A Study on the Modeling and Control Method of PWM DC/DC Converter with Isolated two outputs

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ABSTRACT-This paper presents the circuit modeling and control methods of PWM DC/DC converter with isolated dual outputs. The dual output converter consists of a transformer with a single secondary winding and two switches. The proposed control algorithm is that required inductor current according to the loads is feed-forwarded to the PI current controller. The proposed control method has better response characteristics than conventional PI control method at load change.

1. Introduction

With the remarkable progress of the power semiconductor devices and the control scheme, it is possible to achieve high power density in the low power conversion systems. In many systems, like aviation systems, the power supply requires more than a single regulated dc supply voltage. For example, 5-V supply is used for control power and 12-V supply is supplied to the load. This can be done using two converters with its respective input voltage sources. However, new dc-dc converter [1] and the other dc-dc converters [2-5] use a single voltage source to generate two-output voltage. In such systems, isolation between control power and load power is positively necessary because a single voltage source must supply two different DC output voltages. The described dc-dc converter in this paper is shown in Fig. 1. Two discrete feedback control circuits consist of peak voltage control loop for upper converter and PI control loop for lower converter. Upper and lower converters are regulated by duration of switching on and off. The control algorithm of the new converter is verified through computer simulations.

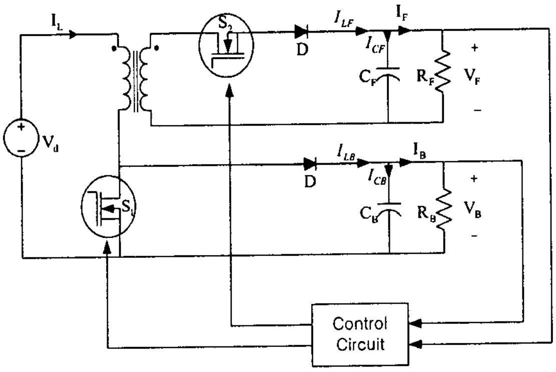


Fig. 1. The new PWM DC/DC converter

2. Concept of new double converter

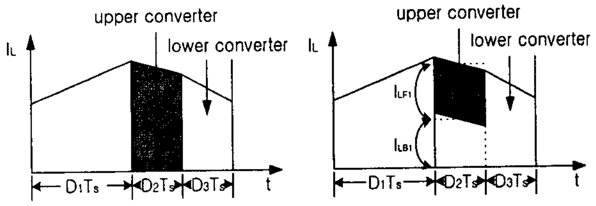
Basically, the new converter shows the structure of the conventional Flyback converter that is upper converter and conventional Boost converter that is lower converter.

2.1 The operation mode of the proposed converter

The new converter acts as Flyback converter and Boost converter during one switching period respectively. The operation mode of the new converter is decided by turn-ratio of the transformer, duties of the two switches, input voltage (V_d) and output voltage of the lower converter (V_B) and upper converter (V_F) as shown in Fig. 1. To obtain the modeling equation of new converter, it is assumed as follows;

1) All components and switches are ideal.
2) The inductance is large enough to be considered as a constant current source.
3) The output filter capacitance is sufficiently large so that the output voltage can be considered to be constant.
4) The turn ratio of transformer is 1:1.

The operation mode of the converter is made up of three stages according to the state of switches S_1, S_2. In the mode I (S1is on, S2 is off), the energy of input voltage source is stored in the inductor. In the mode Ⅱ(S1is off, S2 is on), two cases are occurred by the magnitude of V_B-(V_F+V_B). If V_B is greater than V_F+V_d, inductor current only flows into the upper converter. If V_B is less than $V_F+ V_d$, inductor current flows into the both converters. In the mode Ⅲ(S1is off, S2 is off), the sum of stored inductor energy in the mode I and the energy of input voltage source flow into lower converter. Fig. 2 shows the inductor current in one period.



