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Closed Loop Voltage Mode Controlled High Step-Down/Step-Up Positive Output Buck–Boost Converter

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Abstract

This work presents the positive output buck–boost (POBB) converter with single loop control and simple converter structure. The presented POBB converter achieves the square of the high step-down/step-up voltage conversion gain as compared with the traditional buck–boost (TBB) converter and also the output voltage polarity is positive. These advanced features facilitate work in a wider range of high-step-down/step-up positive output converters. In the high gain POBB converter the two controlled power switches are operated synchronously. The converter is designed to operate in continuous current mode (CCM), one in switch-on mode, during which the two inductors are energized and two capacitors are discharged, and the later one in switch-off mode, during which the two inductors are de-energized and two capacitors are charged. The operating principles and the steady-state analysis of high step-don/step-up POBB converter operating in CCM are presented in detail. Further, a closed loop voltage mode control (VMC) is designed and simulated to study the line and load regulations of POBB converter in both high step-down (buck mode) and high step-up (boost modes) respectively. Theoretical analysis and predictions of the closed loop VMC POBB converter have been validated using MATLAB/Simulink platform.

Keywords: Positive output buck-boost (POBB) Converter, Continuous current mode (CCM), Traditional buck-boost (TBB) converter, voltage mode control, line and load regulation.

1 Introduction

Switching-mode power supply (SMPS) is the core of modern power conversion technology, which is used in a range of applications such as: lighting, renewable energy systems, railways, industrial and commercial among others [1]; [2]. With the foundation of SMPS, many converter topologies have been proposed in the literature. The traditional buck converter and traditional boost converter provide benefits like: simple structure, lower component count and high efficiency. The major drawback is low step-down/step-up voltage conversion gain, which restricts its application [3]; [4]; [5]; [6]. High step-up voltage conversion gain can achieved in Luo converters by using the voltage lift technique, but they have several limitations such as converter complexity, cost, volume and losses [7]. Interleaved converters have a major advantage of obtaining a high step-down/step-up voltage conversion ratio with reduced ripple current and minimum voltage stress on controlled switch, while their operating mode, converter structure, and control strategy are complicated [8]. The quadratic converters can achieve the high conversion gain of cascade converters with fewer switches, but the efficiency of these converters is low due to the greater number of components [9]. Further switched capacitor and switched inductor networks are accumulated with conventional configurations to obtain high step-down/step-up voltage conversion gain, which results in the complicated structure and increased cost due to more components [10]; [11].

The aforementioned converter configurations can only step-down or step-up the voltage and can regulate the output voltage under a wider range of line and load variations, and are widely used in lighting, renewable energy sources, electric vehicles and portable electronic devices etc. The traditional buck-boost converter has a simple converter structure and achieves high efficiency, whereas it is limited to certain applications due to low step-down/step-up voltage conversion gain, negative output voltage, and floating power switch, along with discontinuous nature of input and output currents. One of the authors proposed a quadratic buck-boost converter in [12] which has high gain, and common ground is shared by both input and switch, which simplifies control complexity. However, this converter can only work in step-down mode as diodes D_1 and D_2 clamp the output voltage to the input voltage while the duty cycle is bigger than 0.5.

In order to obtain high step-down/step-up voltage conversion gain, the converters must operate under extremely high or low duty cycle, which results in low efficiency and limitations in practical realizations.

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Hence, it is very important and valuable to explore new and innovative configurations of the buck-boost converter to overcome the limitations of the traditional ones in terms of meeting the requirements in lighting, renewable energy source and industrial applications. Few authors have proposed coupled inductor (CI) converters with high step-down/step-up voltage conversion gain, reduced device stress and high efficiency. However, the applications of CI converters are limited due to the leakage energy of CI [13]; [14]; [15]; [16]; [17]. Therefore, a POBB converter is proposed by adding a new switched network into the TBB converter. The major advantage is that step-down/step-up voltage gain is square that of the TBB converter, so that we can operate it in a wide range of output voltage, i.e., we can achieve a high step-down/step-up voltage conversion gain without an extreme duty cycle. Additionally, the output voltage of the POBB converter has common ground with the input voltage and its polarity is positive.

This article provides an introduction and review in Section 1 followed by detailed analysis of the POBB converter in Section 2. Simulation results and discussions are presented in section 3 followed by conclusions in section 4.

