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13th INTERNATIONAL SYMPOSIUM on
POWER ELECTRONICS - Ee 2005
XIII Međunarodni simpozijum Energetska elektronika – Ee 2005
NOVI SAD, SERBIA & MONTENEGRO, November 2nd - 4th, 2005

POWER ELECTRONIC CIRCUITS SIMULATION USING IDEAL SWITCHES

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Abstract: *The recent model of an internally or externally controlled ideal switch is described. General nonperiodical switching is considered. No limitations regarding the circuit structure and complexity are imposed. Application to variety of electronic circuits is demonstrated. Special attention is paid to electronic power circuits such as switched power supplies and converters.*

Key Words: ***Electronics, Power circuits, Simulation, Switches.***

1. INTRODUCTION

Power electronic components (transistors, thyristors, and diodes) are often, for convenience, modeled as switches. Instances of such models may be found in switched capacitor or switched-current networks, switched power supplies, mixed signal circuits such as A/D converters [1] etc. The advantage of using ideal switches in circuit simulation is explained in [2]. To simplify, if nonideal models are used in a SPICE-like simulation, simulation of the resulting stiff system demands long simulation times. When switches are modeled as ideal, simulation for the switch transition is performed in one time instant, rather then as a step transition of voltages and currents. It saves simulation time without significant error in the simulation results. It is our experience that in circuits where switches are predominant elements time overheads are reduced by order of magnitude.

Several approaches have been used for analysis of switched networks. Externally controlled switches and a restricted set of circuit elements are used in switched-capacitor (SC) networks [3, 4]. SC networks are a subset of periodically switched linear networks. Techniques to analyze such problems are described in [5] and [6], but such methods cannot be used for the circuits with internally controlled switches.

One group of methods used for the time-domain simulation of internally controlled switched networks is based on state variable formulation. These are, however, difficult to implement in a general purpose electronic simulation program. A summary of this class of methods can be found in [7]. Recently in [8] additional results were reported suffering, however, the same deficiencies related to both possibility of implementation in general purpose simulation program, and restriction to the set of circuit elements.

Algorithms for analysis of linear networks with internally controlled switches are described in [7] and [9]. The method in [9] enables simulation of linear systems where inconsistent initial conditions occur after switching. In networks with internally controlled switches, the Dirac impulses of voltage or current can cause changes of states of other switches in network. Algorithms that take this into consideration are described in [7] and [10]. It is shown that nonlinear storage elements (capacitors and inductors) must be represented by charges and fluxes.

Recently in [11] new switch models were reported suffering, however, the same deficiencies related to possibility of implementation in systems with large number of switches commutated asynchronously.

We started our research in this field by recognizing the fact that circuits with switches, no matter how many of them are present in the circuit, and no matter the structure of the circuit and the nature of the rest of the elements, are nonlinear per se. Or, putting that in other words: there are no linear circuits if switches are present. Nonlinear circuits are, in general, described by nonlinear equations that are unavoidably solved by iterative procedures. The switch is nonlinear as it can be, so that, the ideal switch model proposed recently [12, 13] is suitable for the time-domain simulation of networks containing externally and internally controlled switches. Our switch model is intended for use with standard SPICE-like simulator. Namely, the switch is considered as a circuit element and managed during circuit description, or simulator's code writing, as any other element (resistor, diode etc.)

The main motivation for this research was the fact that the current versions of the switch model implemented in SPICE are non-ideal, with low R_{on} resistance and high R_{off} resistance [14]. When finite values of switched resistances are used, however, the eigenvalues in the system are extreme, and the simulation demands very long CPU times. Switch models with energy storage elements [15] can prevent such extreme eigenvalues and the simulation becomes somewhat faster.

The structure of the paper is as follows. Ideal switch model is presented in Section 2. The paper is concluded with a simulation examples demonstrating computational efficiency of the presented ideal switch model.

2. NONLINEAR IDEAL SWITCH MODEL

2.1. Limitations of the Usual Ideal Switch Model

A closed switch, connected between nodes j and k is modeled as a zero-valued voltage source

$$v_j - v_k = 0 \tag{1}$$

If the switch is open, the model is equivalent to zero valued current source:

$$i = 0 \tag{2}$$

where i is the current through the switch, flowing from the node j to node k. We adopt the Newthon/Raphson procedure that is applied in most circuit analysis programs, and our model is expressed in such a way to be easily applicable in this kind of programs.

It would seem that one could replace the stamp (contribution to the system matrix) of the closed switch by another when the switch transition occurs. Unfortunately, this leads to numerical problems in a SPICE-type program, since the switch transition changes the network topology, and this is reflected in the change of the structure of the nonzero entries in the system matrix. If such model were implemented, a new reordering and pivoting in the matrix would be necessary after every switch transition.

2.2. Nonlinear Model of the Closed Switch

Our first concern is to define the switch model that would have the same structure of nonzero entries for both states [12, 13]. Let us first consider the closed switch. The problem here is that the zero entry appears on the main diagonal of the matrix. However, for circuit simulation (1) can be replaced by

$$(v_j - v_k) - r \cdot i = -r \cdot i^m \tag{3}$$

where r is a new model parameter with dimension of resistance. Superscript m denotes iteration counter, and i^m denotes the value of the current obtained in the previous iteration. When convergence is reached, the current in (m+1) th iteration equals that from m th iteration:

$$i = i^m \tag{4}$$

and one obtains the equation for the closed switch (1).