(a) $V_B > (N1/N2) * V_F + V_d$ (b) $V_B < (N1/N2) * V_F + V_d$

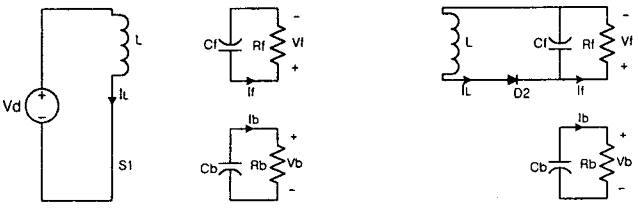
Fig. 2. Inductor Current

The each stages of the converter are shown in Fig. 3. Considering mode II, two equations of the converter can be expressed as following

$$L\frac{di_L}{dt} = V_d(1-S2) - V_F(1-S1)S2 - V_B(1-S1)(1-S2)$$
$$C_F\frac{dv_F}{dt} = -\frac{V_F}{R_F} + i_L(1-S1)S2 \tag{1}$$
$$C_B\frac{dv_B}{dt} = -\frac{V_B}{R_B} + i_L(1-S1)(1-S2)$$

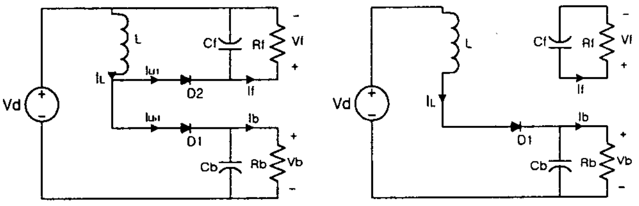
$$L\frac{di_L}{dt} = V_B - V_d(1-S2)$$
$$C_F\frac{dv_F}{dt} = -\frac{V_F}{R_F} + i_{Lf1}S1(1-S2) \tag{2}$$
$$C_B\frac{dv_B}{dt} = -\frac{V_B}{R_B} + i_{Lb1}S1(1-S2) + i_L(1-S1)(1-S2)$$

Eq. (1). shows the system state equations when inductor current only flows into the upper converter in the mode II. Eq. (2). shows the system state equations when inductor current flows both converters in the mode II.



(a) Mode I

(b) Mode II (Vf + Vd < Vb)



(c) Mode II (Vf + Vd > Vb)

(d) Mode III

Fig. 3. Operation Mode

2.2 Steady-State analysis

2.2.1 When V_B is greater than V_F+ V_d

The output characteristics of new converter are acquired through the following process;

Step 1. In case of an inductor operating in a steady-state condition, the average inductor voltage must be zero. It is shown in Fig. 4. Consequently, this is illustrated as

$$V_dD_1 = V_FD_2 + (V_B - V_d)D_3 \tag{3}$$

Step 2. Sum of the switch duty ratio can be expressed as Eq. (4) during one switching period.

$$D_1 + D_2 + D_3 = 1 \tag{4}$$

Step 3. The stored energy of the magnetizing inductor of the transformer is delivered to the lower and upper converter by turning on and off of the S_1 and S_2. Its ratio is the same as the ratio of consumed energy in their respective loads. Thus, it can be represented by Eq. (5).

$$\frac{V_FI_{LF}D_2T_S}{V_BI_{LB}D_3T_S} = \frac{V_FI_FT_S}{V_BI_BT_S} \tag{5}$$

where, $I_{LF} = I_{LB}$ by assumption (2).
Therefore,

$$\frac{D_2}{D_3} = \frac{I_F}{I_B} = \gamma_p \tag{6}$$

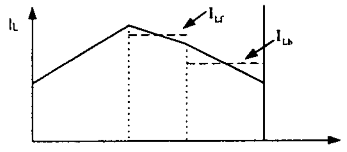
where, γ_P shows the ratio of upper load power to lower load power.

Step 4. By using Eq. (3) through Eq. (6), we can obtain duty equations as follows;

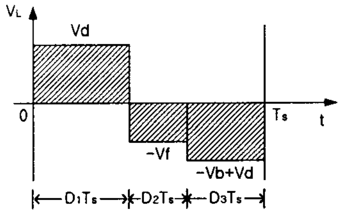
$$D_1 = \frac{\gamma_pV_F + V_B - V_d}{\gamma_p(V_d+V_F)+V_B} \qquad D_2 = \frac{\gamma_pV_d}{\gamma_p(V_d+V_F)+V_B}$$
$$D_3 = \frac{V_d}{\gamma_p(V_d+V_F)+V_B} \tag{7}$$

