INTERACTIVE ANALYSIS OF SWITCHED DC-DC CONVERTERS IN MICRO-CAP

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ABSTRACT:

Interactive Transient, DC and AC analyses of switched DC-DC converters in Micro-Cap program v.9 are described. Averaging models of converters complete the conventional switch-level models in order to display converter average voltages, currents, powers, and efficiency directly on the schematic workplace. The results of the simulation are dynamically updated just after modifying the circuitry. The models presented also enable a direct steady-state computation including information about the switching effects such as the voltage and current ripple.

Keywords: DC-DC converter, boost converter, SPICE, averaging

1 INTRODUCTION

Modeling of switched DC-DC converters with a view of their analysis in SPICE-family programs should take into account the existence of electronically controlled analog switches inside the circuit. It has negative impact on all three basic SPICE analyses. The Transient analysis becomes very uneconomical because the analyzed phenomena consist of a slow "signal" component and of incomparably faster switching effects [1]. The internal SPICE algorithms have to accommodate its computational steps to the fast component. This fact results in time-consuming transient analyses [2]. Moreover, users are mostly interested in converter steady-state behavior, which are often reached hardly via repeated analyses of slowly converged transients. DC and AC analyses are not directly utilized in switched circuits. On the other hand, the steady-state "DC" values of voltages and currents, and from them computed average powers and converter efficiency, as well as „line-to-output" and „control-to-output" frequency responses [3] belong to most practical and monitored parameters. The above problems can be solved by the so-called averaging modeling [1], which enables the utilization of conventional DC and AC analyses. For Transient analysis, the analysis runs are much faster but at the cost of the loss of any information about the switching effects which are completely smoothed during the averaging process.

Combining switch-level and average models enables versatile analysis of switched converters, utilizing all three basic SPICE analyses. The weak point is the Transient analysis because it is most time-consuming. It is in a contrast to the needs of a fast interactive analysis, when designer modifies some converter parameters, let us say the load resistance or the duty ratio, and he requires – preferably immediately – the effect, i.e. new behavior of the circuit. Such requirements are in a direct contrariety to the time-consuming SPICE algorithms and also to the limitation of most SPICE-family programs with respect to their support of interactive modes of the analysis.

The solution, proposed in the paper, has the following logic: 1. It is necessary to make use of such SPICE-family program which includes advanced techniques of interactive analyses. 2. It is necessary to utilize “clever” algorithms which enable avoiding the time consuming Transient analysis.

Utilization of Micro-Cap program [4] is a consequence of item 1. Cooperation with Spectrum-Software company led to several substantial Micro-Cap innovations. Some interactive analyses are implemented in version 9, directly supporting the above demands on the interactive mode of operation.

The item 2 involves the analysis of switching effects by another way than via Transient analysis. This unconventional demand has been fulfilled through developing an original method of finding periodical steady states via fast DC analysis [5]. To provide more precise averaging analysis, a generalized model of the PWM (Pulse Width Modulation) switch has been developed which models realistically some parasitic parameters of semiconductor switches [6].

2 IMPLEMENTED ALGORITHMS OF AVERAGING MODELING AND STEADY-STATE ANALYSIS OF SWITCHING EFFECTS

For more precise modeling of the active (transistor) and the passive (diode) switch with consideration of their on-resistances and voltage drop on passive switch, a generalized model of PWM switch was developed as an extension of model according to Dijk [7]. The principle is shown in Fig. 1.

