Single Inductor Multiple Output Buck-Boost Converter

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Abstract - *There are many devices which provide multiple power supplies of different voltages. Voltage level may be greater than the source voltage or less than the source voltage depending on the application. Multiple supplies through the single source can be achieved by connecting multiple DC-DC converters in parallel but that will result in the requirement of large number of inductors of different values but inductors are bulky and difficult to integrate. To overcome this disadvantage we can use a Single Inductor Dual Output (SIDO) DC-DC converter. This SIDO DC-DC converter operates with one output in both buck and boost mode and other output in boost mode only. SIDO DC-DC converter has two switches, two diodes and a single inductor to multiplex the both output circuits by suitable switching. This reduces the size of the device, reduces cost, improve efficiency. Here the SIDO buck- boost converter is modified to Single Inductor Multiple Output (SIMO). By this we get three outputs with buck, boost and buck-boost operation. The simulation of the converter is performed using MATLAB/Simulink. The prototype for SIDO buck-boost converter with switching frequency of 20 kHz and an input voltage of 10 V is designed and implemented using PIC16F877A.*

Keywords - *Single Inductor DC-DC Converter , Cross Regulation, Buck-Boost operation, Multiple Output.*

I. Introduction

In recent years, many portable equipment and handheld consumer appliances such as mobile phones, digital cameras, MP3 players, personal digital assistants, and Global Positioning Systems usually include a variety of loads such as LCD displays, memories, microprocessors, Universal Series Bus (USB) and Hard Disk Drives (HDD). These loads require different operating voltages [4]. Voltage level may be greater than the source voltage or less than the source voltage depending on the application. By suitable arrangement of converters, multiple power supplies of different voltages can be achieved. But it will result in large number of inductors of different values. A more interesting and efficient solution is to use one converter with a single inductor to generate multiple outputs. By using a Single Inductor Dual Output (SIDO) DC-DC converter, we can overcome the disadvantage of using large number of inductors. This reduces the size of the device, reduces cost, improves efficiency and has small form factor. Because of circuit simplicity and low cost, this class of converters has found low-power applications requiring multiple-output voltages such as hand-held electronic devices.

Single Inductor Multiple Output Buck-Boost Converter is modified from Single Inductor Dual Output Buck-Boost Converter. Multiple outputs can be obtained by using SIMO converters. A Single Inductor Multiple Output Buck-Boost converter can simultaneously fulfil the requirement for multiple output voltages and the reduction in external components. However, cross regulation among different outputs is most critical issue in Single Inductor Multiple Output converters. It is the main technical challenge of the converter. It is very important to reduce the cross regulation problem. Since it is an intrinsic problem of continuous conduction mode control, we cannot remove it completely but can be reduced [2] by suitable methods. Some of the methods to reduce the cross regulation are based on time multiplexing control techniques, free-wheeling switching techniques, decoupled control techniques, digital control methods etc. [1].

II. System Description

In SIDO buck-boost converter there is a single inductor, two capacitors, two diodes and dual outputs. For proper operation of the converter, V_{o1} must be less than V_{o2}. If V_{o1} greater than V_{o2}, it means that capacitor C_1 potential will become more than the capacitor C_2 potential and diode D_b will get forward biased during the conduction of S_b switch. That will lead to no control over second output voltage V_{o2}. Consider d_1, d_2 are duty ratios of S_a, S_b switches respectively. Circuit diagram of SIDO Buck-Boost converter is shown in Fig.1.

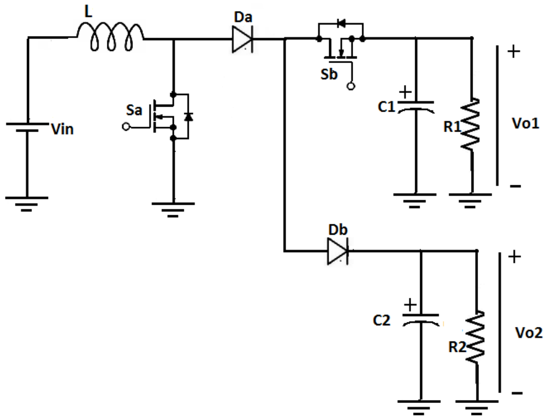

Fig.1: Circuit Diagram of SIDO Buck-Boost converter.

