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A Multi-Output DC-DC Converter

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Abstract: **A Multi-output DC - DC converter topologies can be used to generate multiple DC outputs from a single DC input source. The voltage gains can be step-up and /or step-down type. This paper proposes a dual-port DC-DC converter topology which generates two outputs, one step-up and one step-down, from a single DC input. Operating modes and steady state behaviour of the proposed converter has been studied in this paper. Using MATLAB/SIMULINK (R2013a) the proposed converter topology is simulated with open loop and closed loop control system to generate two outputs (a step-up and a step-down) from a single DC input and the results are compared.**

***Index Terms*—Buck, Boost, Single - input Multiple – output Converters (SIMO), Integrated Dual Output Converter, Continuous Conduction Mode (CCM)**

I. INTRODUCTION

The Single-Input Multiple-Output (SIMO) dc-dc converters can be used for several applications like stand-by power supplies, LED drives, etc. This type of converter uses a single dc input (V_{in}), to generate a number of distinct dc outputs as V_1, V_2,V_3, etc. The topology using separate dc-dc converters to generate the multiple outputs from a single dc input requires a large number of switches for getting the required output. Fig.1 shows the schematic of single-input multiple-output converter that uses separate dc-dc converters. Generally, for getting an N-output from the SIMO dc-dc converters, it requires 2N number of switches. Also for the better power flow management, there should be a proper coordination of control between each of the converters. Instead of using the separate converters for getting the multiple outputs, it can be replaced by a single integrated architecture [1]. This converter has the advantage of reducing the number of switches of the converters than the separate converters. These converters can be represented as Integrated Multiple-Output dc-dc converters, as shown in Fig.2, uses (N+1) switches for obtaining the N number of outputs. Thus the cost of the converter can be reduced. The coordination control is much easier, since the same set of switches are used to generate the outputs due to the integrated structure of the converter.

A class of SIMO converters, utilizing one input to create multiple high frequency ac outputs (step-up or step-down depending upon the turns ratio), which is coupled with multiple secondary windings, all of which are not well regulated has been discussed [2]. A multiple full-bridge dc-dc converter [3] has been integrated into a single topology by having each converter share a common leg. Two- transformer special-connected designs uses complementary PWM that provides better cross regulation at all conditions has been reported in [4]. An isolated multiple-output dc-dc converter based on resonant converter [5] has also been proposed that have ZCS and ZVS for all its switches.

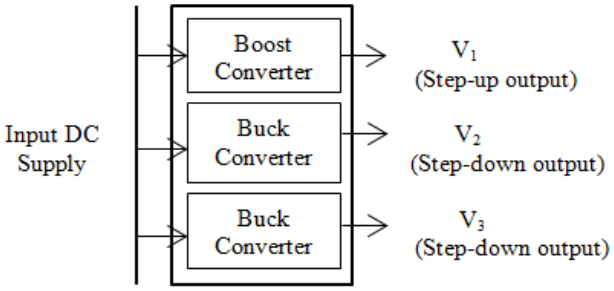

Fig. 1: Schematic of power converter architectures with separate DC–DC converters realizing the three outputs.

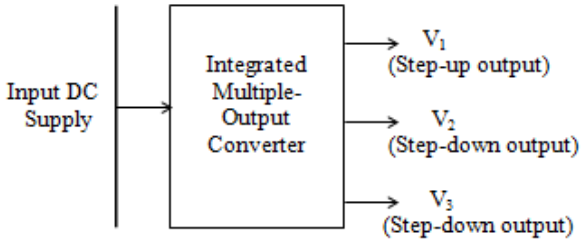

Fig.2: Integrated single stage architecture interfacing the three outputs.