2 Operation and design analysis

Fig. 1 depicts the circuit configuration of the POBB converter, which consists of two controlled power switches (S_1 & S_2), two diodes (D_1 & D_0), two inductors (L_1 & L_2), two capacitors (C_1 & C_0), and resistive load R. Also, the input voltage is represented by V_{in}, the output voltage/current is represented by V_o/I_o. The various circuit variables are defined as follows: i_{L1} and v_{L1} are primary inductor current and voltage respectively, i_{L2} and v_{L2} are auxiliary inductor current and voltage respectively and i_{C1} and v_{C1} are current and voltage of capacitor C_1 respectively.

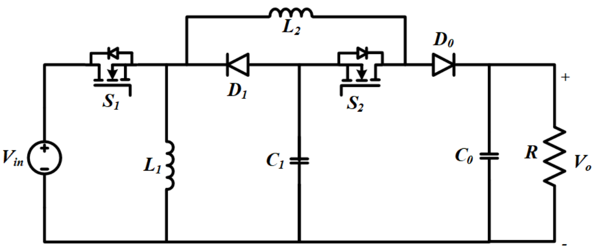

Figure 1: System configuration of positive output buck-boost converter

Fig. 2 illustrate the idealized waveforms of the positive output buck-boost converter. The gating signals for

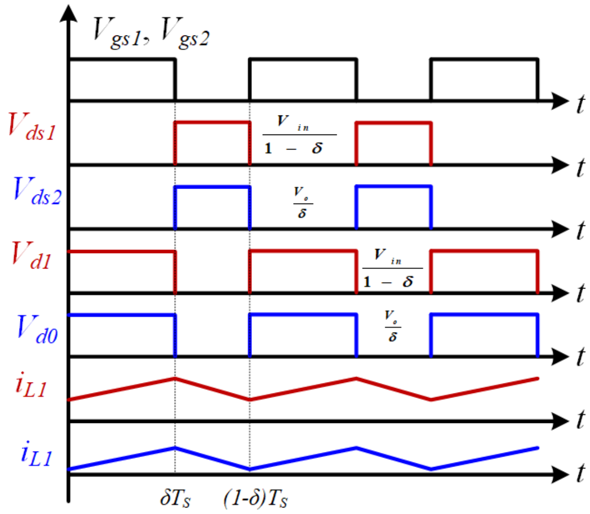

Figure 2: Ideal waveforms of positive output buck-boost converter

both the main switches S_1 and S_2 are (V_{gs1} & V_{gs2}) and are synchronized, therefore only one driving signal V_g is chosen. The duty cycle and switching period are defined as δ and T_S respectively. In order to simplify analysis of the closed loop VMC POBB converter, the following assumptions were made.

i. All the controlled power switches and diodes are ideal.

ii. To maintain constant output voltage, the output capacitors are assumed to be higher values.

2.1 Operating modes

The working principle of the closed loop VMC positive output buck-boost converter under continuous current mode is described in two operating modes over a switching period (T_S). The equivalent circuits of each mode of operation are as shown in fig. 3 and explained as follows:

Mode-1: During this mode of operation both controlled switches S_1 and S_2 are turned-on simultaneously, and diodes D_1 and D_0 are turned off, i.e., reverse biased. Both the inductors are energized, but from different sources. From fig. 3(a) it is seen that inductor L_1 is energized from input voltage V_{in} whereas, inductor L_2 is de-energized from input voltage V_{in} and capacitor C_1. Output capacitor C_0 supplies the energy to the load. According to Kirchhoff's voltage law (KVL), the following equations can be established;

