The 2nd Power and Energy Conversion Symposium (PECS 2014)
Melaka, Malaysia
12 May 2014

State-Space Derivation of an Interleaved Boost Converter

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***Abstract*— Nowadays applications of the DC converters are not only importance for low power DC application, but also for high DC applications. By these reason developments of the interleaved converters to increase the DC converter power rating become very important. However, increasing phase numbers in the interleaved converter also will increase the switching components number and will increase the complexity of the converter model. In this paper a modeling of the two phases interleaved boost converter by using an state space averaging model analysis is presented. With thorough analysis of the operating principle of the converter and equivalent circuits model for continuous conduction mode are derived. The effectiveness of the model is verified by computer simulations model in the MATLAB/SIMULINK environment. The simulations result shown that the simulation model can generate output voltage of the converter in condition, dynamic and steady state response..**

***Index Terms*— Interleaved boost converter, continuous conducting mode, state–space averaging model.**

I. Introduction

Generally, A multi-phase interleaved boost converter is designed for high power conversion applications [1,2]. This technique has advantages such as reduce the inductor size [1,3,4], reduce the current ripple and for same rated value of components the rated of the output converter can be increased. However this technique requires more number of components.

Recently, the interleaved boost converter has been studied for various applications, such as power factor correction circuits, photovoltaic arrays, fuel cell systems, and so on [5,6]. The interleaved boost converter can be developed by some pair of the single-boost converters that be arranged in parallel connection with the switching frequency of each pairs are shifted over the switching period [1]. With the help of interleaving technique, the inductor current of interleaved boost converter can be reduced [4].

To analyse the stability and large signal time-domain transient analysis or small signal frequency-domain analysis of the converter, the average modeling has become widely employed [7,8]. Total value and complete equation of the converter can be derived by averaging the state equation in each condition over one period. Besides that, to simplify the complexity of the equation of the converter system, the reduced-order averaged modeling is employed [7].

II. Principle of An Interleaved Boost Converter

An interleaved converter consists of a pair of the inductors, the diodes and power switches. The circuit diagram of interleaved boost converter is shown in Fig. 1.

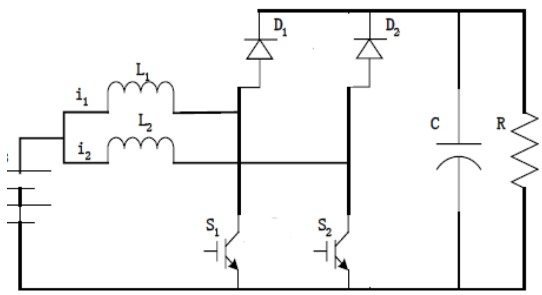

Fig. 1. Circuit diagram of the interleaved boost converter.

Principally, in two-phase interleaved converter the turn-on condition of the power switches S1 and S2 have 1800 phase difference over period. The current fluctuation of input power supply is reduced greatly because the two 1800 phase difference inductor currents minify the fluctuation of each other [3]. According to the opened and closed condition of the power switches and the diodes, there are eight possibility circuits composition as shown in table 1.

III. State-Space Averaged System Model

The state space equations are analyses according to the equivalent circuits in each operation condition. Supposing $\boldsymbol{i_1}$, $\boldsymbol{i_2}$, $\boldsymbol{V_c}$ as the state variables while $\boldsymbol{V_s}$ and $\boldsymbol{V_o}$ as the variable of the input and the output voltage respectively. The state equation of the converter in each mode operation can be state as follow.

TABLE I. POWER SWITCHES AND DIODES CONDITION FOR DIFFERENT MODES OF OPERATION

Mode	S_1	S_2	D_1	D_2
1	Closed	Opened	Opened	Closed
2	Closed	Opened	Opened	Opened
3	Opened	Opened	Closed	Opened
4	Opened	Closed	Closed	Opened
5	Opened	Closed	Opened	Opened
6	Opened	Opened	Opened	Closed
7	Closed	Closed	Opened	Opened
8	Opened	Opened	Closed	Closed

$$X^{'} = A_n X + B_n V_{in} \tag{1}$$

$$V_o = C_n X \tag{2}$$

Where n is mode operation and the matrix A, B and C in each mode operation are

$$A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{L_2} \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_1 = \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix}, C_1 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_2 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix}, C_2 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 0 & 0 & \frac{-1}{L_2} \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_3 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix}, C_3 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_4 = \begin{bmatrix} 0 & 0 & \frac{-1}{L_1} \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_4 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix}, C_4 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_5 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_5 = \begin{bmatrix} 0 \\ \frac{1}{L_2} \\ 0 \end{bmatrix}, C_5 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_6 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{L_2} \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_6 = \begin{bmatrix} 0 \\ \frac{1}{L_2} \\ 0 \end{bmatrix}, C_6 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_7 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_7 = \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix}, C_7 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_8 = \begin{bmatrix} 0 & 0 & \frac{1}{L_1} \\ 0 & 0 & \frac{1}{L_2} \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_8 = \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix}, C_8 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

The total state-space parameters per period can be defined as follow

$$A_{total} = \sum_{n=1}^{8} A_n D_n \tag{3}$$

$$B_{total} = \sum_{n=1}^{8} B_n D_n \tag{4}$$

$$C_{total} = \sum_{n=1}^{8} C_n D_n \tag{5}$$

where: D_n is duty cycle of each mode operation.