The SIDO converter is modified into Single-Inductor Multiple-Output buck-boost converter in which there are three capacitors, three diodes and three outputs. For proper operation of the converter, V_{o3} must be greater than V_{o1} and V_{o2}. Consider d_1, d_2 and d_3 are duty ratios of S_a, S_b, S_c switches respectively. Circuit diagram of SIMO Buck-Boost converter is shown in Fig. 2.

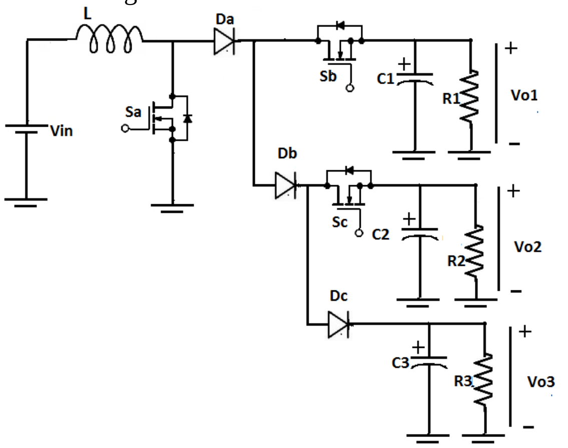

Fig. 2: Circuit Diagram of SIMO Buck-Boost converter.

A. *Mode of Operation*

Mode of operation can be studied by considering different conditions of d_1, d_2 and d_3. It has been assumed that circuit is operating in Continuous Conduction Mode (CCM). Output V_{o1} is operating in buck mode only, output V_{o3} can only operate in boost mode and output V_{o2} can operates in both buck and boost mode. In order to operate V_{o2} in buck mode only switch S_c has to operate for short duration after S_b switch is OFF and for boost operation switch has to operate for long duration up to maximum limit of d_3. From the circuit it is clearly seen that the conduction of diode D_a is complement of switch S_a, conduction of diode D_b is complement of switch S_b and conduction of diode D_c is complement of switch S_c.

1) *Case 1: $d_1 = d_2 = d_3$*

Switch S_a is ON during d_1T period. Since diode D_a is complement to S_a, it will get OFF up to d_1T and inductor will get charged by slope V_{in}/L. The equivalent circuit for d_1T period is shown in Fig. 3(a). There is no conduction of input with switches S_b and S_c because D_a is OFF during d_1T period. During $(1-d_1)T$ period , S_b and S_c switches will get OFF due to $d_1 = d_2 = d_3$ and diode D_a, D_b and D_c will start conducting and inductor will discharge by slope $(V_{in}-V_{o3})/L$. At this period S_a, S_b and S_c are OFF. The equivalent circuit for $(1-d_1)T$ period is shown in Fig. 3(b). Hence V_{o1} and V_{o2} will become zero and V_{o3} output will behave like boost converter. Hence the circuit will be in single output mode of operation. The theoretical waveform of inductor current when $d_1 = d_2 = d_3$ is shown in Fig. 4.

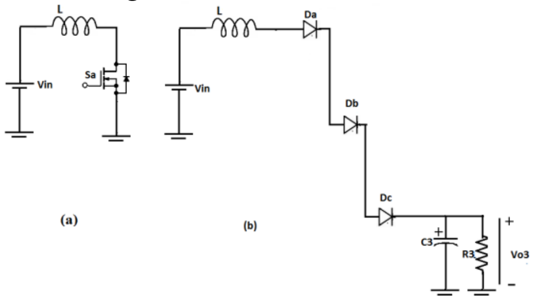

Fig. 3: Equivalent circuit (a)For d_1T period (b)For $(1-d_1)T$ period.

