単一インダクタ正負２出力 DC-DC コンバータの検討

A Single-Inductor Dual-Output DC-DC Converter

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Abstract: This paper presents a dual-output boost and buck-boost converter with a single inductor that operates in Pseudo-Continuous Conduction Mode (PCCM). The converter provides positive and negative dual-output voltages with low-cost small-area characteristics. Theory analysis of the SIDO shows that output voltages are independently regulated, thus suppresses the cross regulation problem.

Keyword: *Single-Inductor Dual-Output, Pseudo-CCM, DC-DC converter*.

1. Introduction

Recently, there has been a lot of discussion regarding Single Inductor Multiple Output Switching Converters (SIMO) for regulating portable applications that require multiple different supply voltages because of their low-cost and small-area characteristics [1]-[10]. The SIMO can provide more than one output while it requires only one off-chip inductor that helps saving the area and reducing overall cost since the inductor is the highest cost component of a switching converter. A SIMO that operates in Continuous Conduction Mode (CCM) can handle a heavy load current with small current ripple but it has a serious stability problem --Cross Regulation--, which makes their outputs difficult to independently be regulated. Conversely, a SIMO that operates in Discontinuous Conduction Mode (DCM) can improve the cross regulation but it can only provide limited power to the load. This means that when a large load current is required, the peak of the inductor current becomes very high which generates large current ripple which affects the efficiency of the circuit. In [9]-[11], SIMOs that operate in Pseudo-Continuous Conduction Mode (PCCM) are presented. Not only they can regulate outputs that are independent from each other, thus minimize the cross regulation, they also can handle large load current stress while retaining the ripple current small.

Fig.1 depicts the inductor currents of three different operation modes, CCM, DCM, and PCCM in a single-output buck converter [11]. As can be seen, by adjusting the level of I_B and time period of the freewheel switching stage, the inductor current of PCCM operation could stay above zero like CCM converter does for large load currents, while it also has a smaller peak-to-peak current ripple compared to DCM operation ones.

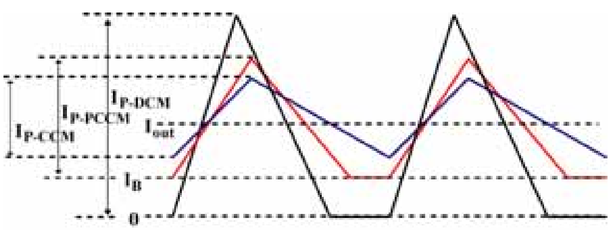

Fig.1 Inductor current waveforms in three different operation modes.

In this paper, a dual positive and negative outputs switching converter that only uses a single inductor is discussed. This switching converter works in pseudo-CCM with a freewheel switch as an additional component. It is a combination of two basic topologies of switching converter, boost and buck-boost converters. It only uses one inductor for providing dual outputs, which eliminates the need for inductors for each output -thus reducing the production cost-, while it also can minimize the cross regulation problem and keep the current ripple small when a heavy load current is required. The converter provides dual positive and negative outputs, which are required for example in OLED displays, LCD and CCD bias supplies.

The architecture and power conversion theory analysis will be discussed in section 2. A simulation result will be presented in section 3, and section 4 will summarize this paper.

2. Single-Inductor Dual-Output (SIDO) Boost & Buck-boost Converter

The schematic of a single-inductor dual-output (SIDO) converter is shown in Fig.2, and we investigate this topology. It is a combination of boost and buck-boost converter. A freewheel switch S_{fw} is added across the inductor so the converter can works in a pseudo-CCM operation.

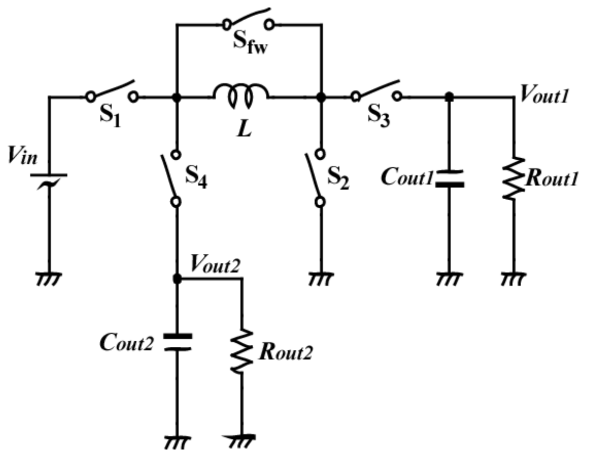

Fig.2 SIDO Boost & Buck-boost converter.

