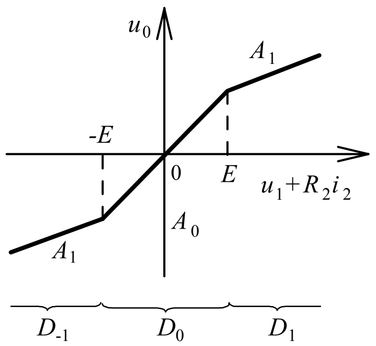

Fig. 3. Transfer PWL characteristic of VCVS.

Utilizing the reference values of voltage E (Fig. 3), resistance R_0, and capacitance C_0 the normalized state variables including the time scaling can be given as

$$x = \frac{u_1}{E}, \quad y = i_2\left(\frac{R_0}{E}\right), \quad \tau = \frac{t}{R_0 C_0} \ . \qquad (19a,b,c)$$

Then the corresponding normalized capacitance, inductance and all resistances are

$$\alpha = \frac{C_1}{C_0} \ , \quad \beta = \frac{L_2}{R_0^{\,2} C_0} \ , \quad r_1 = \frac{1}{g_1} = \frac{R_1}{R_0} ,$$
$$r_2 = \frac{R_2}{R_0} \ , \quad r_3 = \frac{1}{g_3} = \frac{R_3}{R_0} \ , \quad r_4 = \frac{R_4}{R_0} \ . \qquad (20)$$

Denoting $k = \mathrm{sgn}(R_0 C_0)$ the state equations (18) can be rewritten into the normalized forms

$$\dot{x} = \frac{k}{\alpha}\left[\left(A_1 - 1\right) g_1 - g_3\right] x + \frac{k}{\alpha}\left[1 + A_1 g_1 r_2\right] y + \frac{k}{\alpha}\left(A_0 - A_1\right) g_1 \ h\left(x + r_2 y\right), \qquad (21a)$$

$$\dot{y} = \frac{k}{\beta}\left(A_1 - 1\right) x + \frac{k}{\beta}\left[\left(A_1 - 1\right) r_2 - r_4\right] y + \frac{k}{\beta}\left(A_0 - A_1\right) h\left(x + r_2 y\right). \qquad (21b)$$

Comparing them with the general matrix form (15) the following equations can be obtained

$$a_{11} = \frac{k}{\alpha}\left[\left(A_1 - 1\right) g_1 - g_3\right] , \quad a_{12} = \frac{k}{\alpha}\left(1 + A_1 g_1 r_2\right) ,$$
$$b_1 = \frac{k}{\alpha}\left(A_0 - A_1\right) g_1 \ , \qquad w_1 = 1 \ , \qquad (22a,b,c,d)$$

$$a_{22} = \frac{k}{\beta}\left[\left(A_1 - 1\right) r_2 - r_4\right] , \quad a_{21} = \frac{k}{\beta}\left(A_1 - 1\right) ,$$
$$b_2 = \frac{k}{\beta}\left(A_0 - A_1\right) , \qquad w_2 = r_2 \qquad (23a,b,c,d)$$

and then utilized as independent formulas for designing the individual circuit parameters. For the case when α and k are chosen as free parameters the results are summarized in the following design formulas, where both the general and optimized state models are considered.

$$g_1 = \frac{1}{r_1} = \frac{R_0}{R_1} = \frac{\alpha}{\beta}\frac{b_1}{b_2} = \frac{\alpha}{\beta}\frac{\left(\nu'' - \mu'' K\right)}{\left(\mu' - \nu'\right)} \ ,$$

$$r_2 = \frac{R_2}{R_0} = w_2 = \frac{\nu'' - \mu'' K}{\mu' - \nu'} \ ,$$

$$g_3 = \frac{1}{r_3} = \frac{R_0}{R_3} = \frac{\alpha}{k}\left(a_{21} w_2 - a_{11}\right) = \frac{\alpha}{k}\left(\nu'' \frac{\nu'' - \mu'' K}{\mu' - \nu'} - \nu'\right) ,$$

$$r_4 = \frac{R_4}{R_0} = \frac{\beta}{k}\left(a_{21} w_2 - a_{22}\right) = \frac{\beta}{k}\left(\nu'' \frac{\nu'' - \mu'' K}{\mu' - \nu'} - \nu'\right) ,$$

$$A_1 = 1 + \frac{\beta}{k} a_{21} = 1 + \frac{\beta}{k}\nu'' \ ,$$

$$A_0 = 1 + \frac{\beta}{k}\left(a_{21} + b_2\right) = 1 + \frac{\beta}{k}\left[\nu'' + \frac{(\mu' - \nu')^2}{\nu'' - \mu'' K}\right],$$

where the parameter β is generally given as

$$\beta = \frac{L_2}{R_0^2 C_0} = \frac{k\alpha\, b_1 w_2}{\alpha\left(b_2 a_{12} - b_1 w_2 a_{21}\right) - k b_2}\ .$$