$$V_{L1} = V_{in} \tag{1}$$

$$V_{L2} = V_{in} + V_{c1} \tag{2}$$

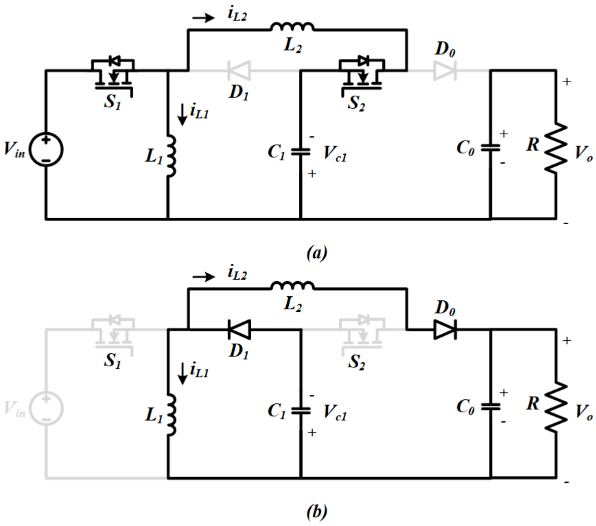

Figure 3: Equivalent circuits of the POBB converter. (a) Mode 1. (b) Mode 2

Mode 2: During this mode switches S_1 and S_2 are turned off simultaneously, and diodes D_1 and D_0 are turned on, i.e., forward biased. Both the inductors are de-energized during this mode. From fig. 3(b) it can be clearly observed that the energy stored in inductor L_1 is released to capacitor C_1 via diode D_1. Simultaneously, the energy stored in inductor L_2 is released to capacitor C_1, output capacitor C_0, and the resistive load R via diodes D_0 and D_1. According to Kirchhoff's voltage law (KVL), the following equations can be established;

$$V_{L1} = -V_{c1} \tag{3}$$

$$V_{L2} = -(V_{c1} + V_o) \tag{4}$$

By using the volt-second balance principle on inductor L_1, the voltage across charge pump capacitor C_1 is obtained from equations 1 and 3 as follows;

$$V_{c1} = \frac{\delta}{1-\delta} V_{in} \tag{5}$$

Similarly, by using the voltage-second balance principle on inductor L_2, the voltage gain of the high step-down/step-up gain POBB converter can be obtained from equations 2, 4 and 5 as follows;

$$M = \frac{V_o}{V_{in}} = \left(\frac{\delta}{1-\delta}\right)^2 \tag{6}$$

From equation 6 it can be observed that the high step-down/step-up gain POBB converter can step-down the input voltage when the duty cycle is less than 0.5 and step-up the input voltage when the duty cycle is larger than 0.5. Further, the voltage gain of POBB converter is higher than traditional buck-boost converter.

The inductor ripples current i_{L1} and i_{L2} can be denoted as follows;

$$\Delta i_{L1} = \frac{V_{L1}}{L_1}\delta T_s = \frac{\delta V_{in}}{L_1 f_s} \tag{7}$$

$$\Delta i_{L2} = \frac{V_{L2}}{L_2}\delta T_s = \frac{\delta V_{in}}{(1-\delta) L_2 f_s} \tag{8}$$

If the current ripple of the inductor, input voltage V_{in}, duty cycle δ, and switching frequency f_s are known, the inductance of L_1 and L_2 can be calculated from equations 7 and 8, so that the appropriate inductors can be selected in practical engineering.

The voltage ripples across capacitors C_1 and C_0, i.e., Δv_{C1} and Δv_{C0} are

$$\Delta v_{c1} = \frac{\Delta Q}{C} = \frac{\delta V_o}{(1-\delta) R C_1 f_s} \tag{9}$$

$$\Delta v_{co} = \frac{\Delta Q}{C} = \frac{\delta V_o}{R C_o f_s} \tag{10}$$

By knowing the capacitors ripple voltages, output voltage V_0, duty cycle δ, resistive load R, and switching frequency f_s then capacitance of C_1 and C_0 can be calculated based on equations 9 and 10.

2.2 Control scheme

Fig. 4 illustrates a voltage mode controlled high step-down/step-up positive output buck-boost converter.

The voltage mode controller based pulse width modulation (PWM) technique is simulated using the Matlab/Simulink environment. In order to control the switch-on period (T_{on}), a closed loop controller is designed. The T_{on} period of the switch is varied with the variation of source voltage and/or load to achieve the desired output voltage for the fixed switching frequency of 20 kHz. For constant switching frequency, when T_{on} changes T_{off} will change accordingly. The control scheme is formed by a proportional integral (PI) controller and PWM, which generates switching pulses V_{gs1} and V_{gs2} to controlled power switches S_1 and S_2 respectively. A PI voltage controller is designed for good voltage regulations with zero steady state error for line and load variations.