Step 5. Substitution of Eq. (6) into Eq. (3) yields output voltage equation of the lower and upper converter as follows respectively;

$$V_F = \frac{V_d(D_1+D_3)}{D_2 + \frac{R_B}{R_F}\frac{D_3^2}{D_2}} \qquad V_B = \frac{V_d(D_1+D_3)}{D_3 + \frac{R_F}{R_B}\frac{D_2^2}{D_3}} \tag{8}$$



(a) Inductor current



(b) Inductor voltage

Fig. 4. Inductor current and voltage

2.2.2. When V_B is lesser than V_F+ V_d

Step 1. In case of an inductor operating in a steady-state condition, the average inductor voltage must be zero. It is shown in Fig. 5. Consequently, this is illustrated as

$$V_dD_1 = (V_B - V_d)(1-D_1) \tag{9}$$

Step 2. The stored energy of the magnetizing inductor of the transformer is delivered to the lower and upper converter by turning on and off of the S_1 and S_2. Its ratio is the same as the ratio of consumed energy of their respective loads. Thus, it can be represented by Eq. (10).

$$\frac{V_FI_{Lf1}D_2T_S}{V_B(I_{Lb1}D_2 + I_{LB}D_3)T_S} = \frac{V_FI_FT_S}{V_BI_BT_S} \tag{10}$$

where, $I_{LB} = I_L$ by assumption (2).

Therefore,

$$\frac{I_{Lf1}D_2}{I_{Lb1}D_2+I_LD_3}=\frac{I_F}{I_B}=\gamma_{p2} \tag{11}$$

Step 3. Inductor current in the mode II is the sum of I_{Lf1} and I_{Lb1}. Thus, in the mode II

$$I_L=I_{Lf1}+I_{Lb1} \tag{12}$$

From Eq (11), (12)

$$I_{Lf1}=\frac{\gamma_{p2}(1+\frac{D_3}{D_2})}{1+\gamma_{p2}}I_L \quad I_{Lb1}=\frac{(1-\gamma_{p2}\frac{D_3}{D_2})}{1+\gamma_{p2}}I_L \tag{13}$$

Step 4. From Eq (11), we can obtain the relation D_2 and D_3

$$D_3=\frac{(I_{Lf1}-\gamma_{p2}I_{Lb1})}{\gamma_{p2}I_L}D_2 \tag{14}$$

By using Eq (4), (9), (14), we can obtain duty equations as follows;

$$D_1=\frac{V_B-V_d}{V_B} \quad D_2=\frac{\gamma_{p2}I_L}{I_{Lf1}+\gamma_{p2}(I_L-I_{Lb1})}\frac{V_d}{V_B}$$

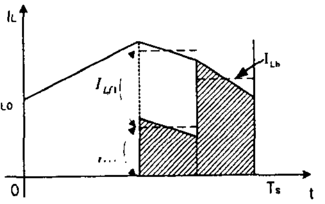
$$D_3=\frac{I_{Lf1}-\gamma_{p2}I_{Lb1}}{I_{Lf1}+\gamma_{p2}(I_L-I_{Lb1})}\frac{V_d}{V_B} \tag{15}$$

Step 5. The output voltage of lower converter can be obtained by Eq (9). The output voltage is the same as boost converter.

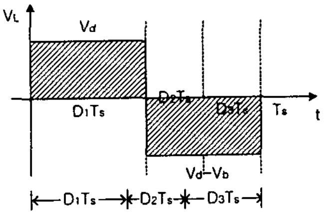
$$V_B=\frac{1}{1-D_1}V_d \tag{16}$$

From Eq (11), (16)

$$V_F=\frac{D_2I_{Lf1}}{(D_2+D_3)I_L-D_2I_{Lf1}}\frac{R_F}{R_B}\frac{1}{1-D_1}V_d \tag{17}$$



(a) Inductor current



(b) Inductor voltage

Fig. 5. Inductor current and voltage

2.3 Control Algorithm

PI control algorithm is shown in Fig 6 is used to control the voltage of lower converter. Upper converter is controlled by Peak voltage control method. The PI controller of lower converter consider the used energy in upper converter as disturbance because upper converter uses the inductor energy in advance

The proposed control method is that the required inductor current according to the loads and the output of PI voltage controller are used by the input of current PI controller. Therefore, the proposed controller has better response than conventional PI controller does at load change.