4.2 Circuit Model Utilizing CCCS

Consider the autonomous RLC circuit (Fig.4) containing current-controlled current source (CCCS) with the PWL transfer characteristic function $i_0 = f(i_1 + G_2 u_2)$ having three segments (Fig. 5) expressed as

$$i_0 = B_1\left(i_1 + G_2 u_2\right) + \left(B_0 - B_1\right) h\left(i_1 + G_2 u_2\right) \tag{24}$$

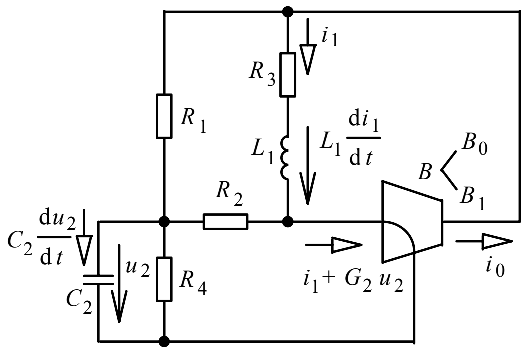

Fig. 4. Autonomous 2nd order circuit with PWL current source.

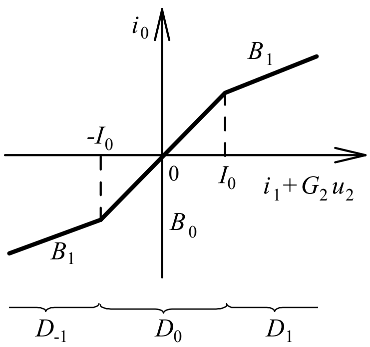

Fig. 5. Transfer PWL characteristic of CCCS.

Choosing the inductor current i_1 and the capacitor voltage u_2 as the state variables, both Kirchhoff's equations for this circuit can be written in the basic form

$$R_3 i_1 + L_1 \frac{\mathrm{d}i_1}{\mathrm{d}t} - u_2 - R_1\left(i_0 - i_1\right) = 0\ , \tag{25a}$$

$$i_0 - i_1 - C_2 \frac{\mathrm{d}u_2}{\mathrm{d}t} - \frac{u_2}{R_4} - \frac{u_2}{R_2} = 0\ , \tag{25b}$$

and then rewritten into the complete (non-normalized) state equation form, i.e.

$$\frac{\mathrm{d}i_I}{\mathrm{d}t} = \frac{B_1 R_1 - \left(R_1 + R_3\right)}{L_1} i_1 + \frac{B_1 R_1 G_2 + 1}{L_1} u_2 + \frac{B_0 - B_1}{L_1 G_1} h\left(i_1 + G_2 u_2\right),$$

$$\frac{\mathrm{d}u_2}{\mathrm{d}t} = \frac{B_1 - 1}{C_2} i_1 + \frac{B_1 G_2 - \left(G_2 + G_4\right)}{C_2} u_2 + \frac{B_0 - B_1}{C_2} h\left(i_1 + G_2 u_2\right).$$

(26a,b)

Utilizing the reference values of voltage E (in Fig. 5 $I_0 = E/R_0$), resistance R_0, and capacitance C_0 the normalized state variables including the time scaling can be defined as

$$x = i_1\left(\frac{R_0}{E}\right), \qquad y = \frac{u_2}{E}, \qquad \tau = \frac{t}{R_0 C_0}\ . \tag{27a,b,c}$$

Then the corresponding normalized inductance, capacitance, and all resistances are

$$\alpha = \frac{L_1}{R_0{}^2 C_0}, \qquad \beta = \frac{C_2}{C_0}, \qquad r_1 = \frac{R_1}{R_0},$$

$$r_2 = \frac{1}{g_2} = \frac{R_2}{R_0}, \quad r_3 = \frac{R_3}{R_0}, \qquad r_4 = \frac{1}{g_4} = \frac{R_4}{R_0}\ . \tag{28}$$