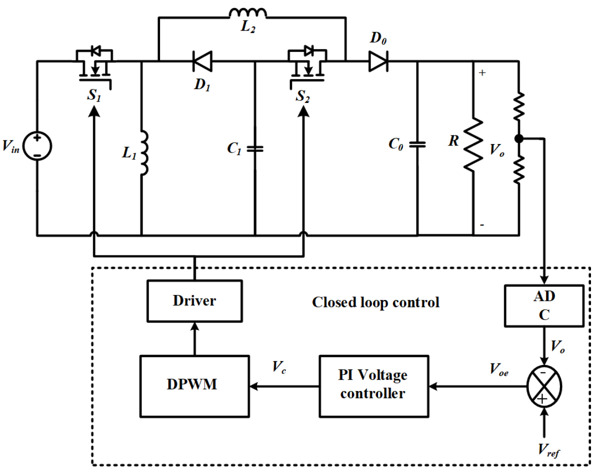

Figure 4: Closed loop voltage mode controlled high gain POBB converter

3 Simulation results and discussions

In order to verify the feasibility of closed loop VMC high gain positive output buck boost converter can be constructed using Matlab/Simulink environment based on fig. 4. The system specifications and design parameters used in the simulation studies for the high gain positive output buck boost converter are presented in table 1. The simulation circuit of the closed loop VMC high gain positive output buck boost converter is carried out using the MATLAB/SIMULINK platform as shown in fig. 5.

Fig. 6a-b illustrates the steady state waveforms of gate voltage (V_g), switch voltages (V_{ds1} & V_{ds2}) and switch currents (i_{ds1} & i_{ds2}) of the closed loop VMC POBB converter during buck mode and boost mode. Fig. 6 confirms that the switches (S_1 & S_2) is turning on when gate pulse is high and switches (S_1 & S_2) are turning off when gate pulse is low during both modes of operation. Further, the voltage and current stress of both the switches is confined with the theoretical analysis.

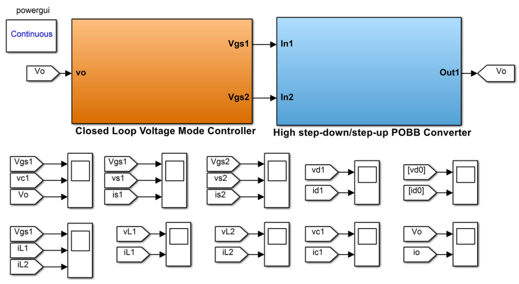

Figure 5: Simulation model of the closed loop voltage mode control POBB converter

Table 1: Specifications and design parameters of high gain POBB converter

Parameter	Buck	Boost
V_{in}	18V	18V
V_o	8V	40.2V
P_O	6.4W	10.8W
f_s	20kHz	20kHz
L_1	1mH	1mH
L_2	3mH	3mH
C_1	10uF	10uF
C_o	20μF	20μF
R	10Ω	150Ω

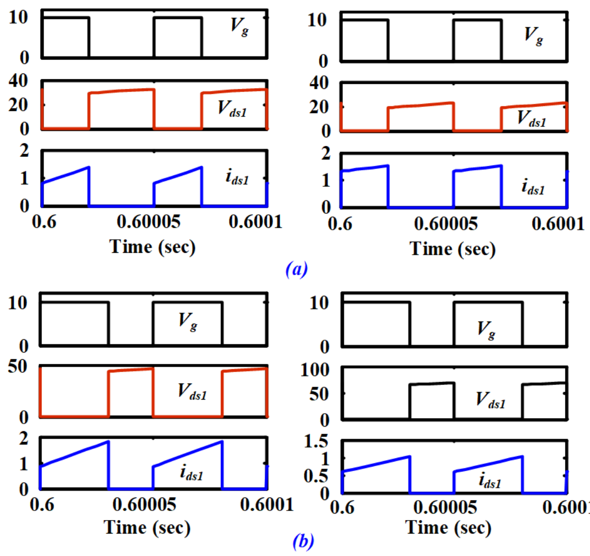

Figure 6: Simulation waveforms of V_g, switches (S_1 & S_2) voltages & currents: (a) Buck mode, (b) Boost mode.

Fig. 7a-b illustrate the steady state waveforms of input voltage (V_{in}), output voltage (V_o) and output current (I_o) of the closed loop VMC high gain converter in buck mode and boost mode respectively. Fig. 7 clearly indicates that the converter is achieving high step-down voltage conversion gain during buck mode and high step-up voltage conversion gain during boost mode. Further the output voltage and current ripple are maintaining within the limits of design values.

