MODELING AND SIMULATION OF SWITCHING MODE DC/DC CONVERTERS

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Abstract

Modeling and simulation of switching mode DC/DC converters can be done on several ways, depending on the desired goal of modeling, complexity of converter model, availability of software tools, simulation time consumption etc. There are three basic approaches to the problem. Circuit oriented modeling (static modeling) enables simulation of converter's behaviour by means of standard or dedicated electrical circuit simulators. Dynamic modeling of power converters enables analysis of converter's dynamic behaviour for design and implementation of converter control. Dynamic modeling can be divided into circuit averaging approach and state-space approach. Each approach has its own advantages and drawbacks. The aim of the paper is to compare circuit oriented modeling and circuit averaging dynamic modeling of switching mode DC/DC converters on several bases (model complexity, accuracy of the results, simulation time etc.)

1. INTRODUCTION

Operation principles of switching mode DC/DC converters are basically very simple. Just 2 or 3 (in discontinuous current mode, DCM) phases of operation can be identified, resulting with appropriate circuit topologies. In each operation phase, converter circuit is usually LTI system (linear time invariant) and there should be no problem with simulation of such a circuit with electrical circuit simulator. The problem lies in the fact that operation phases are changed very quickly at high operating frequencies. To handle the problem of numerical convergence, circuit simulator should have good numerical integration algorithm, but very small integration steps are required to obtain satisfactory accuracy. This leads to very long simulation times. On the other hand, circuit oriented modeling and simulation of switching mode DC/DC converters is very natural for electrical engineers.

The idea of averaged-circuit modeling is trying to retain the possibility of simulation the converter behaviour with electrical circuit simulator, but enabling the dynamical analysis of converter. The resulting simulation times are smaller compared with static modeling approach. In averaged-circuit modeling approach a LTI system property of KVL and KCL validity for instantaneous as well as averaged variables is used. So all LTI components after averaging are remaining the same values. Power switch (BJT, IGBT, etc.) is obviously not the LTI component. For switching mode DC/DC converters, power switch topology can usually be modeled as canonical switching cell [1]. Under small ripple assumption and slow variation assumption for system variables of canonical switching cell it can be replaced with averaged switching cell consisting of LTI elements and dependent voltage and current sources. Averaged switching cell can be approximated with ideal transformer. All named elements can easily be used in electrical circuit simulator. Transformation procedure for power switch is graphically described on Fig.1 (a,b,c,d).

State-space modeling approach provides a complete solution to the task of analyzing and controlling the dynamics of power converter circuits. State-space models are important in analyzing, simulating and controlling both steady-

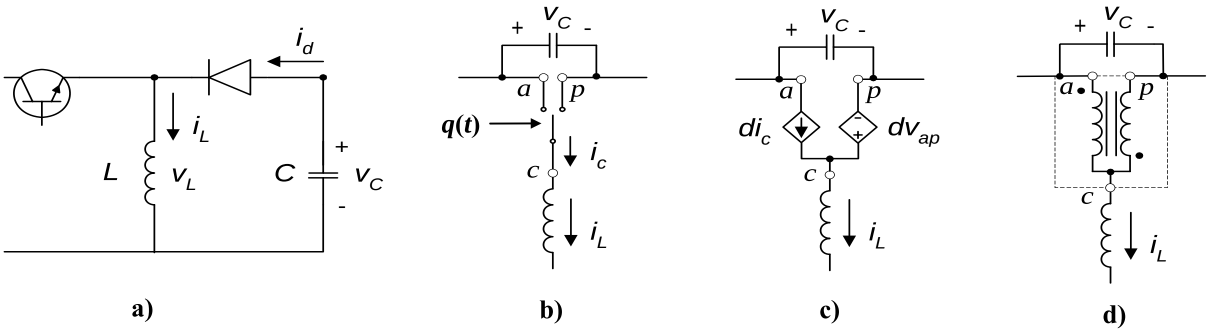

Fig. 1. Transformation of converter's power switches
a) active and passive switch in DC/DC converter (BJT and diode)
b) canonical switching cell with switching function $q(t)$
c) approximate averaged switching cell for continuous conduction
d) approximate averaged switching cell, using ideal transformer

state behaviour of power converter circuits and perturbations away from it. But unfortunately, for simulation of state-space models so called dynamic system simulators (e.g. MATLAB, MATRIXx) should be used instead of electrical circuit simulators. Analysis of the state-space modeling approach is beyond the scope of this paper.