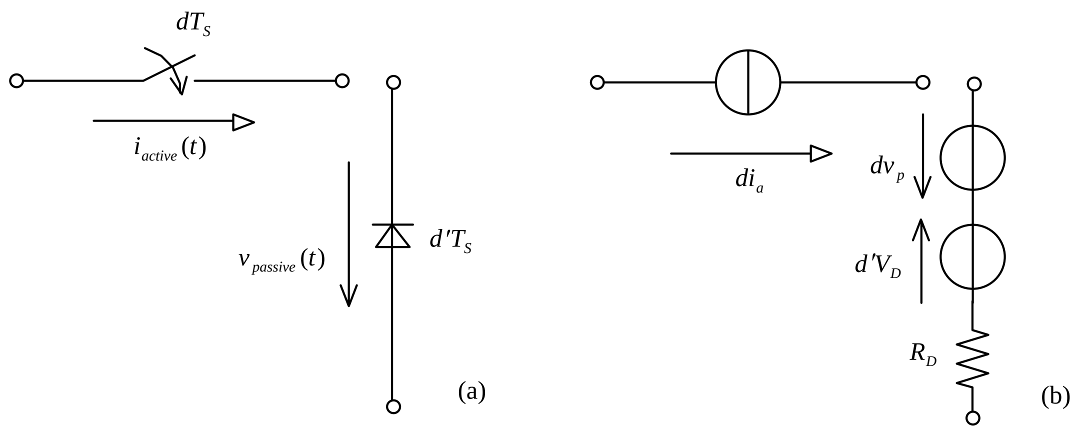

Fig. 1: (a) Pair of active and passive switches, (b) their averaged model. T_s is switching period, d is the duty ration, d‘=1-d, V_D is diode forward voltage drop, R_D is diode differential on-resistance [6].

The current i_a and the voltage v_p can be obtained from the inspection of the converter according to the following rules [6]:

Rule 1: i_a equals the current through the closed active switch during a time interval dT_S, written as a function of the state and input variables.

Rule 2: v_p equals the voltage across the open passive switch during a time interval dT_S, written as a function of the state and input variables.

Note that the symbols v_p and i_a represent averaged values of voltage $v_{passive}(t)$ and current $i_{active}(t)$ within the switching period T_S.

After replacing the switches by their models in Fig. 1 (b), the model of stationary linear circuit is obtained which enables a fast Transient analysis and also makes available DC and AC analyses.

The below described algorithm of computing the coordinates of periodical steady state, implemented in Micro-Cap, works well for DC-DC converters in Continuous Conduction Mode (CCM). It is based on the assumption that in the steady state the capacitor current and inductor voltage can be approximated with sufficient precision by piece-wise line according to Fig. 2. As shown in [5], this assumption is fulfilled in most practical cases when the converter is properly designed. Then the limit values of the state variables, i.e. capacitor voltage and inductor current, are described by Eqs. (1) and (2) [5]:

$$V_{C1-} = V_{C2+} + \frac{dT_S}{2C}(I_{C2+} + I_{C1-}),\ V_{C2-} = V_{C1+} + \frac{d'T_S}{2C}(I_{C1+} + I_{C2-}) \tag{1}$$

$$I_{L1-} = I_{L2+} + \frac{dT_S}{2L}(V_{L2+} + V_{L1-}),\ I_{L2-} = I_{L1+} + \frac{d'T_S}{2L}(V_{L1+} + V_{L2-})\,. \tag{2}$$

In [5], the above equations are starting points for modeling the capacitor and the inductor by means of controlled sources. The converter model is compiled separately for both switching phases and also for transitions from phase 1 to phase 2 and from phase 2 to phase 1. Instead of one original model, more general model consisting of 4 partial models is analyzed. DC analysis then automatically provides the left-and right-side limits of each circuit variable at both time points which correspond to the changes of switch states.

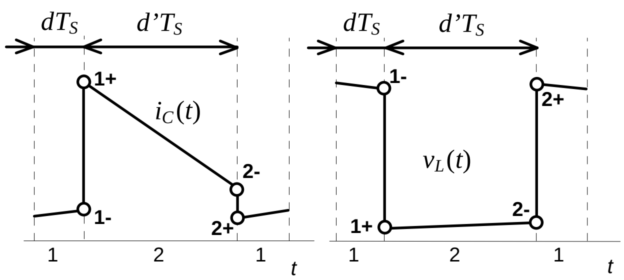

Fig. 2: Piece-wise approximation of time derivatives of converter state variables.

3 INTERACTIVE ANALYSES IN MICRO-CAP

In Micro-Cap version 9, the following techniques of interactive analyses are implemented which can play a key role in the analysis of switched DC-DC converters:

Dynamic DC and Dynamic AC analyses.

When performing these analyses, user is working in the environment of schematic editor. The analysis results are displayed as voltages, currents, powers, states of semiconductor devices, and other selected quantities just in the circuit schematics. Any circuit modification is automatically reflected in the displayed results. DC circuit variables are shown during the DC analysis, and the information about the harmonic steady state at defined frequency (amplitude, initial phase, or real and imaginary values) during the AC analysis.

A number of other tools such as the so-called “Formula Text” [8] serve for displaying the circuit variables and various circuit parameters.

Dynamic Analysis Mode.

This mode can be made active in frame of the basic Transient, AC, and DC analyses. Each modification of the simulation task causes redrawing the actual characteristic of the circuit (waveform in Transient analysis, frequency response in AC analysis, and DC characteristic in DC analysis). Curves can be either redrawn or accumulated according to user’s choice.