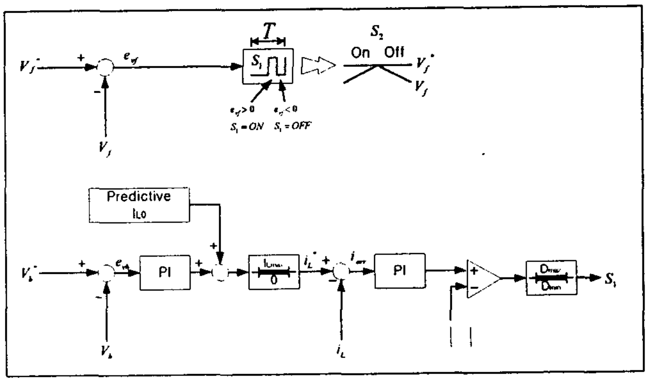


Fig. 6. Control loop

2.3.1. Inductor current prediction (when V_B is greater than V_F+V_d)

The inductor current in one period is shown in Fig. 7. During D_2T_S, the average value of I_{LF} is the half sum of I_{Lpeak1} and I_{Lpeak2}. During D_3T_S, the average value of I_{LB} is the half sum of I_{L0} and I_{Lpeak2}. Thus,

$$I_{Lf}=\frac{1}{2}(I_{Lpeak1}+I_{Lpeak2})=I_{L0}+\frac{V_d}{2L}D_1T_S+\frac{V_B-V_d}{2L}D_3T_S$$

$$I_{Lb}=\frac{1}{2}(I_{L0}+I_{Lpeak2})=I_{L0}+\frac{V_B-V_d}{2L}D_3T_S \tag{18}$$

Like step 3) in the section 2.2.1, the stored energy of the magnetizing inductor of the transformer is delivered to the lower and upper converter by turning on and off of the S_1 and S_2. It is the same as the sum of consumed energy in their respective loads. Thus, it can be represented by Eq. (19).

$$V_FI_{Lf}D_2T_S+V_BI_{Lb}D_3T_S=V_FI_FT_S+V_BI_BT_S \tag{19}$$

From (18), (19) and assumption (2)

$$I_{L0}=\frac{V_FI_F+V_BI_B-\frac{V_FD_2T_s}{2L}\{V_dD_1+(V_B-V_d)D_3\}-\frac{V_BD_3^2T_s}{2L}(V_B-V_d)}{V_FD_2+V_BD_3}$$

$$\cong\frac{V_FI_F+V_BI_B}{V_FD_2+V_BD_3} \tag{20}$$

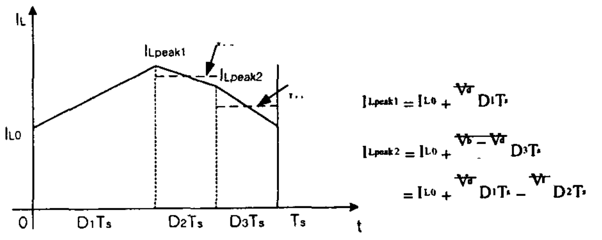


Fig. 7. Inductor current waveform

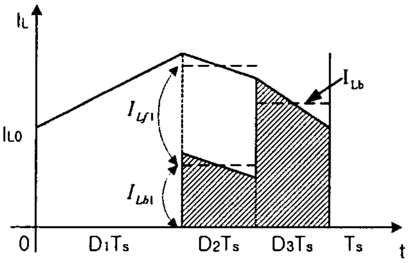
2.3.2. Inductor current prediction (when V_B is greater than $V_F + V_d$)

The inductor current in one period is shown in Fig. 8. Like step 3) in the section 2.2.2., the stored energy of the magnetizing inductor of the transformer is delivered to the lower and upper converter by turning on and off of the S_1 and S_2. It is the same as the sum of consumed energy in their respective loads. Thus, it can be represented by Eq. (21).