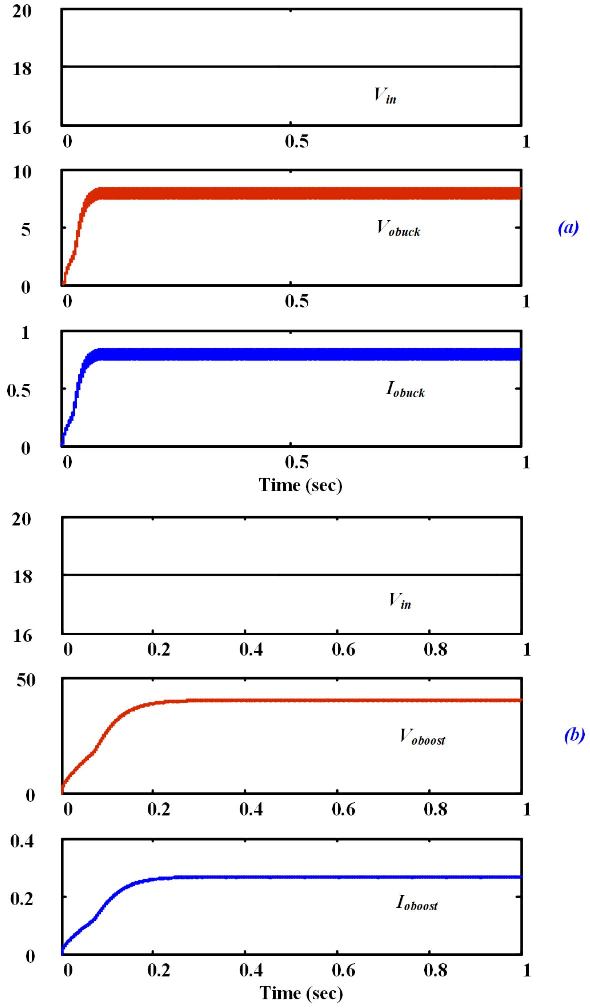

Figure 7: Simulation waveforms of input voltage (V_{in}), output voltage (V_o) and output current (I_o): (a) Buck mode, (b) Boost mode.

Fig. 8a-b illustrates the capacitor voltage and current (v_{C1} & i_{C1}), inductor currents (i_{L1} & i_{L2}) of the two inductors L_1 and L_2 during buck and boost mode respectively. Fig. 8a clearly indicates that capacitor voltage v_{C1}, the inductor

current i_{L1}, and the inductor current i_{L2} are within (11.8V, 13.1V), (-0.5A, -0.2A) and (1.3A, 1.5A), respectively. Also, the ripples of inductor current Δi_{L1}

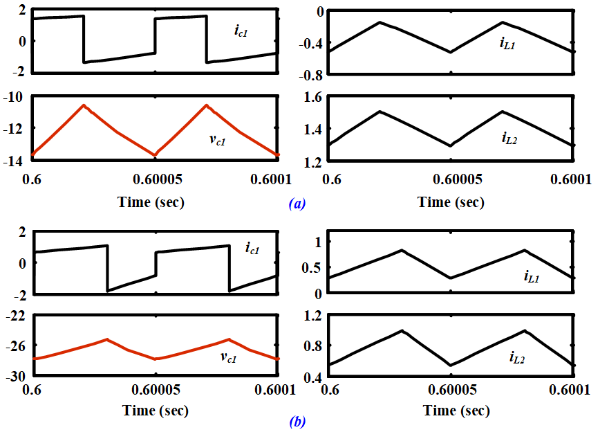

Figure 8: Simulation waveforms of capacitor current (i_{C1}), voltage (v_{C1}), inductor currents (i_{L1} & i_{L2}): (a) Buck mode, (b) Boost mode.

and inductor current Δi_{L2} are 0.3A and 0.2A, respectively. The ripple of capacitor ΔV_{C1} is 1.3V. Also fig. 8b clearly indicates that capacitor voltage v_{C1}, inductor current i_{L1}, and inductor current i_{L2} are within (25.2V, 27.3V), (0.3A, 0.9A) and (0.5A, 1A), respectively. Further, the ripples of inductor current Δi_{L1} and inductor current Δi_{L2} are 0.6A and 0.5A respectively, and the ripple of capacitor Δv_{C1} is 2.1V.