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This paper presents a dc-dc converter that can generate step-up and step-down outputs simultaneously from a single dc input. This SIMO dc-dc converter can be generated by replacing the control switch of a conventional boost converter, by connecting a number of switches in series. The gains obtained in the integrated multiple outputs dc-dc converters are same as that of the separate buck and boost converters. The input and the step-down output currents of these integrated converters are continuous. The control system is similar to the separate buck and boost converter topology. The integrated multiple-output dc-dc converter has generalized as to generate two dc outputs from a single dc input as one step-up and one step-down output as V_1 and V_2. The modification to generate the proposed converter is discussed in section II. The structure of the proposed topology, its operating modes and the steady state analysis have been studied in section III, followed by the control strategy for the converter in section IV. Section V lists the simulation results of the proposed converter in both open loop and closed loop control systems. The comparisons of the control systems are included in section VI.

II. MODIFICATION OF THE CIRCUIT FOR THE PROPOSED CONVERTER TOPOLOGY

The converter topology can be realized by replacing the control switch of a boost converter. Fig. 2(a) shows the schematic of a conventional boost converter. The boost converter uses only one switch, S to control its output. When a gate signal is applied and the switch gets turned on, the diode is reverse biased, thus isolating the output stage ($0 \leq t \leq DT_s$). The input supplies energy to the inductor. When the switch gets turned off, the output stage receives energy from the inductor as well as from the input ($DT_s \leq t \leq T_s$). In the boost converter circuit, when the switch S is replaced by two series connected switches S_1 and S_2 as shown in Fig. 2(b).

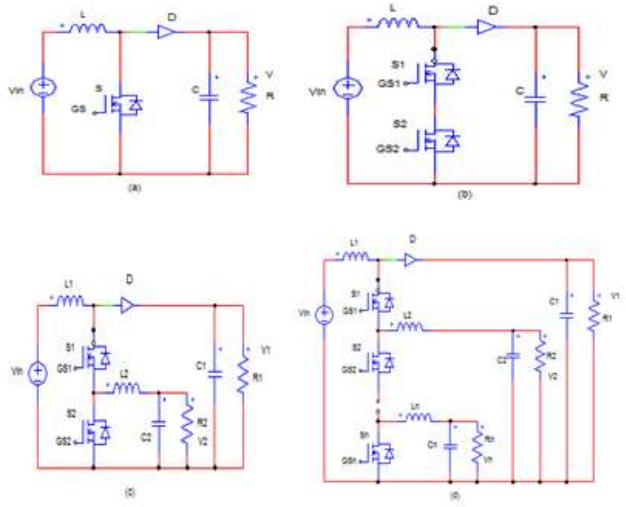

Fig. 2: Modification of the proposed topology from the conventional circuit. (a) Conventional boost converter. (b) Switch S of boost converter is replaced by series connected switches S_1 and S_2. (c) proposed converter topology (d) extension of the proposed circuit to generate N outputs.

The boost operation of this circuit can be achieved when both the switches S_1 and S_2 get turned on simultaneously. The integrated circuit is used for obtaining both the boost and buck outputs, as shown in Fig. 2(c), where the inductor L_2 and the capacitor C_2 acts as low pass filter. Since, only two switches are connected in series, this converter can be termed as integrated dual-output converter. The switches S_1 and S_2 are used to regulate both the outputs. For obtaining multiple dc outputs, the boost converter switch is replaced by a number of switches and filter networks as the number of outputs required as shown in Fig. 2(d).

III. ANALYSIS OF THE PROPOSED CONVERTER TOPOLOGY

The schematic of the proposed converter is shown in Fig. 3. From a single dc input V_{in}, the converter provides step-up and step-down operations at its two output terminals V_1 and V_2 respectively. The converter architecture can be derived by replacing the switch of a conventional boost converter with two bidirectional switches S_1 and S_2 connected in series. The inductor L_2 and capacitor C_2 acts as low pass filters for the step-down output port.

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a. Steady State Operation

The continuous conduction mode (CCM) of operation is considered in this paper. The two bidirectional switches S_1 and S_2 results in three distinct modes of operation and results in three different switching intervals of the converter.