Convergence is faster when lower values of r are used. Nevertheless, too low value of parameter r could lead to numerical problems. We have found the value of $10^{-5}\,\Omega$ enables fast convergence and is high enough to avoid numerical problems.

2.3. Nonlinear Model of the Open Switch

For the open switch we introduce a new model

$$v_j - v_k - R \cdot i - v_j^k - v_k^m \tag{5}$$

where R is a model parameter with the dimension of resistance. When the convergence is reached, the voltages from (m+1) th and m th iteration are equal

$$v_j = v_j^m, \quad v_k = v_k^m \tag{6}$$

and from (6) one obtains (2) which models the open switch.

The convergence will be reached in smaller number of iterations if R is higher, but too high value could lead to numerical problems. We found the value of $10^9\,\Omega$ convenient.

With our choice of values r and R, the numbers of iteration necessary for convergence of nonlinear switched networks is not affected by our switch model, it is determined by other nonlinear devices in the network.

The stamps corresponding to the open and closed ideal switch model can be found in [12, 13]. No zero main diagonal entries are generated and the structure of the nonzero entries in the stamp is the same for both switch states.

With the described model we have obtained switch transitions that change the network topology, but not the structure of nonzero entries in the sparse matrix. Reordering of the matrix after switch transition is not necessary. The use of nonlinear switch model requires iteration even if the rest of the network is linear, but the convergence is reached quickly, while the algorithms for iterative solutions of nonlinear networks are built into any SPICE type program. When analyzing networks with other nonlinearities, our nonlinear switch model does not noticeably increase the number of iterations.

3. SIMULATION EXAMPLES

Simulation examples presented in this section demonstrate the versatility and effectiveness of the ideal switch model described. Simulations were performed using Alecsis [15-17] simulator.

As discussed in [7, 10], the problem of inconsistent initial conditions is not only to conserve the charge and the flux. It is important to take into account Dirac impulses that can occur at the instant of switching. The problem will be explained on the ideal buck-boost switching converter [18, 19], given in Fig. 1(a). The switch S represents the transistor that is externally controlled. The diode is modeled as an ideal internally controlled switch. One can model this diode using a control variable p:

$$D: \begin{cases} \text{closed} & \text{if } p > 0 \\ \text{open} & \text{if } p < 0 \end{cases} \qquad p = \begin{cases} i & \text{if } D \text{ is closed} \\ v_j - v_k & \text{if } D \text{ is open} \end{cases} \tag{7}$$

Therefore, p is an internal circuit variable and its value is determined in every iteration.

When switch S is closed and switch D open, the circuit is shown in Fig. 1(b) and inductor current i_L is linearly increasing. When S is externally opened i_L has no closed loop and drops instantaneously to zero, and a Dirac impulse of voltage appears on the inductor. It changes the switch control variable p to a positive value, and D closes. When this happens, the inductor current has a closed loop, Fig. 1(c), and there is no discontinuity in its value. There is no impulse of the inductor voltage, but the Dirac impulse is needed to switch the diode D, i.e., to change the value of the control variable p.

A similar condition occurs when *S* is again closed. If i_L has not decayed to zero, *D* is still closed and the capacitor is connected to the voltage source trough *S* and *D*. A Dirac impulse of current flows through the capacitor, the switches *S* and *D*, and the voltage source. This current impulse flows in opposite direction trough *D*, and changes the control variable *p* to a negative value. This opens diode *D* at the same time instant as *S* is closed, and, as a consequence, the capacitor is not directly connected to the voltage supply in any time instant.

Simulation results for the buck-boost converter with our switch model are presented in Fig. 2. The element values are $E = 1\,\text{V}$, $L = 150\,\mu\text{H}$, $C = 50\,\mu\text{F}$, and $R = 10\,\Omega$. The switching period for S is $70\,\mu\text{s}$, and the duty cycle was 3/7.

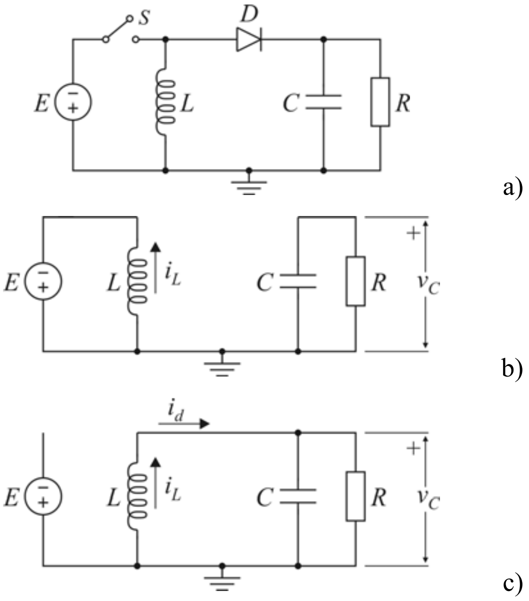

Fig. 1. *a) Ideal buck-boost switching converter. b) Equivalent circuit for s closed and D open. c) Equivalent circuit for s open and D closed.*