The total averaged state-space equation is:

$$X^{'} = A_{total} X + B_{total} V_{in} \tag{6}$$

$$V_o = C_{total} X \tag{7}$$

If the $L_1 = L_2 = L$ and D'=1-D the transfer function of the averaged state space of the two phase interleaved boost converter is

$$H(S) = \frac{\frac{2D^{'}V_{in}}{LC}}{S^2 - \left(\frac{1}{RC}\right)S + \frac{2\left(D^{'}\right)^2}{LC}} \tag{8}$$

IV. Simulation Result and Discussion

A computer simulation using Simulink-MATLAB was carried out to investigate the performance of the model. Block diagram of the converter model show in Fig.2.

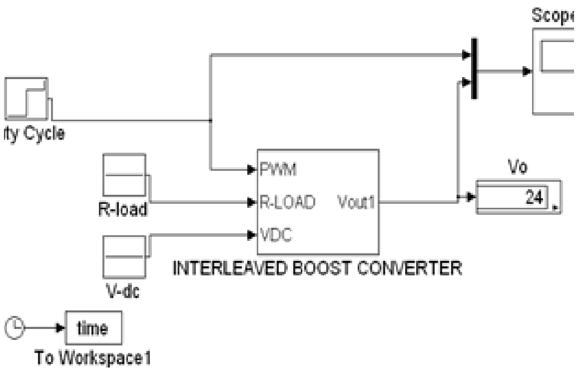

Fig. 2. Simulation block diagram of the converter system.

Parameters of the interleaved boost converter are the resistor load of 10 ohm, the inductor of 10 mH, the capacitor of 1mF, and the input supply 12 volt. The proposed averaged model of the interleaved boost converter is shown in Fig. 3.

To verify dynamic response of the model was tested with various duty cycle values. The output voltage response when the duty cycle of 0.5 and 0.6 are shown in Fig.4 and Fig.5 respectively.

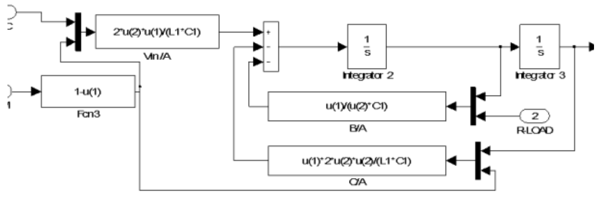

Fig. 3. Simulation block diagram of the converter system.

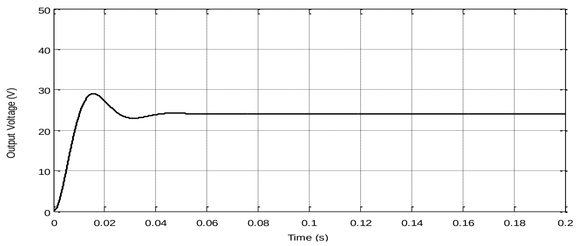

Fig. 4. The output voltage response of the interleaved boost converter when duty cycle 0.5.

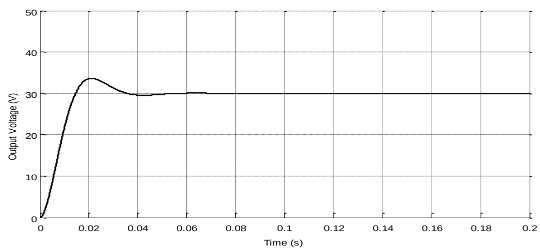

Fig. 5. The output voltage response of the interleaved boost converter when duty cycle 0.6.

From the output simulation results that have been shown, it is clearly illustrate that the model has ability to simulate the interleaved boost converter in dynamic and also steady state response.

V. Conclusion

The simulation model of interleaved boost converter has been presented in this paper. The developed model employs an averaging state-space technique to generate converter equation per period operation. The developed model was used to investigate the effectiveness of the model in both transient and steady state condition. The simulation results show that the model can show the transient response and steady state condition accurate. Hence in future this model can be used to analyze the output characteristic of the converter in design the controller of the interleaved boost converter in closed loop system.

ACKNOWLEDGMENT

The authors would like to gratitude Univeriti Tun Hussein Onn Malaysia for any valuable supports during conducting this research and in preparing this manuscript.

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