As the base for comparison for circuit oriented and averaged-circuit modeling approach the buck-boost (up/down) DC/DC converter is used, Fig.2. Basic data are: V_{in} = 12 V, L = 250 µH, C = 220 µF, R = 2 Ω, f = 50 kHz. Duty ratio for power switch is D, $0<D<1$. For simulation, dedicated power electronic circuit simulator SIMPLORER® is used on PENTIUM 166 MHz PC.

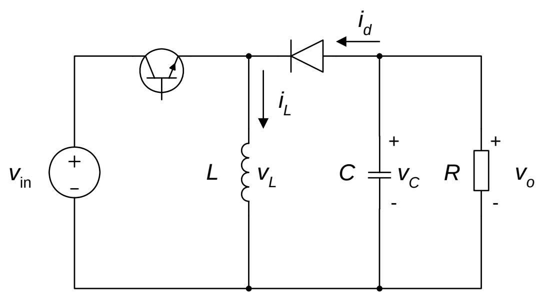

Fig. 2. Buck-boost DC/DC converter circuit

2. CIRCUIT ORIENTED MODELING APPROACH

Buck-boost DC/DC converter can easily be modeled by means of standard or dedicated electrical circuit simulator, e.g. SIMPLORER. There are several possible complexity levels of power switch modeling in SIMPLORER. The simplest model of power switch is ideal switch with R_{ON} = 0 and R_{OFF} = ∞, and this model is used in this simulation. The use of more complex power switch models (e.g. VI static characteristics or SPICE model) can significantly slow down the simulation, not contributing to the accuracy of the observed basic system variables, such as output voltage V_O and inductor current I_L.

How to choose an integration step h in simulation? If decreasing of integration step does not change significantly the results, then the last chosen integration step is adequate. As operating frequency of converter is 50 kHz, e.g. period is T = 20 µs, maximum integration step h_{MAX} should be at least 10 times smaller than period T, and minimum integration step h_{MIN} should be 10 times smaller than h_{MAX} Integration step significantly contributes to the time of simulation as well as to the accuracy of the results. With such conditions, first 5 ms of buck-boost converter start-up were simulated. Required simulation time was 28 s.

For the comparison purposes, the responses on the step change of duty ratio D, resistor R value (output current) change and input voltage V_{IN} change were simulated. Changes were of such an extend that a large signal behaviour should be supposed.

3. AVERAGED CIRCUIT MODELING APPROACH

As mentioned in the introduction, for averaged-circuit modeling power switches of converter (transistor and diode) are transformed according to Fig. 1., resulting with averaged circuit for an buck-boost converter in continuous conduction mode (CCM), Fig.3. Complexity of averaged circuit model is similar to the complexity of circuit oriented and can easily be realized in standard or dedicated circuit simulator. Switching cell is replaced with ideal transformer with d': d ratio (d' = 1–d, $0 < d < 1$). Passive components (R,L,C) retained their values as they are LTI elements. It should be noted that $\overline{x}$ means average value of variable x over switching period T.

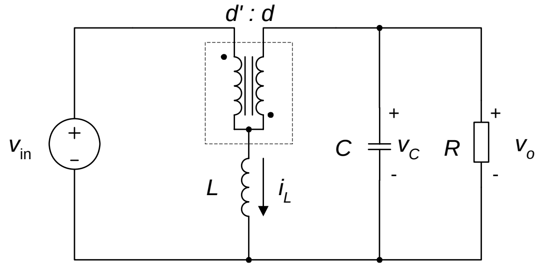

Fig. 3. Averaged circuit for a buck-boost converter (CCM)

Simulation of averaged circuit model is not so integration step sensitive as static simulation. For the same integration step interval as in static simulation (200 ns < h < 2 μs), simulation time required for the start-up of converter was 8 s, significantly smaller than 28 s in static simulation. Even more, practically the same results were obtained using 500ns < h < 5 μs, resulting with just 3 s of simulation time.