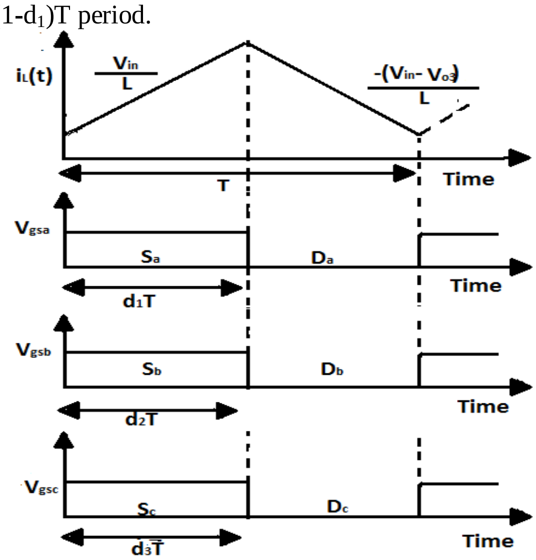

Fig. 4: Theoretical waveform of inductor current when $d_1 = d_2 = d_3$.

2) *Case 2: d_3=1*

Switch S_a is ON during d_1T period, inductor gets charged by slope V_{in}/L and there is no conduction of input with switches S_b and S_c because diode D_a is OFF. The equivalent circuit for d_1T period is shown in Fig. 3(a). During $(1-d_1)T$ period inductor starts discharging through S_c switch by slope $(V_{in}-V_{o2})/L$ because S_c switch is ON for the entire duration T. During this period S_a and S_b

switches are OFF. There will be no discharging through diode D_c and hence $V_{o3}=0$. The equivalent circuit for $(1-d_1)T$ period is shown in Fig. 5. V_{o2} will behave like a boost converter. In this case also circuit will be in single output mode of operation. The theoretical waveform of inductor current when $d_2=1$ is shown in Fig. 6.

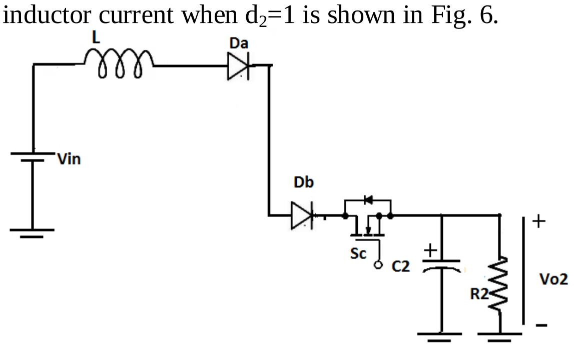

Fig. 5: Equivalent circuit for $(1-d_1)T$ period.

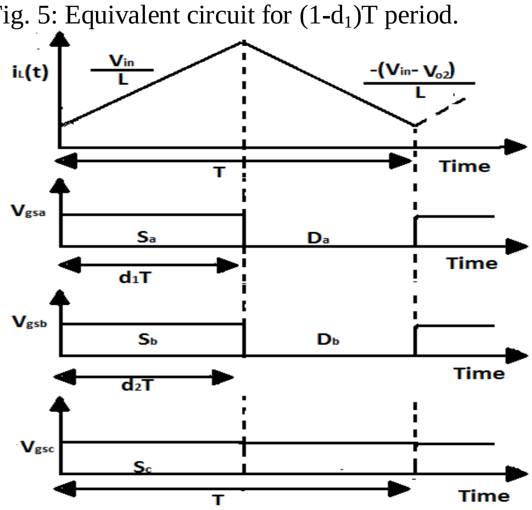

Fig. 6: Theoretical waveform of inductor current when $d_3=1$.

*3) **Case 3: $d_1 < d_2 < d_3 < 1$***

During d_1T period switch S_a is ON, inductor starts to charge by slope V_{in}/L and there is no conduction of input with S_b switch and S_c switch because D_a is OFF. The equivalent circuit for d_1T period is shown in Fig. 3(a). During $(d_2-d_1)T$ period inductor starts discharging through the switch S_b by slope $(V_{in}-V_{o1})/L$. Here S_b is ON and S_a is OFF. The equivalent circuit for $(d_2-d_1)T$ period is shown in Fig. 7. During $(d_3-d_2)T$, both S_a and S_b switches are OFF and switch S_c is ON and inductor starts discharging through switch S_c by slope $(V_{in}-V_{o2})/L$. The equivalent circuit for $(d_3-d_2)T$ period is shown in Fig. 5. During $(1-d_3)T$ period, all switches are off . Inductor will discharge through the diodes by slope $(V_{in}-V_{o3})/L$. The equivalent circuit for $(1-d_3)T$ period is shown in Fig. 3(b). Fig. 8 shows the theoretical waveform of inductor current when $d_1 < d_2 < d_3 < 1$.