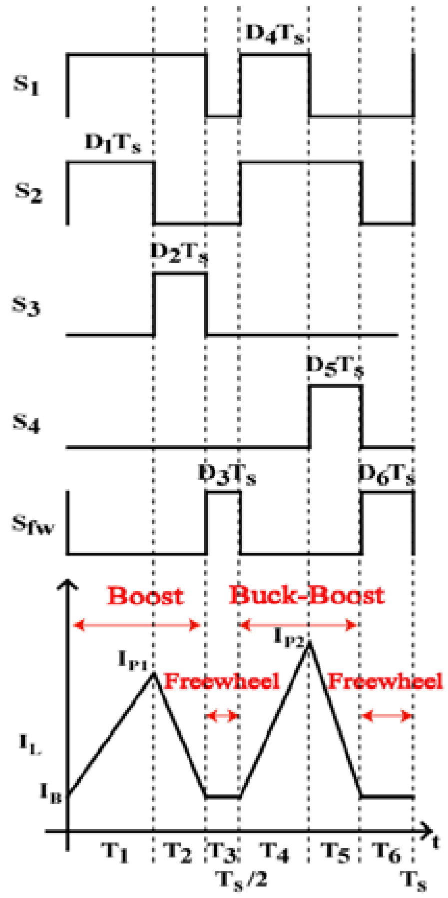

Fig.3 Inductor current and timing diagram of the SIDO Boost & Buck-boost converter in Fig.1.

The SIDO converter operates in three kinds of stages: boost converter stage, freewheel switching stage, and buck-boost converter stage. The timing diagram waveforms and the inductor current of the presented SIDO converter are shown in Fig.3. Here, we can see that the inductor current is remaining above zero and stays at constant I_B during the freewheel switching stage.

In the boost converter stage, circuit operation is divided into two states, T_1 and T_2 states. During state T_1, S_1 and S_2 are closed, connecting the input side of inductor to the input and the output side of inductor to the ground, as the rest of switches are opened. The energy is transferred from the input to the inductor *L* during this state. During state T_2, S_1 and S_3 are closed, let both, the energy stored in the inductor *L* and energy from the input be transferred to the first output *Vout1*. From the Faraday's law, the voltage across the inductor V_L and the rate of change in inductor current

I_L relationship in both states can be written as:

State T_1 **:**

$$L\frac{dI_L}{dt} = V_L = V_i. \quad I_L = I_B + \frac{V_i}{L}t = I_B + \frac{(I_{P1} - I_B)}{D_1 T_S}t. \tag{1}$$

State T_2 **:**

$$L\frac{dI_L}{dt} = V_L = V_i - V_{out1}. \quad I_L = I_{P1} + \frac{V_i - V_{out1}}{L}t = I_{P1} - \frac{(I_{P1} - I_B)}{D_2 T_S}t. \tag{2}$$

From the equations above, we can calculate the first output voltage *Vout1* to the input voltage *Vi* transfer function.

$$\frac{V_{out1}}{V_i} = \frac{(D_1 + D_2)}{D_2}. \tag{3}$$

It shows that *Vout1* has the same polarity but is higher than the input voltage.

During state T_3, the converter enters into the freewheel switching stage where S_{fw} is closed and the rest of the switches are opened. Here, the inductor current stays constant at I_B level.

