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Modelling and Control of Single Inductor Dual Output DC-DC Converter

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ABSTRACT: Single Inductor Multiple Output (SIMO) converters are becoming more popular in industries and are replacing conventional multiple output converters. This paper presents the modelling of Single Inductor Dual Output (SIDO) converter along with the control scheme. Methods for designing the controller and its advantages has been investigated and included in the research. Various operating modes of the converters are discussed.

Keywords: Single Inductor Multiple Output Converter, Modelling of DC-DC Converter, Controller design, PI controller

I. INTRODUCTION

A voltage regulator is a device that produces a constant output voltage, independent of changes in supply voltage and load current. A single regulator can provide a fixed output voltage level for a particular application. In an electronic circuit the number of voltage levels required can be more than one, thus we can say that things are not limited to single output voltage requirements. In an application that require multiple output voltages, say N, a straightforward implementation would be using N multiple switching converters, thus requiring N inductors and 2N power devices (Transistors and Diodes). This requirement paved a way for designing multiple output power converters. For a considerable saving in cost, weight and size, it is natural to investigate the possibility of using only one inductor for an N-output converter, and to determine if number of power devices can also be reduced.

In power converter circuits, inductors are expensive and bulky elements. For obtaining N output voltage levels if we use N power converters, it will take large PCB area, increase in system cost, more number of components and less reliability for many inductors used. Instead of N number of converter if we use Single Inductor Multiple Output Converter (SIMO), only a single inductor is required for providing multiple output voltage levels. To have multiple outputs it is necessary to time share the inductor current between various loads. SIMO can be boost, buck or buck-boost given the application.

Comparing with conventional designs both on-chip and off-chip components are reduced significantly. Apart from advantages like reduced cost, reduced circuit area SIMO suffers from some drawback also, the output nodes of SIMO schemes may suffer from cross-regulation when inductor current switches from one out output to another output during Continuous Conduction Mode (CCM)

The Primary objective of this work is to go through various topologies available for SIMO converter. Design, model and simulate the Single Inductor Dual Output (SIDO) buck converter operating in CCM. Also to design, model and simulate the SIDO boost converter operating in Discontinuous Conduction Mode (DCM). In accordance with the objectives, the various topologies of SIMO converter has been presented and then power stage of SIDO buck and SIDO boost converter has been designed to meet the required specifications. The organization of the thesis is as follows:

Section 2: It provides an overview of various SIMO converters topologies and types of outputs and number of switches used.

Section 3: Circuit operation and design problems has been discussed. For obtaining a particular specification, the circuit parameters design has been done to fulfill the satisfactory operation of the converter.

Section 4: Modelling and controller design has been described for the converter circuit.

Section 5: Simulation results, analysis and conclusion.

II. SINGLE INDUCTOR MULTIPLE OUTPUT DC-DC CONVERTER TOPOLOGIES

As explained in previous section, the SIMO dc-dc converter with its advantages can be a possible replacement to multiple power converters. However, SIMO converter too comes with some drawbacks. In SIMO converters since all the outputs are being derived from single inductor cross coupling effect may occur. This drawback destabilizes the system and results in poor performance of the converter. A survey of available patents on SIMO converter configurations gives a diverse set of topologies to generate multiple outputs. SIMO converters can be categorized into two broad sub-class based on the voltage levels that can be generated, they are buck-derived and boost-derived configurations. In SIMO, inductor is most important element, which functions as a current source deriving outputs. Therefore the operation of converter is defined in the manner in which inductor current is shared. Various converter topologies has been addressed below:

A. SIMO Unipolar Converters

To construct N-output buck-buck converter two switches at input side are required and each output requires one switch for separation. Hence total N+2 switches are needed for constructing N-output SIMO buck-buck converter. Similarly N+1 switches are needed for N output boost-boost converter.

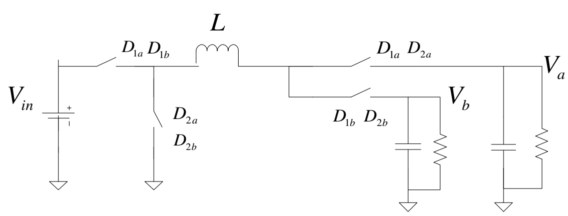


Fig. 1. SIDO Buck-Buck Converter.