For the comparison purposes, the responses on the step change of duty ratio D, resistor R value (output current) change and input voltage V_{IN} change were simulated as in the case of static simulation.

Averaged circuit model of DC/DC converter is valid only for constant duty ratio D, because the relationship between input and output voltage is basically non-linear

$$\frac{V_{IN}}{V_O} = -\frac{D}{1-D} = -\frac{D}{D'} \,. \qquad \textbf{(1)}$$

4. COMPARISON OF SIMULATION RESULTS

Circuit oriented and averaged circuit models of buck-boost switching mode power converter from Fig.2. were simulated. Appropriate simulations are named static (for circuit oriented model) and dynamic (for averaged circuit model). A 20 ms operating cycle was simulated consisting of converter start-up and application of step change (D, R or V_{IN}) after 10 ms.

In the first case, the step change of duty ratio from D = 0.5 to D = 0.6 was analyzed. Results of simulation (Fig.4.) are clearly showing that simple averaged circuit model of buck-boost converter is not appropriate for the analysis of the control variable $d(t)$ influence. Assumption is that the results of static simulation (circuit oriented) are reference.

In the second case, the step change of the input voltage V_{IN} was analyzed. There is also an excellent agreement between the results of static and dynamic simulation (Fig.5.), what can be seen on the enlarged detail.

In the last case, step change of the load R (in ratio 1:2) was analyzed. There is an excellent agreement between the results of static and dynamic simulations (Fig.6.), what can be seen on the enlarged detail.

Time of simulation required for static simulation was 2'33" and for dynamic simulation only 30". Naturally, time of simulation depends on defined integration step and this values should only serve as an indication.

5. LINEARIZATION OF AVERAGED CIRCUIT MODEL

After analysis of simulation results it can be concluded that averaged circuit model of switching DC/DC converter is not suitable for the analysis of duty ratio $d(t)$ variation influence on converter behaviour. Because of non-linear nature of relationship between V_{IN} and V_O, a linearization procedure should be provided to extend the application field of averaged circuit model even in the field of controller design.

Linearization procedure is described in details in literature [1,2,3], so only basic facts are presented. Linearization is made for small-signal conditions, around nominal, steady-state operating point. Nominal values are denoted by uppercase letters and small deviations from the nominal values are denoted by the ~ superscript. So we can write for duty ratio

$$d(t) = D + \tilde{d}(t) \qquad \textbf{(2)}$$

$$d'(t) = D' - \tilde{d}(t) \qquad \textbf{(3)}$$

The same analogy can be applied for other variables. Linearization is based on the fact that terms that involve squares or products of the small perturbations can be neglected, resulting with expressions used in building linearized averaged circuit model

$$d(t)\, i_c - DI_c \approx D\tilde{i}_c + I_c\, \tilde{d}(t) \qquad \textbf{(4)}$$

$$d(t)\, v_{ap} - DV_{ap} \approx D\tilde{v}_{ap} + V_{ap}\, \tilde{d}(t) \qquad \textbf{(5)}$$

After linearization procedure, buck-boost DC/DC converter from Fig.2 can be replaced by linearized averaged circuit model in continuous current mode (CCM), Fig.7.