Next the circuit enters into the buck-boost stage, where it is divided into two states: T_4 state and T_5 state. During the T_4 state, S_1 and S_2 are closed and the rest of switches are opened. It connects the input side of inductor to the input and the output side of inductor to the ground. Energy from the input is stored in the inductor L during this state. During T_5 state, S_2 and S_4 are closed and connecting the inductor directly to the second output *Vout2*, therefore the energy is transferred from the inductor L to the output load. In this stage, the voltage across the inductor related to inductor current as follows:

State T_4 **:**

$$L\frac{dI_L}{dt} = V_L = V_i. \quad I_L = I_B + \frac{V_i}{L}t = I_B + \frac{(I_{P2} - I_B)}{D_4 T_S}t. \tag{4}$$

State T_5 **:**

$$L\frac{dI_L}{dt} = V_L = V_{out2}. \quad I_L = I_{P2} + \frac{V_{out2}}{L}t = I_{P2} - \frac{(I_{P2} - I_B)}{D_5 T_S}t. \tag{5}$$

It gives us the transfer function of the second output *Vout2* to the input *Vi*.

$$\frac{V_{out2}}{V_i} = -\frac{D_4}{D_5}. \tag{6}$$

It can be seen that polarity of the second output *Vout2* is opposite to that of the input.

Last, the converter enters into the freewheel switching stage during T_6. Here, again the inductor current stays at the level of I_B. Note that the theoretical analysis above is calculated under an ideal condition, assuming that all the components are ideal behavior components.

Assuming that the on resistances of S_1~S_4 are R_1~R_4, respectively, transfer functions of *Vout1* and *Vout2* to the input *Vi* can be written as:

$$V_{out1} = \frac{-\{(R_1+R_2)D_1+(R_1+R_3)D_2\}I_L+(D_1+D_2)Vi}{D_2}. \tag{7}$$

$$V_{out2} = -\frac{D_4 Vi-\{(R_1+R_2)D_4+(R_2+R_4)D_5\}I_L}{D_5}. \tag{8}$$

The theoretical analysis equations above show that the converter operates in Pseudo-CCM, and regulates dual positive and negative independent outputs.

The schematic of SIDO boost & buck-boost converter in closed loop circuit is shown in Fig.4. A phase control is introduced between S_a and S_b, to alternate the non-overlapping phases, ϕa and ϕb. When S_a is turned on -ϕa is high-, the SIDO converter works in the Boost converter stage.

Here, the inductor current ramps up till D_1T_S expires and then ramps down till the inductor current reduces to I_B. The freewheel switch S_{fw} is turned on and the converter enters the freewheel switching stage. The freewheel switching stage ends when S_b is turned on -ϕb is high- and the converter enters the buck-boost converter stage. The same action repeats only here the inductor current ramps up until D_4T_S expires. Then it ramps down until the inductor current reduces to I_B. The freewheel switch S_{fw} is turned on and the converter enters into the freewheel switching stage.

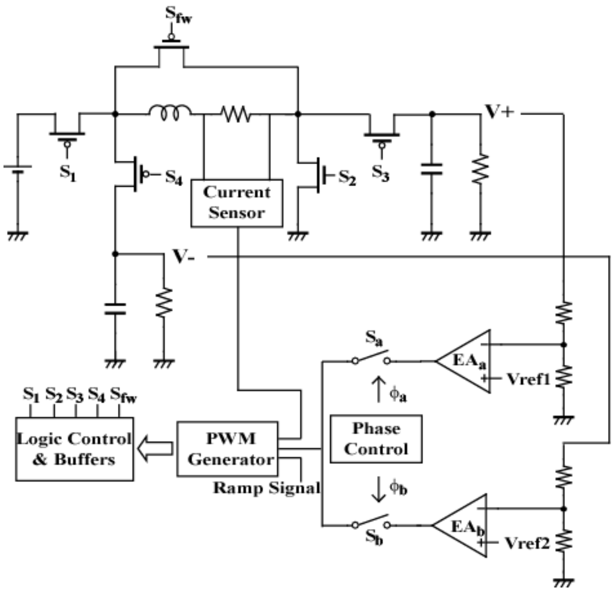

Fig.4 Block schematic diagram of SIDO Boost & Buck-boost switching converter.