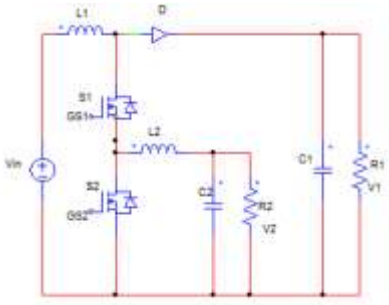


Fig. 3: Schematic of the proposed dual output converter.

Interval I ($t_1 - t_2$):Both switches S_1 andS_2 are ON:

The switching interval I occurs when both the switches S_1 andS_2 are ON. This mode is similar to the operation of a conventional boost converter when the switch is turned ON. During this interval, the diode D is in the reverse biased condition. The inductor L1 get charged through the input and the inductor current i_{L1} builds up. The inductor current i_{L2} freewheels through the switch S_2. The dc loads for the step-up and step-down terminals are considered as R_1 and R_2 respectively. The equivalent circuit of the converter in this interval is shown in Fig. 4(a) and the corresponding waveforms as in Fig. 5. The interval I is represented by the time D_1T_s (where T_s is the switching period) as in the waveform. The duty ratio D_1 is defined for the time duration for interval I operation. The equations for the inductor and capacitor currents and voltages in this interval is as follows

$$v_{L1} = V_{in} \dots\dots\dots\dots\dots\dots (1)$$
$$v_{L2} = -V_2 \dots\dots\dots\dots (2)$$
$$i_{C1} = -\frac{V_1}{R_1} \dots\dots\dots\dots\dots\dots (3)$$
$$i_{C2} = i_{L2} - \frac{V_2}{R_2} \dots\dots\dots\dots\dots\dots (4)$$

Interval II (t_0 - t_1 and t_2 -t_3) :S_1 is ON and S_2 is OFF:

At this interval when the switch S_1 is ON S_2 is OFF, the inductor current i_{L1} is distributes into two components: One flowing through diode D and the other portion through the switch $S_1$to the buck inductor L_2. During this interval, the buck converter draws energy from the source. The duty ratio D_2 is defined for the time duration for the interval II. The equivalent circuit diagram for this interval is shown in Fig. 4(b). At this interval:

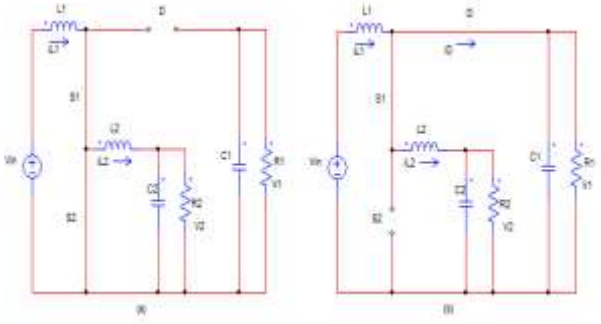
$$v_{L1} = V_{in} - V_1 \dots\dots\dots\dots\dots\dots (5)$$
$$v_{L2} = V_1 - V_2 \dots\dots\dots\dots (6)$$
$$i_{C1} = i_{L1} - i_{L2} - \frac{V_1}{R_1} \dots\dots\dots\dots\dots\dots (7)$$
$$i_{C2} = i_{L2} - \frac{V_2}{R_2} \dots\dots\dots\dots\dots\dots (8)$$

Interval III ($t_3 - t_4$) :Either S_1 is OFF and S_2 is ON or both the switches are OFF:

This interval can be operated by keeping either both the switches S_1 and S_2 in the OFF sate or switch S_1 is OFF and S_2 is ON. The equivalent circuit is shown in Fig. 4(c). The inductor current i_{L1} flows through the diode D. The buck inductor current i_{L2} freewheels through switch S_2 (or if the switch is OFF it get freewheels through the ant parallel diode of the switch S_2). This interval is similar to the condition of the switch getting turned OFF of a conventional buck converter. Thus, both the inductors give out their energy to get the respective outputs. At this interval:

$$v_{L1} = V_{in} - V_1 \dots\dots\dots\dots (9)$$
$$v_{L2} = -V_2 \dots\dots\dots\dots (10)$$
$$i_{C1} = i_{L1} - \frac{V_1}{R_1} \dots\dots\dots\dots\dots\dots (11)$$
$$i_{C2} = i_{L2} - \frac{V_2}{R_2} \dots\dots\dots\dots\dots\dots (12)$$

Fig.5shows the waveforms of the corresponding intervals. It is to be noted that, the mode III in the Fig. 5 is shown by keeping both the switches S_1 and S_2 to be turned OFF.