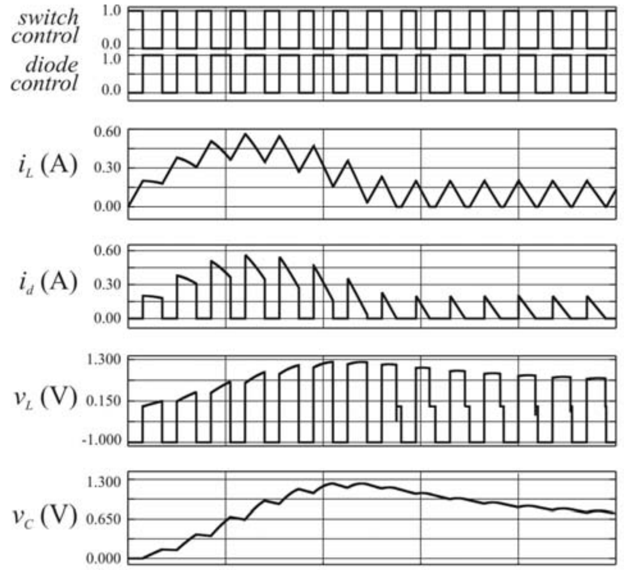

Fig. 2. *Simulation results for the buck-boost converter.*

It can be noted that our model takes into account the Dirac impulse, although no explicit methods are used for that. With our model, one obtains Dirac impulse with very high number (amplitude) after the first iteration. Since the solution from one iteration is used to determine the conditions for the next iteration, this Dirac impulse can change the states of the internally controlled switches in the circuit.

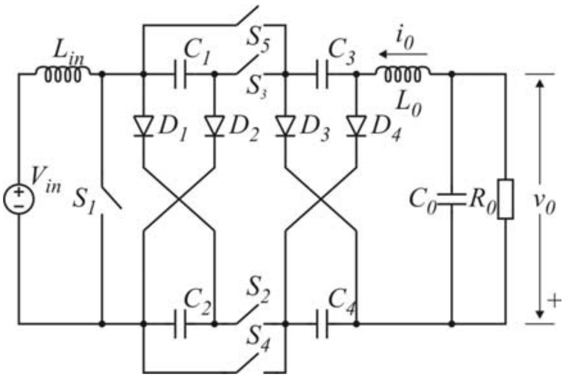

Fig. 3. *The new hybrid Ćuk converter with four capacitors [20].*

We will continue our review of simulation examples by examining the recently proposed hybrid Ćuk converter with four capacitors [20]. It is an improved version of the original Ćuk converter. The circuit schematic is depicted in Fig. 3. Simulation results for this circuit are depicted in Fig. 4. Here, the responses of the load current and the load voltage are presented to a step of input voltage. The switches are externally controlled at rate of $f_S = 50\,\text{kHz}$. The simulated circuit elements are $V_{in} = 12\,\text{V}$, $D = 0.75$, $L_{in} = 600\,\mu\text{H}$, $L_0 = 600\,\mu\text{H}$, $C_1 = C_2 = C_3 = C_4 = 22\,\mu\text{F}$ and $C_0 = 1\,\mu\text{F}$. These parameters are not optimized from the point of view of circuit performance.

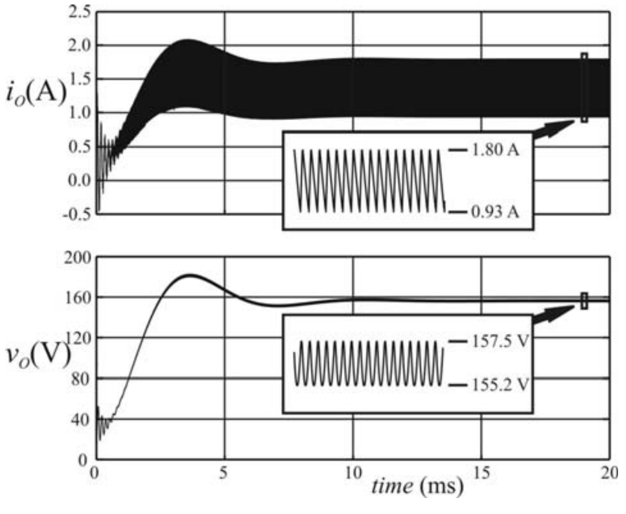

Fig. 4. *Simulation results (step response) for the new hybrid Ćuk converter with four capacitors (Fig. 3.) Top: load current, bottom: load voltage.*

4. CONCLUSION

Considering the fact that any circuit containing ideal switch is nonlinear, we developed model for the ideal switch that is applicable in a general-purpose time-domain circuit simulation program. The switch is considered as circuit element and used by routine as simple as any other circuit element. One of the important properties of the model is that it handles real situations such as managing the Dirac pulse that is encountered when switching real circuits. Here, a set of examples is presented expressing, to our opinion, the effectiveness of the model and its versatility.

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