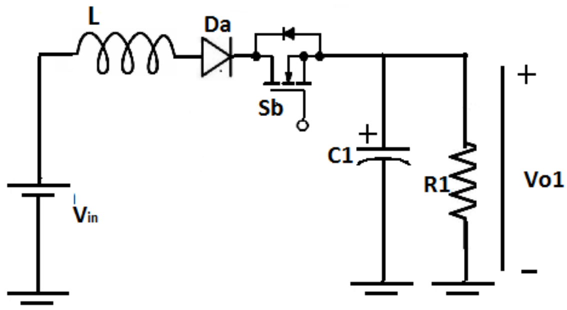

Fig. 7: Equivalent circuit for (d2-d1)T period.

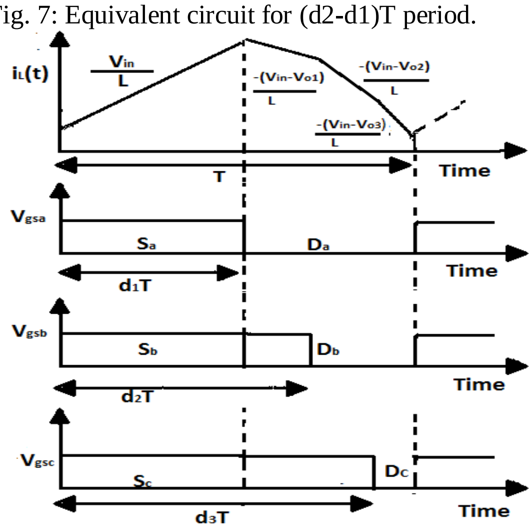

Fig. 8: Theoretical waveform of inductor current when $d_1 < d_2 < d_3 < 1$.

III. SIMULATION MODEL AND RESULTS

The simulation of Single Inductor Multiple Output Converter is done in MATLAB/Simulink. The simulation parameters, simulink model and results are shown below. Simulation parameters of converter are shown in Table 1. Simulation is carried out by using an input of 20 V, switching frequency of 50kHz, inductor with 10mH, capacitors with 1mF each and duty ratios of S_a, S_b , S_c are 0.3, 0.5 and 0.75 respectively.

Table 1: Simulation Parameters

Parameters	Values
Inductor (L)	10mH
Capacitor (C1)	1mF
Capacitor (C2)	1mF
Capacitor (C3)	1mF
Resistor (R1)	10Ω
Resistor (R2)	20Ω
Resistor (R3)	40Ω
Input Voltage	20V
Duty Ratio (d1)	0.3
Duty Ratio (d2)	0.5
Duty Ratio (d3)	0.75
Switching Frequency	50kHz

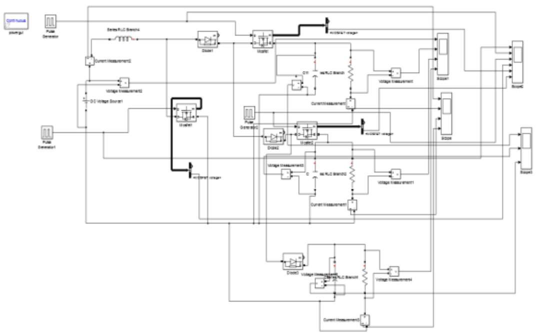

Fig. 9: Simulink model of SIMO boost-boost converter.

A. *V_{o1} In Buck Mode and V_{o2}, V_{o3} Are In Boost Mode*

In order to operate V_{o2} in boost mode, switch S_c has to operate for long duration after switch S_b is off . So the last two output voltages are greater than the input voltage and the first output is less than the input voltage. Fig. 10 shows the input and output voltages. Fig. 11 shows the gate pulses and Fig. 12 shows the voltage across switches. Fig. 13 shows the waveforms of input and output currents. Inductor current is same as the input current. It is clear that the capacitor voltage and output voltages are same. Current ripple across inductor and voltage ripples across capacitors are about 0.1 A and 0.1 V respectively. Power outputs, P_{o1} is 8 W, P_{o2} is 28 W and P_{o3} is 58 W.