In order to study the effectiveness of closed loop VMC a high-gain POBB converter is implemented in Matlab/Simulink platform. Fig. 9a-b illustrates input voltage (V_{in}), output voltage, (V_o) and output current (I_o) of buck mode for sudden change in load and input voltage respectively. It clearly indicates that the output voltage is maintaining a stable value of 40.2 V for both load and line variations from fig. 9. Hence it concludes that the designed closed loop VMC is working effectively for both load and line variations during buck mode. Fig. 10a-b illustrates input voltage (V_{in}), output voltage, (V_o) and output current (I_o) of boost mode for sudden change in load and input voltage respectively. Fig. 10 clearly indicates that the output voltage is maintaining a stable value of 40.2 V for both load and line variations. Hence it concludes that the designed closed loop VMC is working effectively for both load and line variations during boost mode.

The efficiency of the high gain POBB converter is obtained by simulation analysis with various loading conditions in buck and boost mode. Fig. 11 clearly indicates that the efficiency of the boost converter is higher than that of the buck converter through the loading conditions from 0.3 A to 0.8 A. The highest efficiency in boost mode is 85% and in buck mode 76.6%.

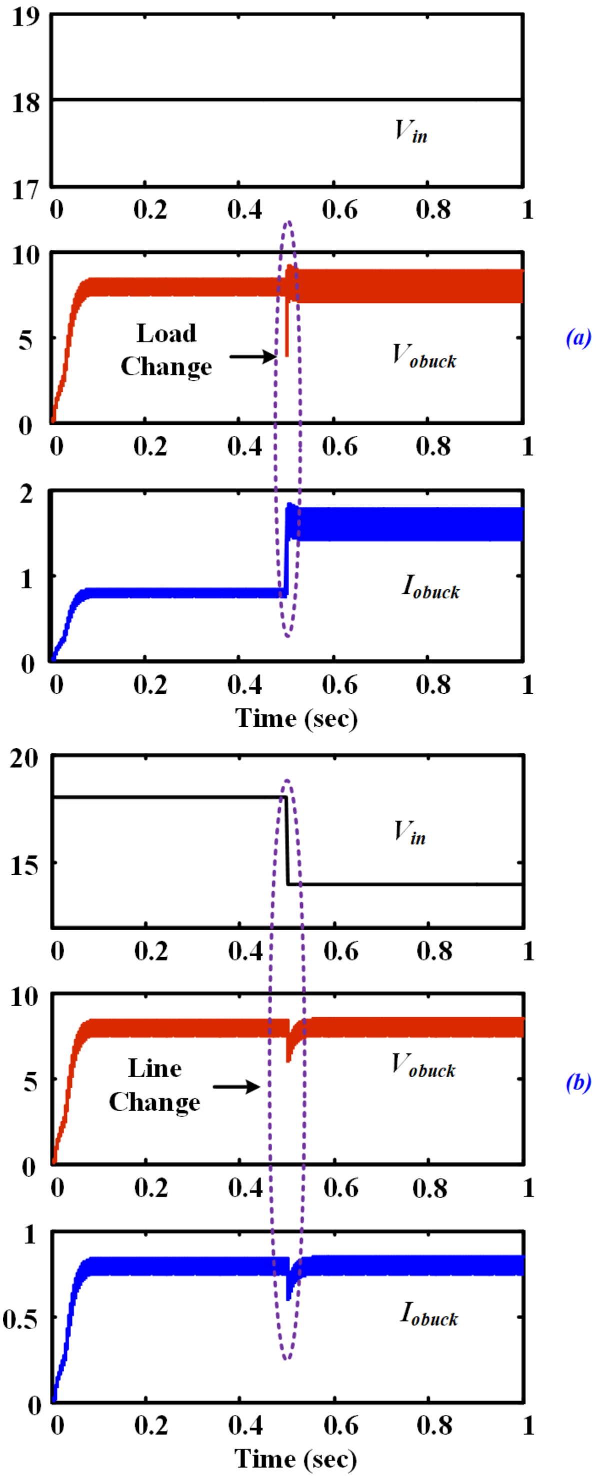

Figure 9: Simulation waveforms of input voltage (V_{in}), output voltage (V_o) and output current (I_o) in buck mode (a) Sudden Change in Load, (b) Sudden change in input voltage.