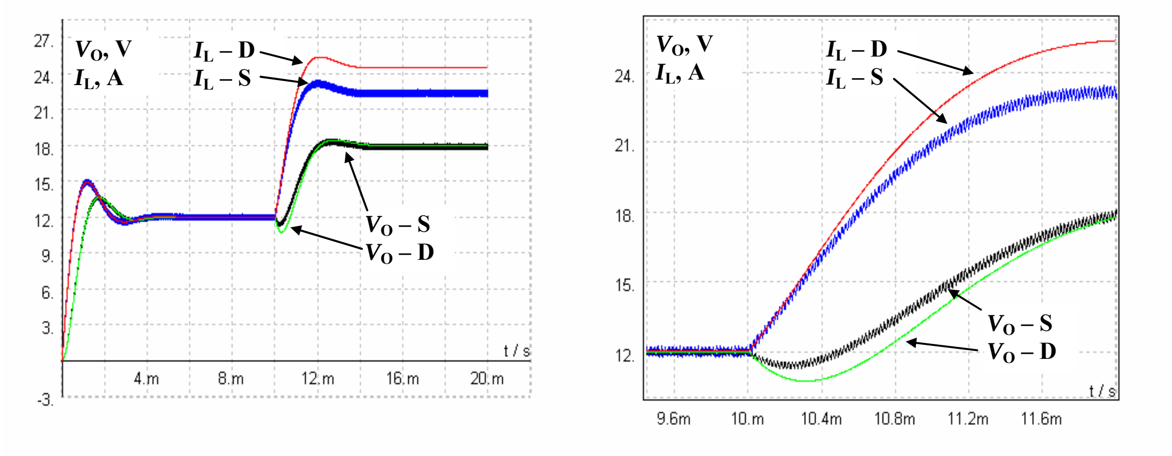

Fig. 4. Comparison of step responses on duty ratio change (D = 0.5 ⇒ 0.6)
Full operating cycle at left and enlarged detail at right.
S – static simulation; D – dynamic simulation

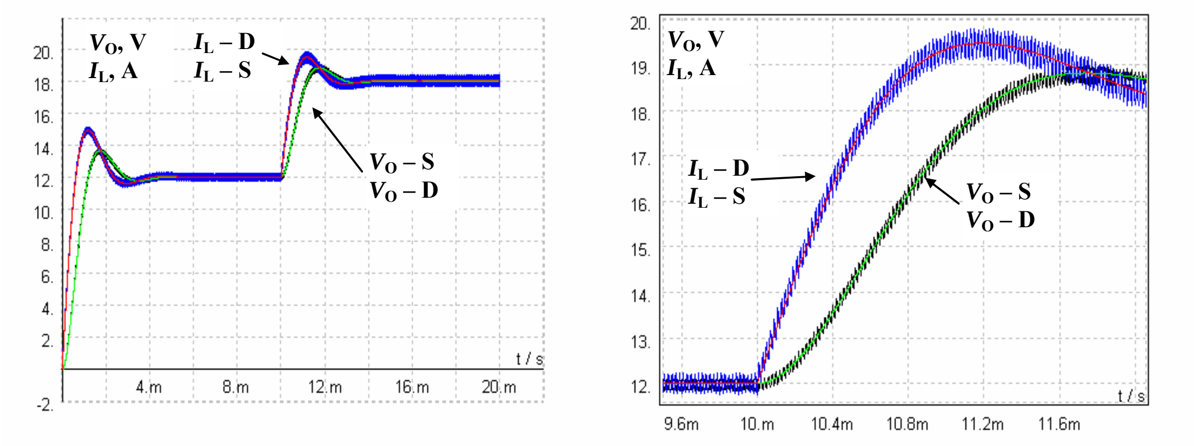

Fig. 5. Comparison of step responses on the input voltage change (V_{IN} = 12 V ⇒ 18 V)
Full operating cycle at left and enlarged detail at right
S – static simulation; D – dynamic simulation