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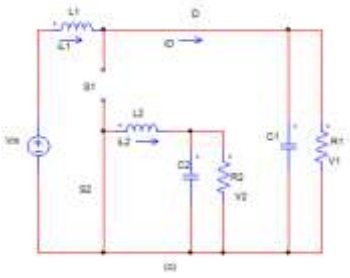
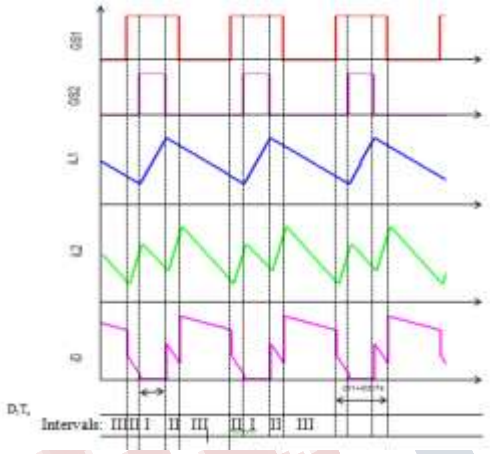


Fig. 4. Equivalent circuit of proposed converter at different operating intervals (a) interval I (b) interval II (c) interval III.



D_1T_s

Intervals: IIIII I II III II I II III

t_0 t_1 t_2 t_3T_s t_4

Fig. 5.Typical waveforms of the gate signals, inductor and the diode currents

Steady-State Analysis

Voltage Conversion Ratio:

For the analysis purpose, it is assumed that there is a small ripple approximation for the inductor currents and capacitor voltages.

For inductor L_1,

$$V_{in} * D_1 + (V_{in} - V_1) D_2 + (V_{in} - V_1)(1 - D_1 - D_2) = 0$$

Therefore,

$$\frac{V_1}{V_{in}} = \frac{1}{1-D_1} \dots\dots\dots\dots\dots\dots\dots (13)$$

For inductor L_2,

$$-V_2D_1 + (V_1 - V_2) D_2 - V_2(1 - D_1 - D_2) = 0$$

Therefore,

$$\frac{V_2}{V_1} = D_2 \dots\dots\dots\dots\dots\dots (14)$$

Hence,

$$\frac{V_2}{V_{in}} = \frac{V_2}{V_1} * \frac{V_1}{V_{in}} = \frac{D_2}{1-D_1} \dots\dots\dots\dots\dots\dots\dots\dots (15)$$

From equations (13) – (15) it can be seen that the two control variables D_1 and D_2 can be used to regulate the two dc outputs of the integrated dual output converter. These duty cycles are defined as the time durations of interval I and II respectively. The step-up output depends on the interval when both the switches S_1 and S_2 get turned ON simultaneously (ie; depends on duty ratio D_1). The step-down output depends solely on the switch S_1 is turned ON and S_2 OFF (ie; both the duty cycles D_1 and D_2). The step-up output voltage thus effectively acts as input to the step-down operation.

Range of Output Voltages:

For the proper operation of the converter, the duty cycles D_1 and D_2 should satisfy the following condition:

$$D_1 + D_2 \leq 1 \dots\dots\dots\dots (16)$$

The range of step-down gain for any particular value of the duty cycle D_1 is:

$$0 \leq \frac{V_2}{V_{in}} \leq 1 \dots\dots\dots\dots (17)$$

Thus the integrated dual output converter can provide step-down output ranges from zero to the input voltage. Since the step-down output depends on both D_1 and D_2, this converter can provide a wide range of step-down outputs at acceptable duty ratios of switches.