B. SIMO Bipolar Converters

In many applications such as LCDs and CCDs, both positive and negative supply are required. A buck converter and a boost converter generates a positive output, while a flyback converter generates a negative output. A SIMO can also be constructed which can give positive and negative output both. The buck/flyback- converter, boost/flyback- converter falls into this category. A buck/flyback- converter requires N+3 switches in its circuitry. A SIDO buck/flyback- converter and SIDO boost/flyback- converter has been provided in figure II.

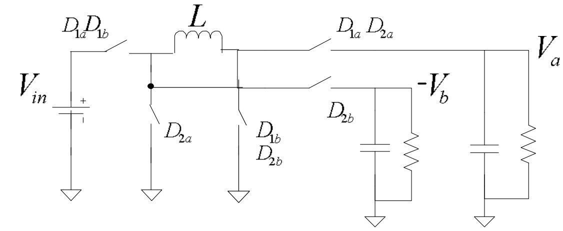


Fig. 2. SIDO Buck/Flyback- converter.

C. SIMO Mixed-type Converters

SIMO converters can also be extended to provide mixed type of output like buck and boost together. SIMO buck/boost, buck/flyback+, boost/flyback + converters falls into this category. A SIMO buck/boost converter has been given in the figure, which includes N+3 switches in its circuitry.

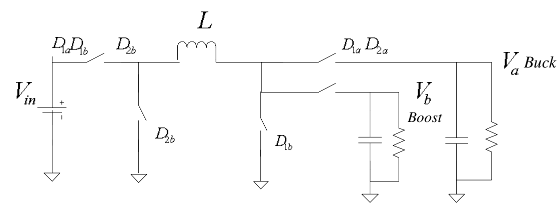


Fig. 3. SIDO Buck/Boost Converter.

III. CIRCUIT OPERATION AND DESIGN PROBLEMS

SIDO Boost-Boost Converter: Figure IV shows the SIDO boost-boost converter. An N-output SIMO boost-boost converter requires N+1 switches, so for a SIDO converter switches required are 3. The switch which reside in input side of converter is named as 'Main Switch (S_M)' whereas switches which reside on output side of converter are named as output switch (S_1 & S_2).

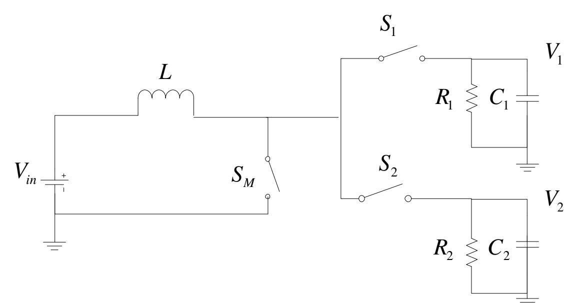


Fig. 4. SIDO Boost-Boost Converter.

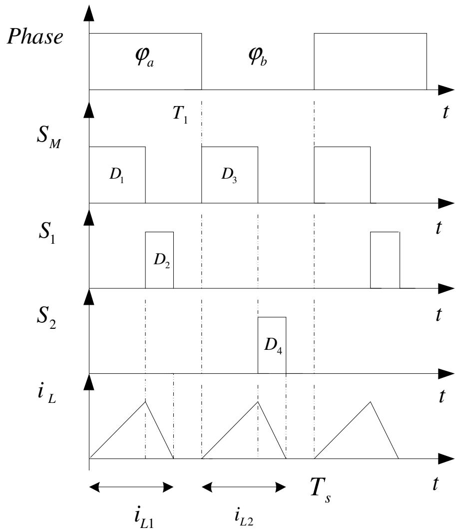


Fig. 5. Timing Diagram of SIDO Boost-Boost converter.