$$V_F I_{Lf1} D_2 T_S + V_B (I_{Lb1} D_2 + I_{Lb} D_3) T_S = V_F I_F T_S + V_B I_B T_S \quad (21)$$

From (13), (21) and assumption (2)

$$I_{L0} = \frac{(1+\gamma_{p2})(V_F I_F + V_B I_B)}{(D_2 + D_3)(V_B + \gamma_{p2} V_F)} \quad (22)$$



$$I_{Lf1} = \frac{\gamma_{p2}(1+\frac{D_3}{D_2})}{1+\gamma_{p2}} I_L$$

$$I_{Lb1} = \frac{(1-\gamma_{p2}\frac{D_3}{D_2})}{1+\gamma_{p2}} I_L$$

Fig. 8. Inductor current waveform

2.4. Simulation Results

Simulation procedure is shown in Fig. 9. The load change is shown in Fig. 10. The system is designed that upper converter has a capacity of 5 watts and lower converter has a capacity of 6 watts. The lower converter load is varied from 50 percents to 100 percents at 0.04s and varied from 100 percents to 50 percents at 0.05s. The upper converter load is varied from 25 percents to 50 percents at 0.06s and varied from 50 percents to 25 percents at 0.07s. The input voltage is varied from 6 volts to 4 volts at 0.08s. The setup time is a starting condition that converter have not the state which inductor current flows both loads in the mode II. The upper converter keeps the regular voltage (5V) after setup time. Simulation result is shown in Fig. 11.

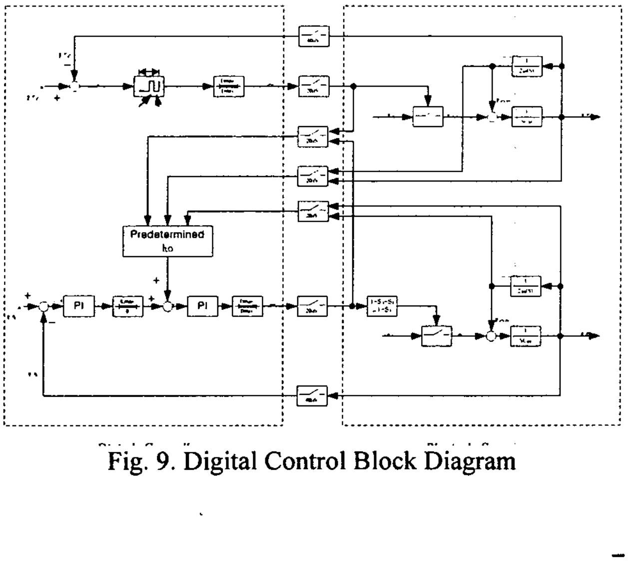


Fig. 9. Digital Control Block Diagram

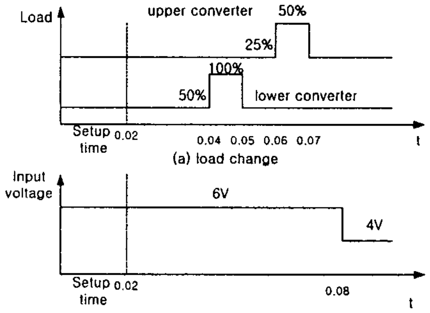
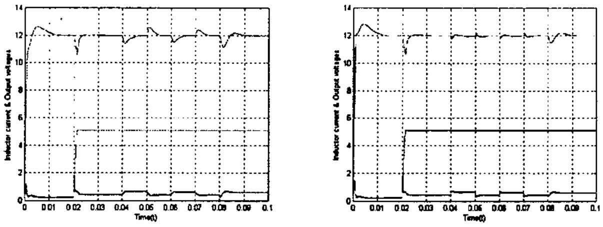


Fig. 10. Load and input voltage change



(a) Original control (b) Proposed control

Fig. 11. Simulation result

3. Conclusion

This paper presents modeling of new converter and better control method than traditional PI control method. The relation of stored inductor energy and consumed load energy is used to obtain the system equations of new converter. The upper converter uses the stored inductor energy before lower converter. Therefore, the converter output voltage can be unstable in load change. If the required inductor current according to the both loads is calculated and feed-forwarded to the input of PI current controller, system response in load change has better characteristic than conventional PI controller does. The validity of proposed control method is verified through the simulated results. This control method could be used for the control of the other converters such as Boost, Buck and Buck-Boost converter.

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