Denoting $k = \mathrm{sgn}(R_0 C_0)$ the state equations (26) can be rewritten into the normalized forms

$$\begin{aligned}\dot{x} = {} & \frac{k}{\alpha}\left[\left(B_1 - 1\right) r_1 - r_3\right] x + \frac{k}{\alpha}\left(1 + B_1 r_1 g_2\right) y + \\ & + \frac{k}{\alpha}\left(B_0 - B_1\right) r_1 h\left(x + g_2 y\right)\end{aligned}, \tag{29a}$$

$$\begin{aligned}\dot{y} = {} & \frac{k}{\beta}\left(B_1 - 1\right) x + \frac{k}{\beta}\left[\left(B_1 - 1\right) g_2 - g_4\right] y + \\ & + \frac{k}{\beta}\left(B_0 - B_1\right) h\left(x + g_2 y\right)\end{aligned}. \tag{29b}$$

Comparing them with the general matrix form (10) for the second-order system the following equations are obtained

$$a_{11} = \frac{k}{\alpha}\left[\left(B_1 - 1\right) r_1 - r_3\right], \qquad a_{12} = \frac{k}{\alpha}\left(1 + B_1 r_1 g_2\right),$$

$$b_1 = \frac{k}{\alpha}\left(B_0 - B_1\right) r_1, \qquad w_1 = 1, \tag{30a,b,c,d}$$

$$a_{22} = \frac{k}{\beta}\left[\left(B_1 - 1\right) g_2 - g_4\right], \quad a_{21} = \frac{k}{\beta}\left(B_1 - 1\right),$$

$$b_2 = \frac{k}{\beta}\left(B_0 - B_1\right), \qquad w_2 = g_2 \tag{31a,b,c,d}$$

and then utilized as independent formulas for the design of the individual circuit parameters. For the case when β and k are chosen as free parameters the results are summarized in the following design formulas where again both the general and optimized state models are considered.

$$r_1 = \frac{R_1}{R_0} = \frac{\alpha}{\beta}\frac{b_1}{b_2} = \frac{\alpha}{\beta}\frac{\left(\nu'' - \mu'' K\right)}{\left(\mu' - \nu'\right)},$$

$$g_2 = \frac{1}{r_2} = \frac{R_0}{R_2} = w_2 = \frac{\nu'' - \mu'' K}{\mu' - \nu'},$$

$$r_3 = \frac{R_3}{R_0} = \frac{\alpha}{k}\left(a_{21} w_2 - a_{11}\right) = \frac{\alpha}{k}\left(\nu'' \frac{\nu'' - \mu'' K}{\mu' - \nu'} - \nu'\right),$$

$$g_4 = \frac{1}{r_4} = \frac{R_0}{R_4} = \frac{\beta}{k}\left(a_{21}w_2 - a_{22}\right) = \frac{\beta}{k}\left(\nu''\frac{\nu'' - \mu''K}{\mu' - \nu'} - \nu'\right)$$

$$B_1 = 1 + \frac{\beta}{k}a_{21} = 1 + \frac{\beta}{k}\nu'' \ ,$$

$$B_0 = 1 + \frac{\beta}{k}\left(a_{21} + b_2\right) = 1 + \frac{\beta}{k}\left[\nu'' + \frac{(\mu' - \nu')^2}{\nu'' - \mu''K}\right] ,$$

and where the parameter α is generally given as

$$\alpha = \frac{L_1}{R_0^2 C_0} = \frac{k\beta b_2}{\beta\left(b_2 a_{12} - b_1 w_2 a_{21}\right) - k b_1 w_2} .$$

Any other details about the realization conditions of the individual circuit elements for both circuit models are presented in [10].

The corresponding circuit models can easily be developed from circuits shown in Fig. 2 and Fig. 4 and then used as the prototypes for the practical realization of the optimized chaotic oscillator.

5. Conclusion

This contribution deals with the second-order nonlinear dynamical systems and their realizations using active RLC circuits in which the VCVS and CCCS with three-segment PWL symmetric transfer characteristics are considered as the active elements. This is suitable especially for voltage- and current-mode realizations. The dynamical behavior of such a system is determined by two sets of complex conjugate state matrix eigenvalues associated with the corresponding regions.

The contribution presents the complete and normalized state equations in which the simple relation between the model and the circuit parameters entails also very simple design formulas in the synthesis procedure either in general or optimized (low eigenvalue sensitivities) forms. Circuits proposed represent one possibility of the second-order system realization and can be easily extended also for the third-order system utilizing the block decomposition of the state matrix [7]. Such higher-order equivalent circuit can model also a chaotic behavior of the system.

Acknowledgements

This research is partially supported by the Czech Grant Agency, grant projects no. 102/02/1312/A and no. 102/04/0469. It represents the parts of the Research Programs of the Czech Ministry of Education – CEZ: J22/98: 262200011 and CEZ: J22/98: 262200022.

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