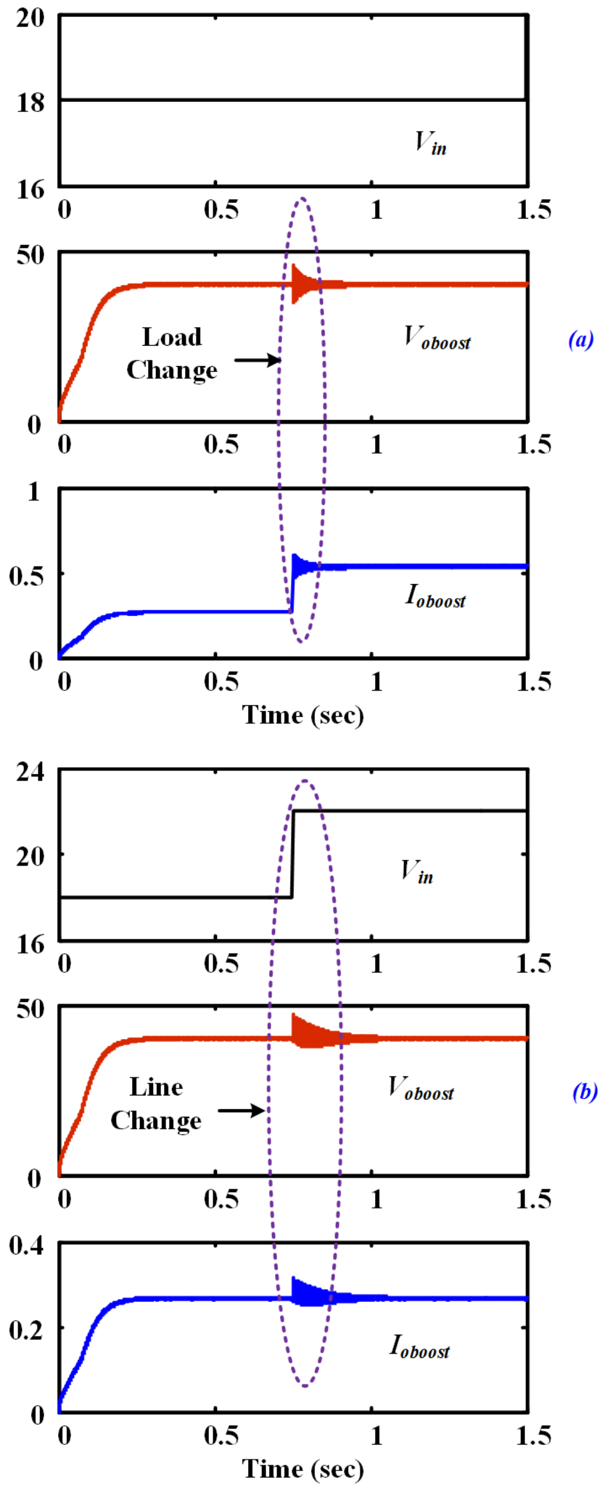

Figure 10: Simulation waveforms of input voltage (V_{in}), output voltage (V_o) and output current (I_o) in boost mode (a) Sudden Change in Load, (b) Sudden change in input voltage.

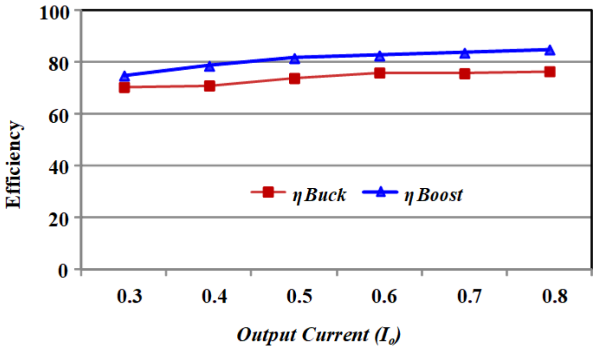

Figure 11: Efficiency vs output current in buck mode and boost mode

4 Conclusions

This paper presents in detail the design and steady-state analysis of a high step-down/step-up POBB converter. Theoretical and Matlab/Simulink analysis shows that the high gain POBB converter has several benefits over the traditional buck boost converter such as: high step-down voltage conversion gain, high step-up voltage conversion gain, simple structure, simple control (single loop voltage mode control) and positive output polarity. Further, the closed loop voltage mode controller is designed and tested with the high step-down/step-up POBB converter for both line and load regulations. Converter output maintains a stable value of 40.2 V for both line and load regulation during buck and boost mode respectively. Therefore the converter configuration is suitable where high step-down/step-up gain is required with stable output voltage.

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