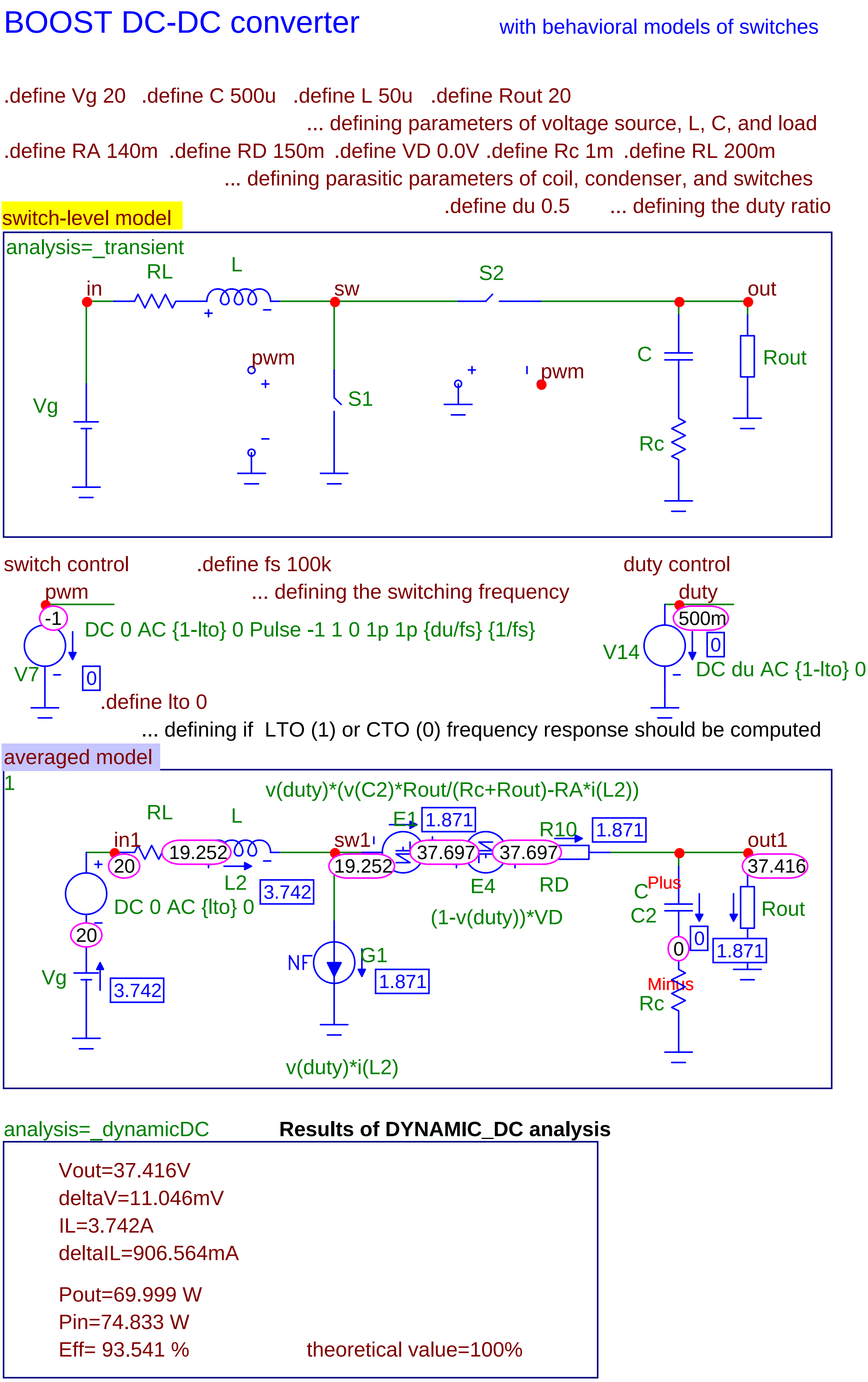

Fig. 3: Demonstration of complex model of DC-DC converter in Micro-Cap.

The “Leave” option, which overcomes the well-known limitations of programs such as OrCad PSpice, can be useful for finding the steady states in conventional Transient analysis. When “Leave” is enabled, program stores the final circuit state at the end of the analysis. When running the analysis again, this state is used as an initial condition.