3. Simulation Verification

A simulation in SIMetrix software is performed to clarify the SIDO boost and buck-boost converter operation. Specifications and parameters used in the simulation are shown in Table I.

Table I. Parameters Used in Simulation

Input Voltage	*Vin*	5V
Output Voltages	$V_{out1,2}$	+15V, -15V
Switching Frequency	*Fs*	500kHz
Output Capacitors	$C_{out1,2}$	100uF
Inductor	*L*	1uH
Loads	$R_{out1,2}$	100Ω

The simulation is performed in an open loop circuit with a constant duty ratio, using ideal components with no inner resistances in the inductor and output capacitor, and very large off and small (4mΩ) on resistances for the switches. Output voltages and inductor current simulation results are shown in Fig.5 and Fig.6, respectively. *Vout1* is set to be +15 V and *Vout2* is set to be -15 V.

The simulation result shows that with proper timing ratio for each state (T1~T6) the SIDO converter provided the desired dual positive and negative output voltage.

Unfortunately, a closed loop circuit which is currently under investigation was not ready in time for this paper.

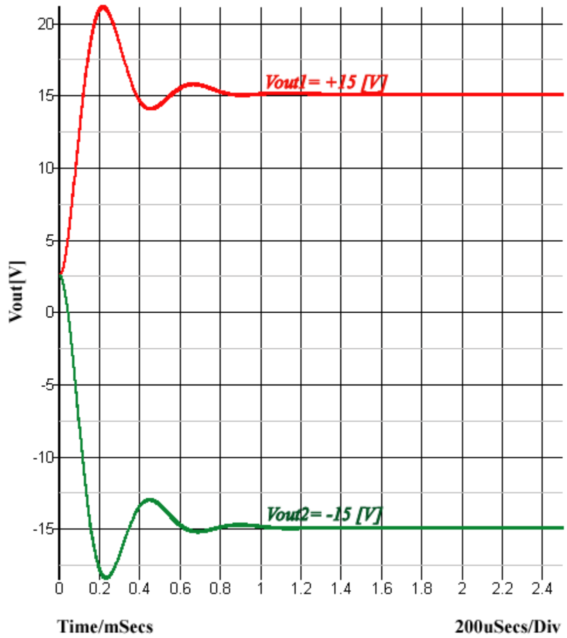

Fig.5 Simulation result of SIDO Boost & Buck-boost converter: Output voltages.

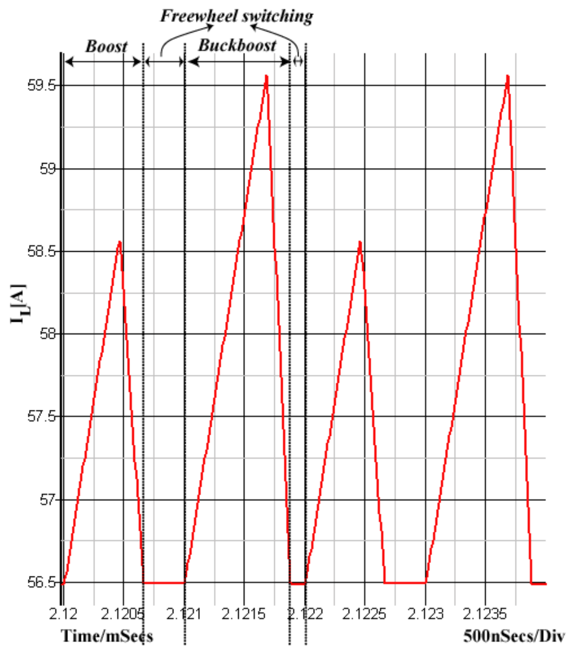

Fig.6 Simulation result of SIDO Boost & Buck-boost converter: Inductor current.

4. Summary

A Single-inductor dual-output (SIDO) operates in pseudo-CCM that provides dual, positive and negative outputs, is discussed. Not only has the low-cost small-area characteristics, theory analysis shows that the SIDO converter provides dual independent outputs, thus mitigates the cross-regulation issue. Simulation result verified the operation. It shows that desired outputs can be obtained with proper timing ratios.

Acknowledgement

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