Whole converter operation can be divided into two parts, since it is DCM operation, both the parts will be decoupled from each-other, which allow us to take two separate parts/phases phase a (φ_a) and phase b (φ_b). Both phases are similar in operation, but are complement to each-other. Thus both the phase occurs in each switching cycle. During phase φ_a operation, since the converter operates in DCM, the inductor current should discharge fully before it starts charging in phase φ_b. This condition for inductor current gives us a duty cycle constraint,

$$D_1 + D_2 \le \frac{1}{2} \qquad \text{.. (I)}$$

Similarly for phase φ_b

$$D_3 + D_4 \le \frac{1}{2} \qquad \text{.. (II)}$$

Phase φ_a operation can be explained in below 3 intervals:

Interval 1 (D_1) (S_M - on, S_1 -off; S_2 - off):

Main switch S_M is on and hence can be considered as short circuited, therefore battery voltage charges the inductor and inductor current rises till not the gate pulse is removed from the main switch. Since output switches are off, no current flows through them.

Interval 2 (D_2) (S_M - off; S_1 - on; S_2 - off):

Main switch S_M is off, hence can be considered as open circuited. Now since the current flowing through inductor cannot change instantaneously, the polarity across of the voltage reverses across it and as a result it starts discharging through the output. Inductor charges capacitor C_1 as well.

Interval 3 (D_2) (S_M - off; S_1 - off; S_2 - off):

At the end of interval 2, inductor is fully discharged and in interval 3 it stays at zero. During this mode all the switches are off.

SIDO Buck-Buck Converter:

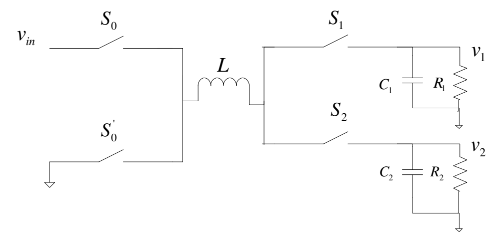


Fig. 6. SIDO Buck-Buck converter.

Figure VI shows the SIDO buck-buck converter. As mentioned earlier SIMO buck-buck converters requires N+2 switches for its operation, hence SIDO buck-buck converter has 4 switches. First input side switch is S_0 and second switch (complement pulse of the first switch) is S_0'. Each output is controlled by the switches S_1 & S_2 respectively.

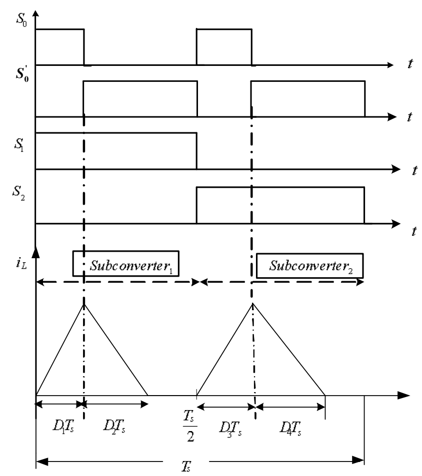


Fig. 7. Switching operation of time-multiplexed SIMO buck-buck converter.

For SIDO converter in one switching cycle inductor is charging and discharging twice and goes to zero for some time as well. Overall inductor current can be divided into two inductor currents in one switching cycle. Considering first sub-converter, operating modes can be divided as;

Mode (1): (S_0-On, S_0' -Off, S_1-On, S_2 –Off): As the switching cycle begins first sub-converter will operate.

Since each sub-converter has three operating modes first sub-converter will also work in 3 modes. In mode (1) inductor charges to a peak value until the main switch S_0 is turned on. Since switch S_1 is also in conducting state slope of charging will be V_{in}-V_1/L.

Mode (2): (S_0-Off, S'_0-On, S_1-On, S_2–Off): Switch S'_0 is the complement switch of main switch S_0. Turning off main switch means the turning on of the switch S'_0, while rest of the circuit functions remains same. In this mode inductor starts discharging through first output. Output voltage will be maintained to V_1, which will be lower than the input voltage because of the buck operation.

Mode (3): (S_0-Off, S'_0-Off, S_1-Off, S_2–Off): When all switch moves to non-conducting state, input voltage will be isolated from the circuit and there is no current in circuit as well. This is the discontinuous mode of operation. Output voltages will be maintained to their respective levels.