Other supporting tool which can be useful for simulating the DC-DC converters is called „Region enable/disable“. More versions of circuit model can be simultaneously defined in the frame of a single circuit file, for example the switched-level and averaging models of the converter. Each portion of the circuit can be drawn inside a special region. Each region cal ne locally enabled or disabled via a Boolean formula. In such a way, one can arrange that the switched-level model can be active only during the transient analysis.

4 DEMONSTRATION OF INTERACTIVE ANALYSIS

A complex model of BOOST converter in Micro-Cap is shown in Fig. 3. The switched-level model is closed to the “Region Box” which is active only during the Transient analysis, whereas the averaging model is always active. Switches in averaging model are modeled according to Fig. 1 (b) and Rules 1 and 2. The converter model for automated computation of steady-state coordinates according to Eqs. (1) and (2) is defined on another schematic page and is not described here. The last “Region Box” is active only for Dynamic DC Analysis. It offers a survey information about average output voltage and inductor current and their ripple in the steady state, about the powers and converter efficiency. For a comparison, theoretical values of these quantities are computed on the assumption of the absence of any losses in the circuit and displayed next to real values. This picture was scanned during the Dynamic DC analysis. That is why the actual circuit variables are displayed just on the schematics. Data from the bottom “Region Box” are drawn from the averaging model and also from the model for computing the steady-state coordinates. Note that any change of data on the workplace, e.g. the lossy resistance of the inductor, duty ratio, etc., causes the refreshing of the analysis results.

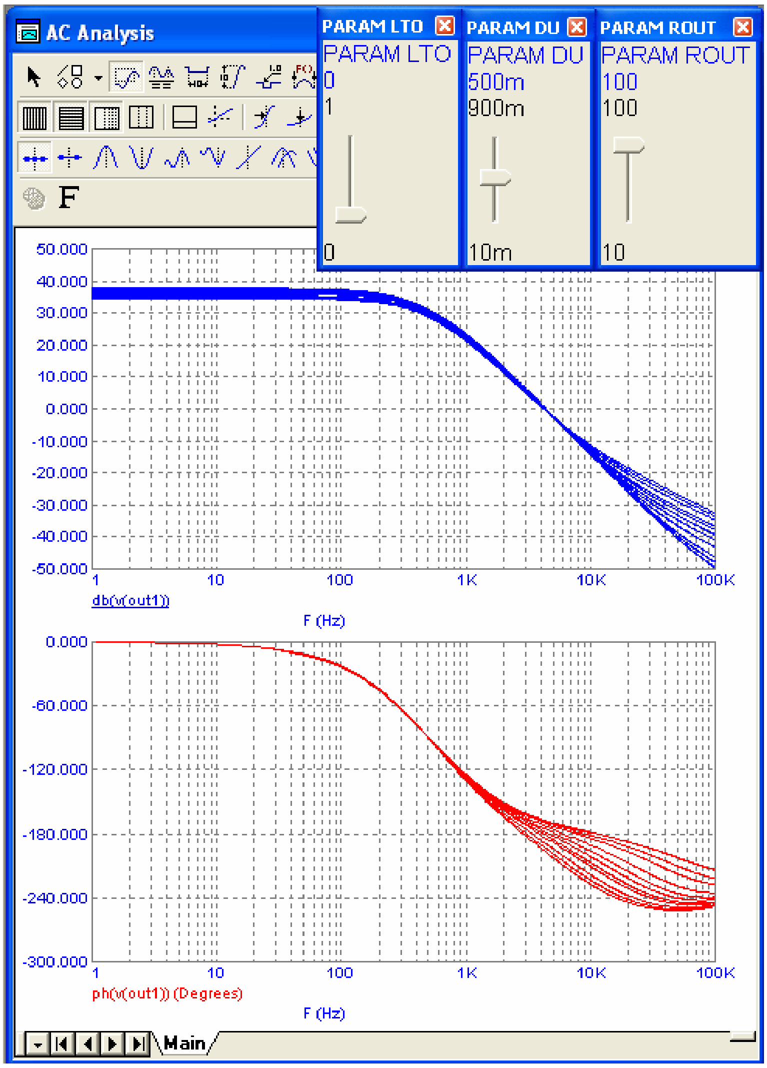

Fig. 4: Demonstration of interactive AC analysis.

Fig. 4 demonstrates the AC analysis in the dynamic mode, namely the Line-to-Output and Control-to-Output frequency responses. The type of the response can be selected via two-state global variable „lto“ (see

Fig. 3). Any change of the input data in the schematic editor is accompanied by redrawing the plots. For convenience, “sliders” can be placed near the “analysis results” window for fast modification of the parameters under the interest (see Fig. 3).