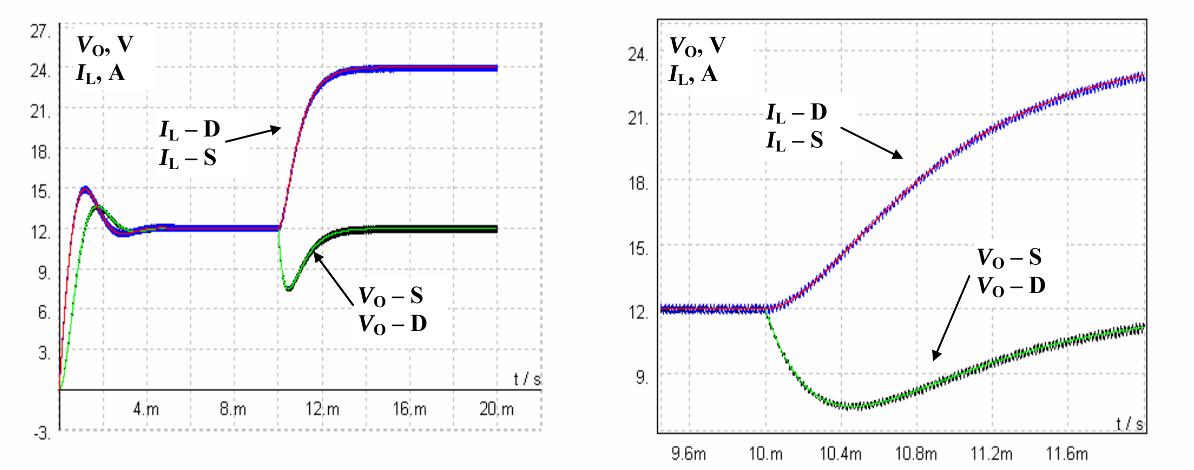

Fig. 6. Comparison of step responses on the load change (R = 2 Ω ⇒ 1 Ω)
Full operating cycle at left and enlarged detail at right
S – static simulation; D – dynamic simulation

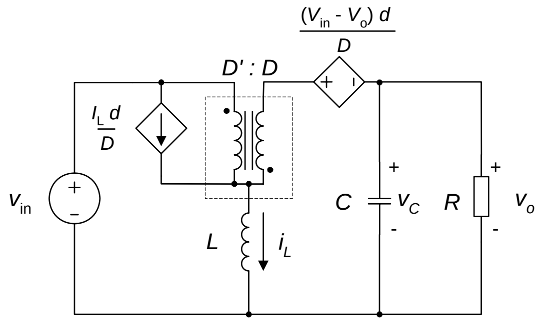

Fig. 7. Linearized averaged circuit model of buck-boost converter (CCM)

Simulation results of step responses for small and large duty ratio variations are compared with appropriate results obtained on the basis of circuit oriented and averaged circuit models. Results are clearly showing that linearized averaged circuit model of DC/DC switching converter can give satisfactory results even for 5% range of duty ratio variation (e.g. D = 0.5 to 0.525), enabling the use of such a model in the controller design process.

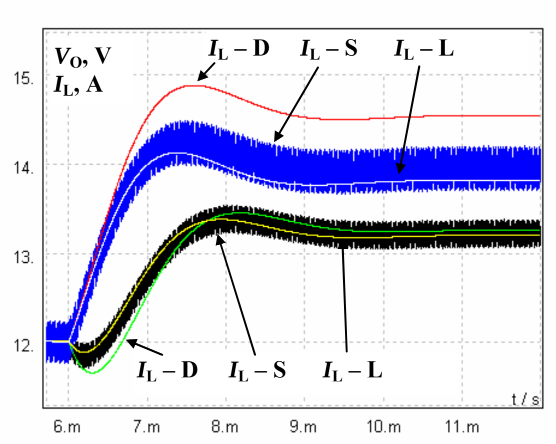

Fig. 8. Comparison of step responses for circuit oriented model (S), averaged circuit model (D) and linearized averaged circuit model (L). Relative change of D is 5%

6. CONCLUSION

Each modeling and simulation approach for switching mode DC/DC converters has its advantages and drawbacks. It is shown that taking into account limitations of averaged circuit model and linearized averaged circuit model of DC/DC switching power converter, fast and accurate simulation results can be obtained. It is possible to analyze different aspects of converter behaviour. Averaged circuit modeling approach to DC/DC converters modeling is especially desirable in education, teaching of power electronics, because it gives fast and accurate results.

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