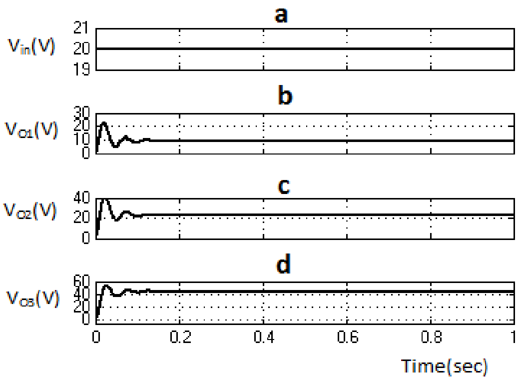

Fig. 10: Simulink result of (a)Input Voltage(V_{in}) (b)Output Voltage(V_{o1}) (c)Output Voltage(V_{o2}) (d)Output Voltage(V_{o3}).

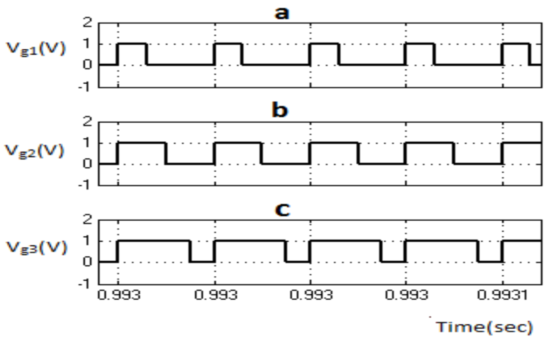

Fig. 11: Simulink result of (a)Gate Pulse of S_a (b)Gate Pulse of S_b (c)Gate pulse of S_c.

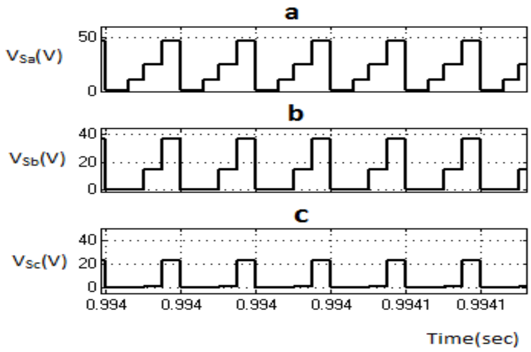

Fig. 12: Simulink result of (a)Stress of S_a (b)Stress of S_b (c)Stress of S_c.

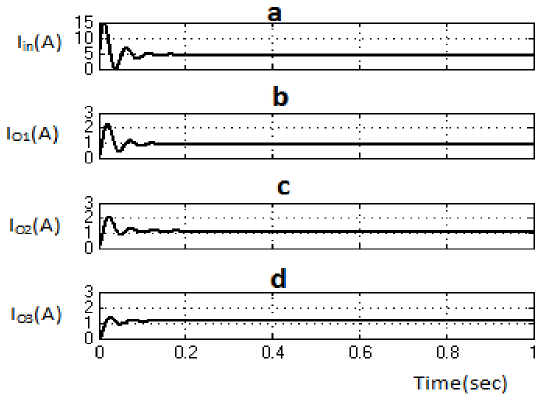

Fig. 13: Simulink result of (a)Input Current(I_{in}) (b)Output Current(I_{o1}) (c)Output Current(I_{o2}) (d)Output Current(I_{o3}).

B. *Vo1, Vo2 In Buck Mode and Vo3 In Boost Mode*

In order to operate V_{o2} in buck mode only switch S_c has to operate for short duration after S_b switch is off . Thus two outputs are less than the input voltage and other one is greater than the input voltage. Fig. 14 shows the voltage waveforms. Fig. 15 shows the gate pulses and voltage across the switches are given by Fig. 16. Input current and output currents are shown in Fig. 17. Current ripple across inductor and voltage ripples across capacitors are about 0.01 A and 0.02 V respectively. Power outputs, P_{o1} is 4 W, P_{o2} is 5 W and P_{o3} is 48 W.