A demonstration of conventional DC analysis is displayed in Fig. 4. Thanks to the complex model of the converter, it enables very fast plotting of important dependences, for example, how the output voltage ripple depends on the duty ratio, etc.

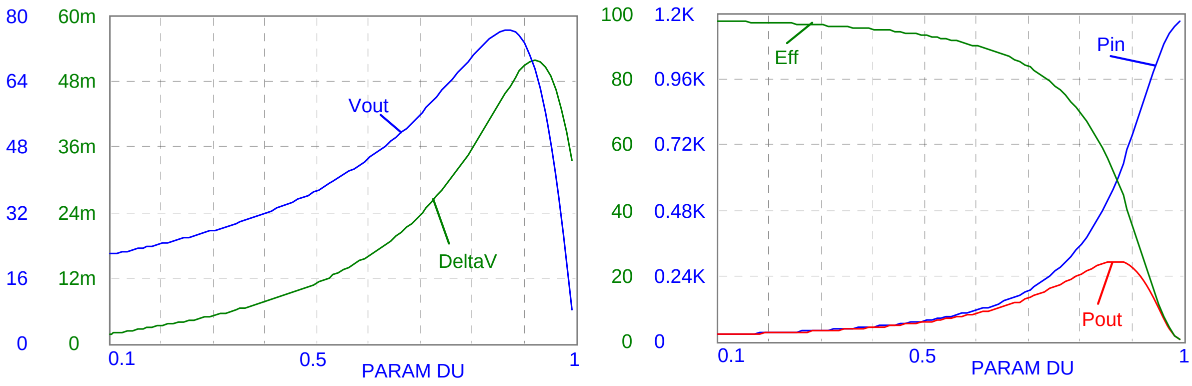

Fig. 4: A demonstration of advanced DC analysis of DC-DC converter.

5 CONCLUSIONS

In comparison with the conventional modeling of switched DC-DC converters in OrCAD PSpice, special techniques described here represent a qualitative step ahead in terms of simulation speed and analysis facilities. It can be useful to designers of such devices and also to instructors and teachers in the practical classwork.

6 ACKNOWLEDGMENT

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Analysis methods are developed that fully determine a switched-capacitor (SC) dc-dc converter's steady-state performance through evaluation of its output impedance. This analysis method has been verified through simulation and experimentation.Â These optimizations then permit comparison among several switched-capacitor topologies, and comparisons of SC converters with conventional magnetic-based dc-dc converter circuits, in the context of various application settings. Significantly, the performance (based on conduction loss) of a ladder-type converter is found to be superior to that of a conventional magnetic-based converter for medium to high conversion ratios. Keywords: PWM DC-DC power converters Switching circuits Switched-mode power supply Power converter simulation Symbolic simulation. ABSTRACT. The problem of Pulse Width Modulated (PWM) DC-DC converter simulation is faced in this paper. It is shown how the analysis of this kind of circuits, nonlinear and switching for their nature, can be easily and quickly executed by using symbolic analysis techniques. The paper also presents the program SapWinPE, which performs an automatic symbolic analysis of the considered circuit, and its outputs are in MATLAB compatible format. Interactive Transient, DC and AC analyses of switched DC-DC converters in Micro-Cap program v.9 are described. Averaging models of converters complete the conventional switch-level models in order to display converter average voltages, currents, powers, and efficiency directly on the schematic workplace.Â The voltages and parameters in (16) and (17) are as follows: V outp is the predicted value of the converter output voltage at the steady state, V out1 is the value of the voltage V out at the end of the last period of the analysis, V T is the voltage on the transistor switch at the end of the last period. of the analysis, and I L 1 is the value of the chocking-coil current at the end of the last period of the analysis. Those DC-DC converters are circuits which convert a source of direct current from one voltage level to another. Since the adjustment of the wind turbine output to the transmission levels will have to be performed in several steps, a high number of DC-DC converters will be necessary in large wind farms. Many dierent DC-DC converter types are currently available and the overall losses may dier substantially between dierent DC-DC converter topologies.Â 8 2 Hard-Switching DC-DC Converters Figure 2.5: Voltage and Current Waveforms of a Boost Converter in CCM Figure 2.6: Voltage and Current Waveforms of a Boost Converter in DCM. 2.2 Boost (Step-Up) Converter. 9.