Signal Flow Graph Modeling of Cascade Boost Converters

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ABSTRACT- In this paper signal flow graph non-linear modeling of cascade boost converters is presented. Unified signal flow graph model of the converter is developed and then deduction of large, small-signal and steady-state models from the unified graph is demonstrated. Converter performance expressions are derived. Large-signal model is developed and programmed in TUTSIM simulator. Large-signal responses against supply and load disturbances are obtained. Validity of the proposed SFG modeling is verified through PSIM simulator results.

I. INTRODUCTION

Development of cascade converters with new control strategies is coming up to increase the power processing capability and to improve the reliability of the power electronic system. Particularly, aeronautics and telecommunication appliances require large conversion ratios. These requirements can be fulfilled either with the help of isolated step-down/step-up pulse width modulated (PWM) dc-dc converters or non-isolated converters. However, the use of step-down/step-up converters with transformers, isolated converters, results in large switching surges that may damage the switching devices [1-2]. Further, use of transformer limits the switching frequency of the converter. An alternative option, for realizing larger dc conversion ratios, is cascading of the converters. This scheme mainly uses multi-stage approach that consists of n-basic boost converters connected in cascade.

State space averaging is the well known analysis method for dc-dc converters [3]. However, this method is tedious when the converter circuit contains a large number of elements. Furthermore, the linearised models, obtained from state-space averaging, do not predict the large-signal stability information, and are only sufficient to predict small-signal stability. To overcome this problem, a signal flow graph (SFG) modeling method has been developed for PWM converters [4-5]. This modeling method translates a given switching converter into its dynamic model directly and provides a visual understanding of the switching converter system with a possibility of incorporating the cause and effect relationship of the dynamics. The important advantage of this modeling method is that, it converts the two or multi-stage switching converter into a unified dynamic model from which it is possible to derive large, small-signal and steady-state models with minimum mathematical manipulations. This paper presents the SFG modeling of dc-dc cascade boost converters. SFG’s for large, small-signal and steady-state cases are drawn. Further, large-signal dynamic behavior of the converter system is presented for supply voltage, load disturbances. PSIM results are given to validate the SFG modeling method.

11. I%CELL CASCADE BOOST CONVERTER SFG

This section describes SFG development of a dc-dc cascade converter (consisting two identical/non-identical boost cells connected in cascade) as shown in Fig. 1. The analysis of the system is carried out under the following assumptions:

(i) Switching elements of the basic converter cells are assumed to be ideal.

(ii) The individual cells of the cascade converter system operate in the continuous inductor current mode.

(iii) The switches SI, S2 operate in synchronism fashion.

(iv) The ESR of the capacitance and stray capacitances are neglected.

(v) Passive components (R, L, and C) are assumed to be linear time-invariant.

It is assumed that the two boost cells operate in the continuous inductor current mode and the two switches (SI, S2) are synchronized in their operation.
During the time $0 < t \leq T_{ON}$ the switches $S_1, S_2$; and during $T_{ON} < t \leq T$ the switches $D_{DI}, D_{D2}$ are respectively conducting and thus generating two different sub-circuits. The converter switches between these two sub-circuits, which are linear and a linear system theory can be extended. Considering the switch $S1$ operation as reference, signal flow graphs $G_{ON}, G_{OFF}$ are generated for ON, OFF sub-circuits respectively sharing common nodes and part of the branches as shown in Figs. 2 and 3.