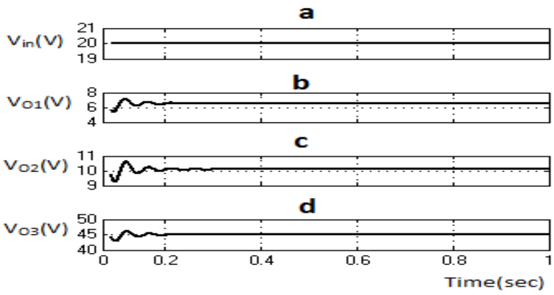

Fig. 14: Simulink result of (a)Input Voltage(V_{in}) (b)Output Voltage(V_{o1}) (c)Output Voltage(V_{o2}) (d)Output Voltage(V_{o3}).

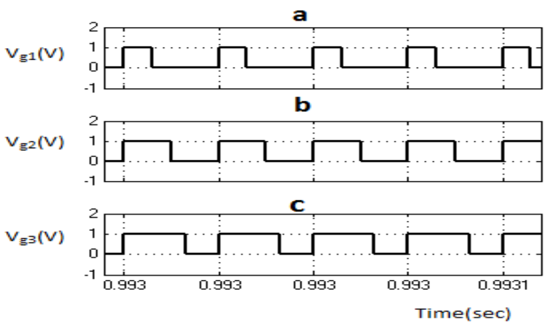

Fig. 15: Simulink result of (a)Gate Pulse of S_a (b)Gate Pulse of S_b (c)Gate pulse of S_c.

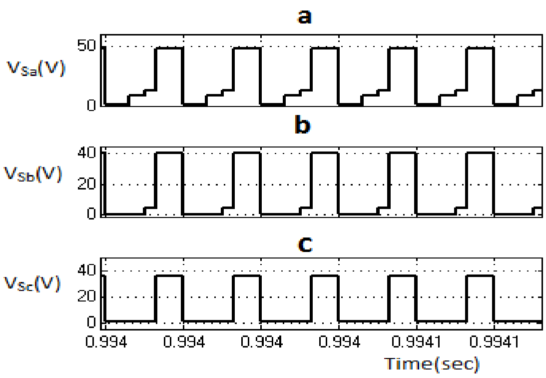

Fig. 16: Simulink result of (a)Stress of S_a (b)Stress of S_b (c)Stress of S_c.

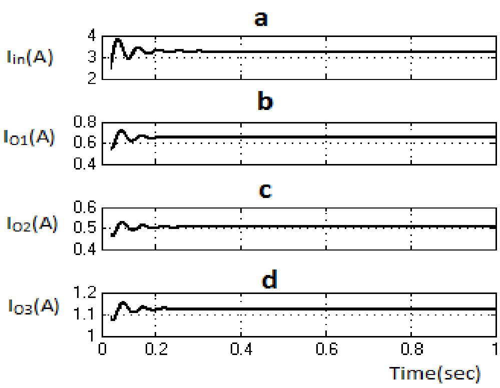

Fig. 17: Simulink result of (a)Input Current(I_{in}) (b)Output Current(I_{o1}) (c)Output Current(I_{o2}) (d)Output Current(I_{o3}).

IV. EXPERIMENTAL SETUP AND RESULTS

The prototype for SIDO buck-boost converter with switching frequency 20 kHz and an input voltage of 10V is designed and implemented using PIC16F877A. Fig. 18 shows the experimental setup of the SIDO buck-boost converter. Output Voltage(V_{o2}) of both boost-boost and buck-boost operations are almost similar.

Fig. 18: Experimental Setup of SIDO Buck-Boost Converter.