III. Modelling and Controller Design

For SIDO Boost-Boost Converter Control-to-Output transfer function:

$$\frac{\hat{V}_1}{\hat{D}_1}=\frac{\frac{T_sV_{in}D_1}{LC_1}\left(\frac{2}{D_1T_s}-s\right)}{s^2+\left(\frac{1}{R_1C_1}+\frac{2(M-1)}{D_1T_s}\right)s+\frac{2(M-1)}{D_1T_sR_1C_1}}$$

$$\frac{\hat{V}_1}{\hat{D}_1}=\frac{K\left(\frac{2}{D_1T_s}-s\right)}{s^2+\left(\frac{1}{R_1C_1}+\frac{2(M-1)}{D_1T_s}\right)s+\frac{2(M-1)}{D_1T_sR_1C_1}}$$

Where, $K=\frac{T_sV_{in}D_1}{LC_1}$

Parameters of Converters:

V_{in} (V)	V_1 (V)	L(μH)	C_1(μF)	R_1	D_1	T_s(μs)
4	5	8	50	20	.132	25

Now, Control-to-Output transfer function:

$$\frac{\hat{V}_1}{\hat{D}_1}=\frac{-7486.8\ (s-2.265*10\text{^}5)}{(s+1.493*10\text{^}5)\ (s+2239)}$$

Controller Design:

A PI controller has been designed assuming to give following margins,

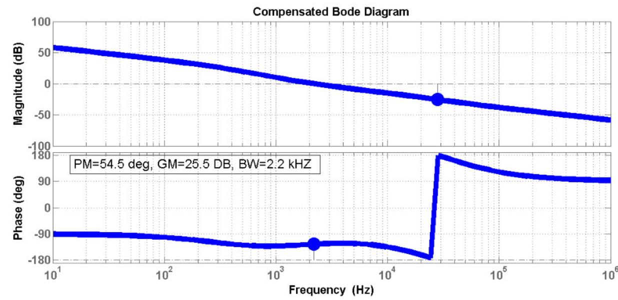
$$PM = 50 - 60\ deg$$

$$Bandwidth = 3 - 5\ kHz$$

The PID parameters found are:

$$K_p = 1,\ K_I = 10000,\ K_D = 0$$

Since Derivative gain is zero, it can be termed as PI controller. Compensated system bode plot is shown below. Compensated system has **PM=54.5 deg** and **BW= 2.2 kHz**.



For SIDO Buck-Buck Converter Control-to-Output transfer function:

$$\frac{\hat{V}_1}{\hat{D}_1}=\frac{\frac{1}{C_1}\left(\frac{V_{in}}{L}+\frac{2I_{L1}V_1}{D_1^2T_s(V_{in}-V_1)}\right)}{s^2+\left(\frac{1}{R_1C_1}-\frac{2M_1}{D_1T_s(M_1-1)}\right)s+\frac{2I_{L1}V_{in}}{D_1T_sC_1(V_{in}-V_1)^2}+\frac{2M_1}{D_1T_sR_1C_1(1-M_1)}}$$

Where, $M_1=\frac{V_1}{V_{in}}$

Parameters of converters.

V_{in} (V)	V_1 (V)	L(μH)	C_1(μF)	R_1	D_1	T_s(μs)
5	1.5	5	50	10	.16	10

Control-to-Output transfer function:

$$\frac{\hat{V}_1(s)}{\hat{D}_1(s)}=\frac{2*10\text{^}10}{s\text{^}2+5.37*10\text{^}5\ s+6.42*10\text{^}9}$$

Controller Design:

A PI controller has been designed assuming to give following margins,

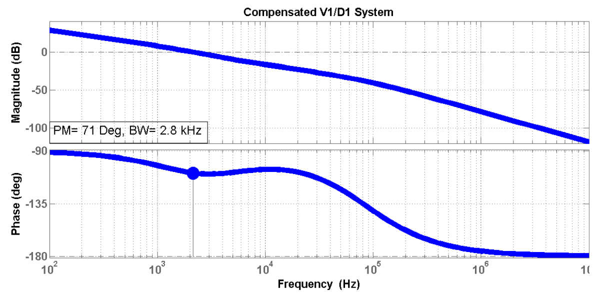
$$PM = 60 - 70\ deg$$

$$Bandwidth = 3 - 5\ kHz$$

The PID parameters found are:

$$K_p = .239,\ K_I = 5555,\ K_D = 0$$

Since Derivative gain is zero, it can be termed as PI controller. Compensated system bode plot is shown below. Compensated system has **PM=71 deg** and **BW= 2.8 kHz.**

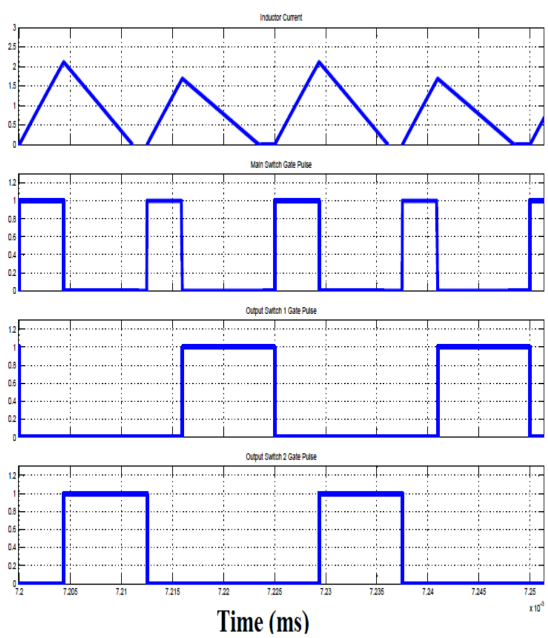


IV. RESULTS

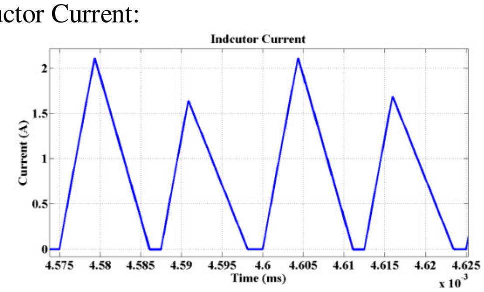
Closed loop Simulation of the Single Inductor Multiple Output converter (SIMO) with the designed values was done in the MATLAB Simulink. The simulation results were found satisfactory and as expected. The various waveforms are as follows:

Time-Multiplexed SIMO Boost-Boost Converter:

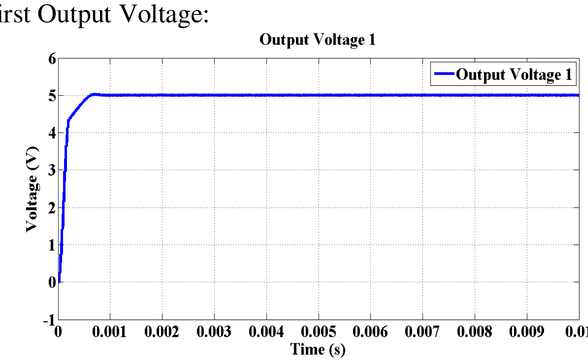
1. Switching operation along with inductor current:



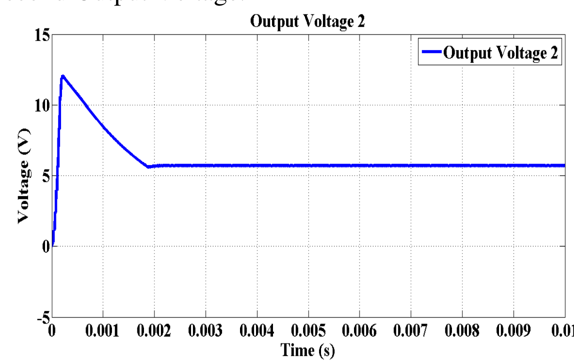
2. Inductor Current:



3. First Output Voltage:

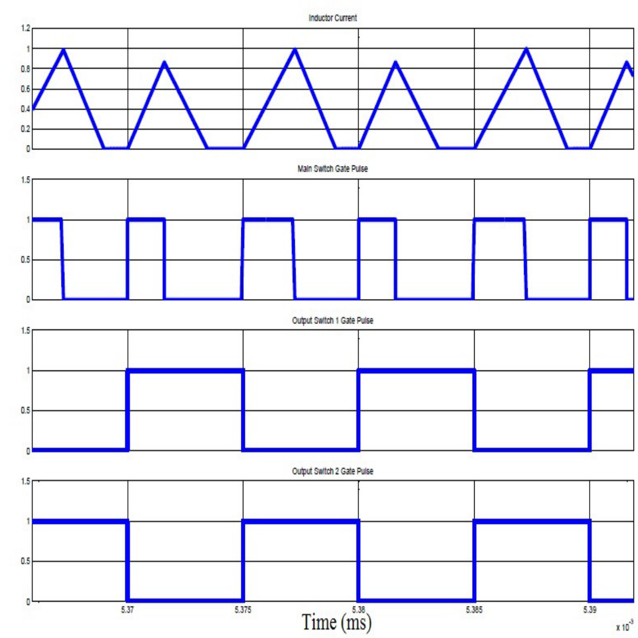


4. Second Output Voltage:

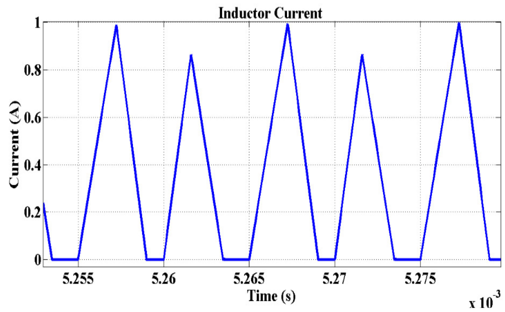


Time-Multiplexed SIDO Buck-Buck Converter:

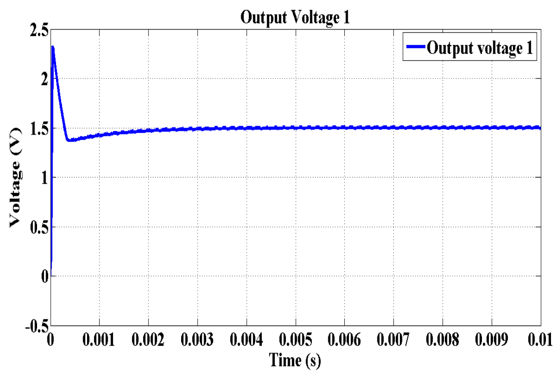
1. Switching Operation along with the Inductor current:



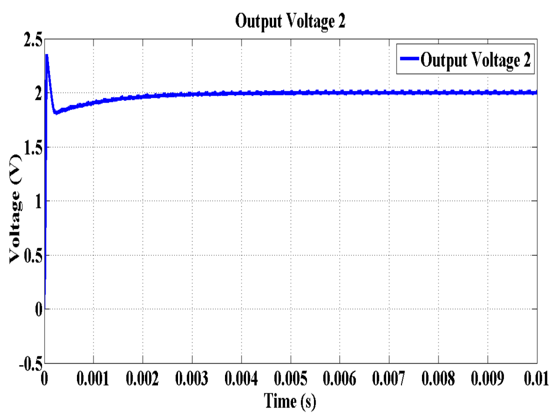
2. Inductor Current Waveform:



3. First Output Voltage:



1. Second Output Voltage:



CONCLUSIONS

State-space averaged modelling has been done and control-to-output transfer functions has been obtained. Since outputs are decoupled among themselves there will not be any cross transfer function. PI Controller for this class of SIMO converter has been designed. Ripple-based modelling has been applied to this class of SIMO converters and various control-to output transfer functions has been obtained. Since outputs are coupled to each-other, cross-regulation will exit. Cross-transfer functions has been obtained as well. PI Controller has been designed for particular output to regulate itself.

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