Similarly, the step-up gain varies between:

$$1 \leq \frac{V_1}{V_{in}} \leq \frac{1}{1-D_1} \dots\dots\dots\dots\dots\dots\dots (18)$$

Thus, this converter gives the qualities of both buck and boost converter in an integrated architecture.

Input Current Expression:

By neglecting the component losses, the power balance equation of this converter can be expressed as follows. Assume that the average input current to be I_{in} ($=I_{L1}$) and the average output currents to be I_1 and I_2. Then,

$$V_{in} * I_{in} = V_1 * I_1 + V_2 * I_2$$

or

$$I_{in} = \frac{V_1}{V_{in}} * I_1 + \frac{V_2}{V_{in}} * I_2$$

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The first component determines the step-up component and the second one denotes the step-down component. Therefore, by comparing with the conventional boost converter, the input current to this converter is higher, due to the additional power drawn by the step-down load.

IV. CONTROL STRATEGY

A simple control scheme which directly utilizes the control structure of conventional buck as well as boost converters with minimum changes is used for the control purposes. For the integrated dual output converters, the modulating signals ($v_{GS1\ mod}$ and $v_{GS2\ mod}$) are compared with the same carrier with switch S_1 being provided with a PWM signal of duty ($D_1 + D_2$) and S_2 being provided with a signal of duty D_1. The main constraint of the duty ratios are given by the relation (16). Fig. 6 shows the reference control signals for generating PWM. The generalized control architecture for multiple-output converter is shown in Fig. 7. The compensators used to control individual converters can be directly used, and the error amplifier output of the bottom-most switch ($v_{GSn\ mod}$) controls the top-most dc output (v_1). Due to the integrated structure, the error amplifier of each higher stage is the sum of the error amplifier output of the bottom stage and the present stage error amplifier value. Since D_1 and D_2 can be separately regulated, we can have independent control of step-up and step-down outputs.

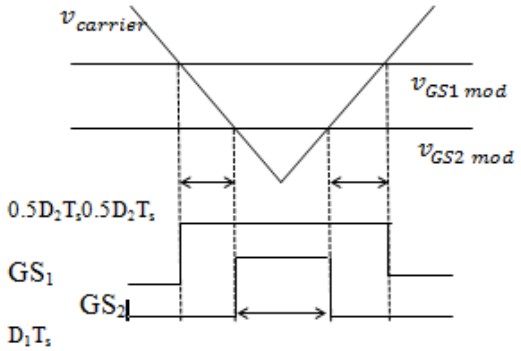

Fig. 6. Reference control signals for generating PWM signals.

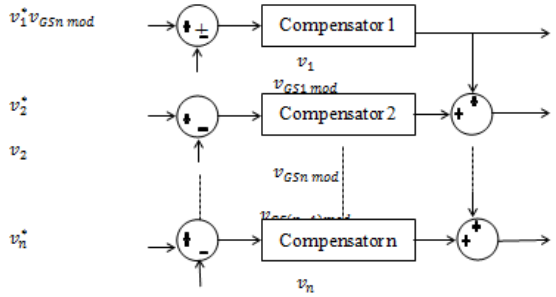

Fig. 7: Generalized PWM control for multiple-outputs.

V. SIMULATION RESULTS

The first section describes the software implementation of the open-loop control system of the proposed converter topology-Integrated dual output converter. The second section gives the simulation results of the system with closed loop control system. The next section explains the comparison between the results of open loop and closed loop control outputs of the proposed system.

Simulation Results of the Proposed System in Open-loop control system.

The proposed integrated dual output converter has been simulated using the MATLAB/SIMULINK R2013a. The result shows the converter can generate both the step-up and step-down outputs simultaneously. The design parameters are shown in Table I.