Table 2: Components used for hardware

COMPONENTS	SPECIFICATION
MOSFET	IRF540
Inductor	15mH
Capacitors	1mF each
Controller	PIC16F877A
Driver IC	TLP250
Diode	MUR810
Load Resistors	75Ω, 150Ω

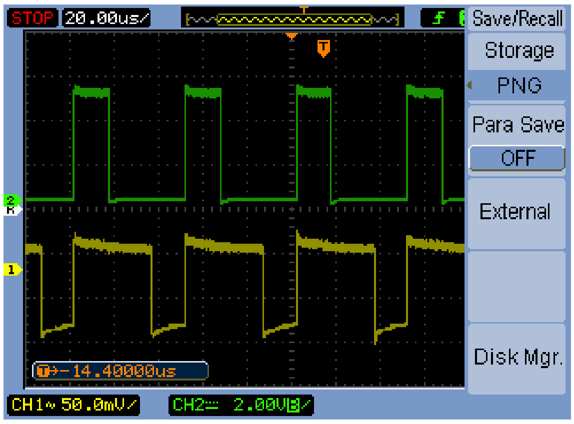

Fig. 19: Gate Pulses for S_a and S_b

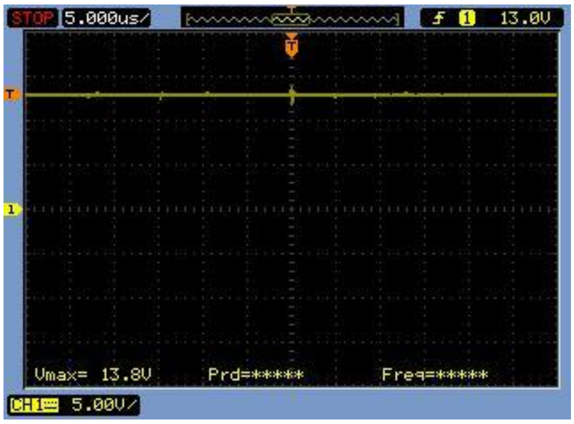

Fig. 20: Output Voltage(V_{o1}) of boost-boost operation.

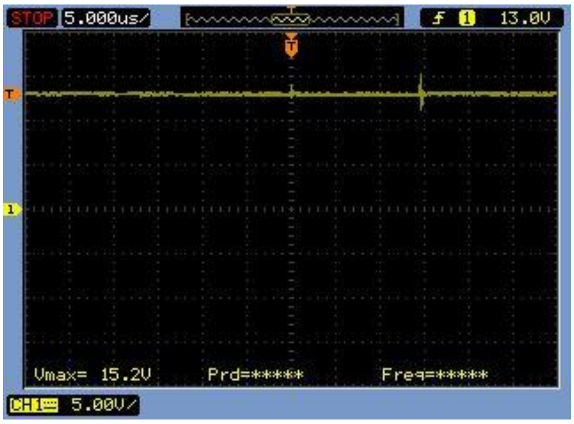

Fig. 21: Output Voltage(V_{o2}) of boost-boost operation.

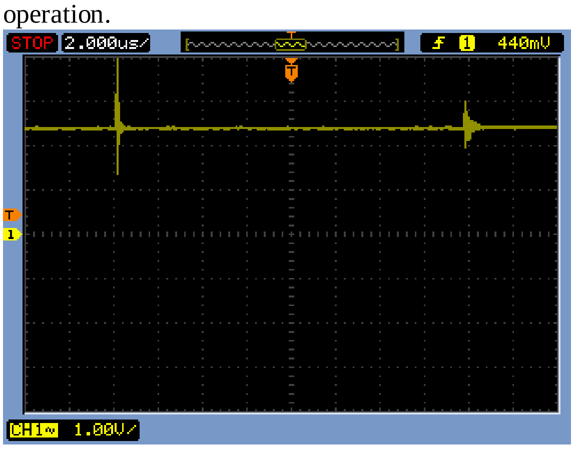

Fig. 22: Output Voltage(V_{o1}) of buck- boost operation.

V. CONCLUSIONS

A Single Inductor Multiple Output Buck-Boost converter operating in CCM mode with first output voltage operating only in buck mode. Second output operates in both buck and boost mode and the third output operates only in boost mode. Thus from a single input we get three different outputs. The output voltages are depend on the duty ratios d_1, d_2 and d_3 of switches S_a , S_b and S_c respectively. The main advantage of SIMO converter is that it requires only a single inductor to achieve the multiple output voltages. Due to this, SIMO converters can overcome the disadvantage of using large number of inductors of different values which can increase the complexity of the circuit.

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