The two signal flow graphs $G_{ON}, G_{OFF}$ are combined to form a simplified signal flow graph. While merging the two signal flow graphs ($G_{ON}, G_{OFF}$) into a single graph $G$, some of the branches exist in the two graphs and some may not. Branches that exist in $G_{ON}$ but not in $G_{OFF}$ are replaced by $K_1$ branches, and the branches that exist in $G_{OFF}$ but not in $G_{ON}$ are replaced by $K_2$ branches. The resulting graph topology, shown in Fig. 4, can be mathematically written as $G = K_{GON} + K_{GOFF}$, where $K_1$ (1 or 0) and $K_2$ (0 or 1) are the switching functions whose values depend on the switching times. Assuming filter corner frequency is much smaller [4] than the switching frequency, the effective signals carried at the outputs of $K_1, K_2$ branches having an average values $dl(t), d(t)$ respectively are $y(t) = z(t)dl(t), y(t) = z(t)d(t)$. Incorporation of these large-signal models for the switching functions in the simplified SFG, results in a large-signal flow graph model of the converter as shown in Fig. 5. From the large signal switching branch models the steady-state switching branch models can easily be derived. In the steady-state, $K_1$ branch will have a transmittance of $ml(t) = D_1$ and $K_2$ branch will have a transmittance of $m_a(t) = D_2$. Simplifying the large-signal flow graph with the above steady-state switching branch models and setting complex frequency $s \rightarrow 0$, a steady-state model is obtained. From this switching flow graph various steady-state relations can be derived by employing the well known Mason’s gain formula.
A small-signal SFG of the converter can be obtained from the unified SFG model, by replacing the switching branches with their small-signal equivalents. On the assumption of neglecting second-order perturbations, the small-signal switching equations for $K_1$, $K_2$ branches, respectively are $\dot{Q}(t) = D_1i(t) + X_d(t)$, $\dot{S}(t) = D_2z(t) - X_i(t)$. Upon substitution of the above small signal models for switching branches in the simplified SFG, a small-signal flow graph is generated as shown in Fig. 6. Using these SFG models, various performance characteristics (small signal transfer functions, steady state) are derived using the Mason's gain formula, tabulated in Tables 1 and 2. These expressions are in agreement with those obtained from state-space averaging method. Using the same approach, outlined above, the signal flow graph is constructed for a 3-cell cascade boost converter systems and is shown in Fig. 7.

III. RESULTS AND DISCUSSIONS

Comprehensive simulation studies were made to investigate the signal flow graph modelling of dc-dc cascade boost converters as shown in Fig. 1. To verify the theoretical analysis and signal flow graph modelling equations developed in the previous sections, the following design example was considered. The cascade boost converter parameters chosen are: $R_1 = 0.01 \text{ ma}$, $r_2 = 0.01 \text{ ma}$, $R = 5.0 \text{ a}$, $L_1 = 200 \text{ pF}$, $L_2 = 200 \text{ pF}$, $C_1 = 200 \text{ pF}$, $C_2 = 200 \text{ pF}$, $f = 10 \text{ kHz}$. Large-signal response simulation studies of the dc-dc cascade converter (consisting two identical boost cells) are presented here for illustration. The large-signal flow graph (Fig. 5) is programmed in the TUTSIM simulator to determine the large-signal responses. For different values of the duty ratios, the step responses of the load current and voltage of the cascade converter are obtained. For illustration, few sample results of simulated load voltage and current characteristics are presented, for a duty ratio of 0.5, for two cases: (i) supply voltage change from 5.0 V to 7.5 V, (ii) change of load resistance from 5 $\Omega$ to 2.5 $\Omega$. These results are plotted in Figs. 8 and 9.

To validate the large-signal response characteristics obtained from the signal flow graph modeling method, PSIM simulator results are provided and they are given in the Figs. 10 and 11. These results closely match with those obtained from the signal flow graph modeling. Slight differences in these results are attributed to the following factors: (i) in the signal flow graph modeling, non-idealities of the converter elements such as forward voltage drops, on-state resistances of the switching devices and other parasitics are not taken into account, (ii) use of in-built device models available in the PSIM simulator.

IV. CONCLUSIONS

In this paper, the SFG approach was extended to model the dc-dc cascade boost converters operating in continuous current mode. Large, small- signal and steady-state models lead to simple graphical circuits that are very much suitable for analysis and simulation. To confirm the modelling method theoretical results, obtained from SFG analysis, were compared with PSIM simulations. They are in close agreement with each other.
Table 1. Small-signal transfer functions.

Table 2. Steady-state performance expressions of the converter.

REFERENCES