Table I
Parameter specification of the proposed system

Sl.No.	Parameters	Specifications
1	Input Voltage, V_{in}	12V
2	Step-up output Voltage, V_1	18V
3	Step-down output Voltage, V_2	6V
4	Switching frequency, f_s	100kHz
5	Inductor, L_1	15µH
6	Inductor, L_2	10µH
7	Capacitor, C_1	550µF
8	Capacitor, C_2	220µF

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***Open loop control system*:**

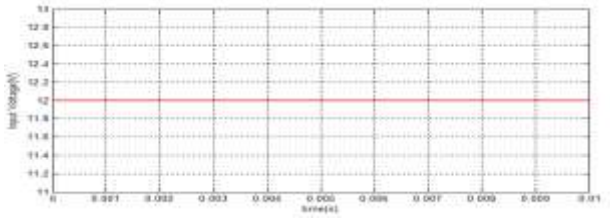

Fig. 8. Input voltage waveform

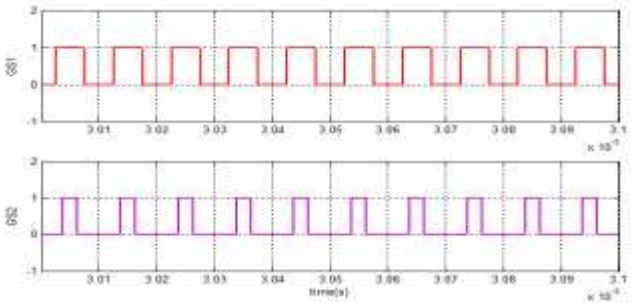

Fig. 9. Gate pulses for the switches.

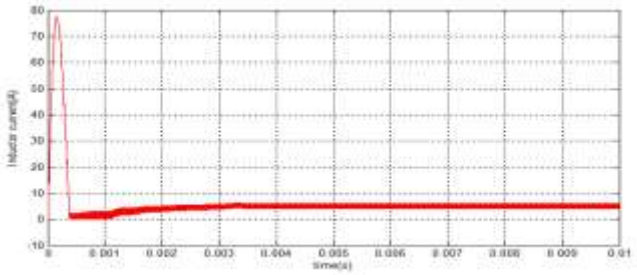

Fig. 10.inductor current, i_{l1} waveform

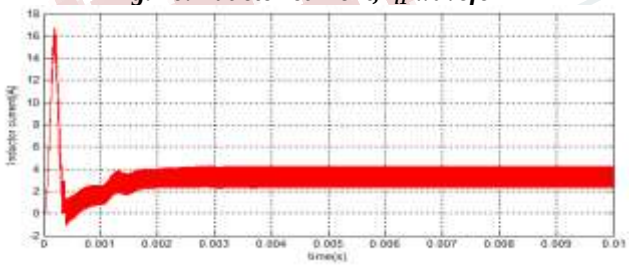

Fig. 11.inductor current, i_{l2} waveform

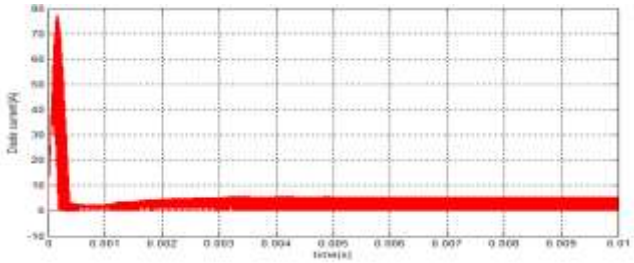

Fig. 12.diode current waveform

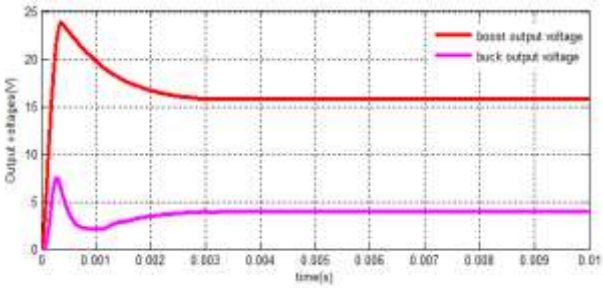

Fig. 13.output voltage waveforms

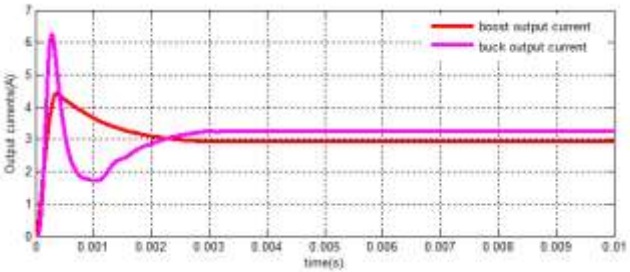

Fig. 14.output current waveforms

Closed loop control system:

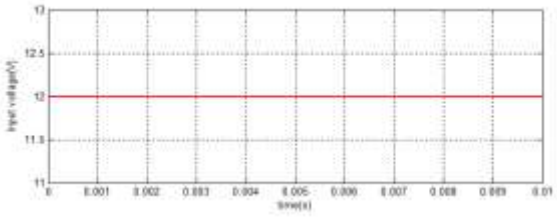

Fig. 15. Input voltage waveform.

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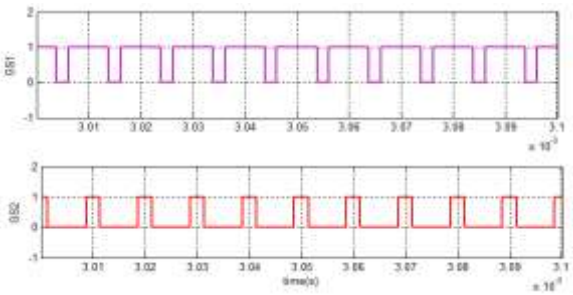

Fig. 16. Gate pulses for the switches.

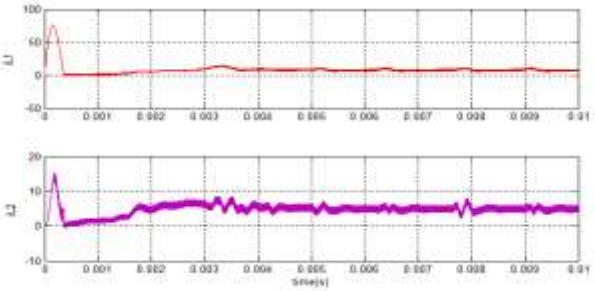

Fig. 17.Inductor current waveforms

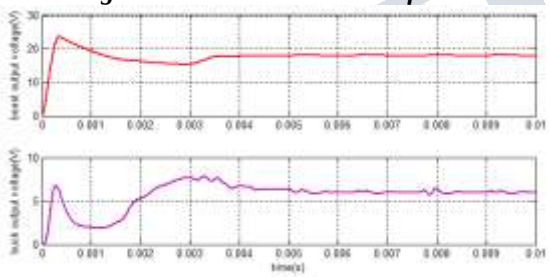

Fig. 18.Output voltage waveforms

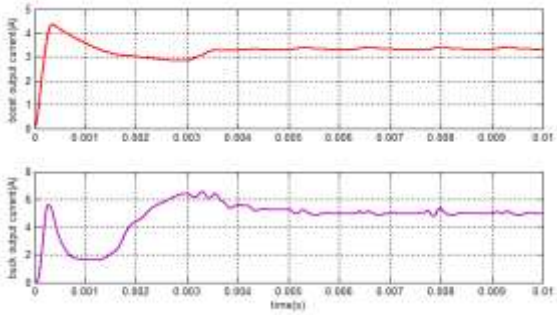

Fig. 19.output current waveforms

COMPARISON

Sl. No.	Parameter	Open-loop control system	Closed-loop control system
1	Input Voltage	12V	12V
2	Boost Output Voltage	15.77	17.86V
3	Buck Output Voltage	3.89V	5.98V

VI. CONCLUSION

A single-input multiple-output dc-dc converter topology that generates both step-up and step-down outputs simultaneously is discussed in this paper. Analysis and operation of different modes of operation of the converter is done. A comparison between the open-loop and closed-loop control system is also done with the help of simulation results.

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