A Closed Loop Control Strategy of Transformer-less Buck-Boost Converter with PID Controller

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ABSTRACT

A new technique of buck-boost converter with PID controller and its closed loop control technique are proposed in this study. The lower voltage gain in the existing converter is overcome by the newly proposed converter. The controller has better response compared to others. High voltage gain and positive output voltage are the main objective of this paper. The required duty cycle is achieved by the PID controller. This paper involves two strategies, as these switches conducts, the inductor is charged and as the diodes are forward biased, the capacitor is energized. Switches are excited using PWM technique. The modes of operation, simulation results, various analyses and experiments are presented in detail.

KEY WORDS: Positive output voltage, Voltage gain, PID controller, Closed loop control, Voltage stress.

1. INTRODUCTION

A buck-boost converter is generally a DC-DC converter that produces output voltage based on the supplied input voltage. Lower voltage gain is a drawback for stepping converters in several applications. Various converter technologies are established to meet the limitations. Voltage lifting technique is used by Luo converter for obtaining output voltage at higher value. The major drawbacks are cost and increase in losses in the lifting technique (Luo, 2001). For obtaining better voltage gain with less ripples at continuous conduction mode, a converter combining SR buck converter and KY converter is proposed (Hwu and Yau, 2009) "KY converter and its derivatives. Operating in wide range of output voltage its voltage gain is not that much sufficient, as its gain is multiples of twice the duty cycle. Interleaved converters are employed to achieve high step-up conversion and vise versa, but they are limited due to their complicated control strategy (Hwu and Yau,).

Another converter called Quadratic converter is used to get better voltage gain with less number of switches, however, the efficiency of these type of converters are limited (Chen, 2015). The existing buck-boost converters use more number of switches and have very low efficiency. The traditional converter is widely used but they have certain demerits such as low voltage gain, negative polarity voltage, power fluctuation, discontinuous operation.

Switched capacitors or switched inductor converter technology are employed for getting high voltage gain. But due to complex switching structures they are not widely available for power electronic equipment (Ye and Cheng, 2014; Axelrod & Berkovich, 2008). Other converters are also used, but as we consider their voltage gain, it's a major drawback. A new cuk converter is developed with low voltage distortion and less frequency interference as shown in (Axelrod & Berkovich, 2008). They have more voltage gain compared to other cuk and zeta converter but due to seventh order circuit, the converter has very complex construction and they do not have same ground.

A quadratic converter proposed in (Ajami & Ardi, 2014) has high voltage gain and a common ground switch, however the diodes clamp the output as the duty cycle is 0.5 and it can be operated only in step-up conversion. A cascaded buck-boost converter with two converters having current source and current is used as shown in (Maksimovic and Cuk, 1991). Besides, the converter's voltage gain continued to be low. So, to achieve high voltage buck or boost conversion, these converters must operate in high or low duty cycle as per the need. Hence a new technique of buck-boost converter is proposed, to overcome the practical difficulties in the conventional converters and to increase their industrial applications.

2. METHODS & MATERIALS

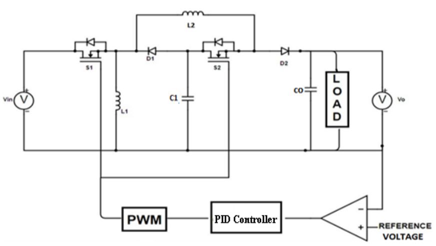

Figure.1. Proposed Buck-Boost Converter With Closed Loop

Fig.1, shows the circuit of the closed loop control of transformer less buck-boost converter which consists of PID controller, two diodes (D1, D2), two power switches (S1, S2), PWM generator, two inductors namely L1 & L2, two capacitors namely C1 & C2 and load.

Power switches S1 and S2 are controlled synchronously. The lower voltage gain in the existing converter is overcomed in the newly proposed buck-boost converter with PID controller. The PID controller yields better steady state response and transients. PWM generator produces gating signal for switches.

A PID controller is generally used in control system by using its feedback mechanism and also used for industrial requirements. This controller can be used to regulate certain parameters like temperature, pressure, flow, speed and other variables. In this proposed converter, PID controller is equipped for controlling output voltage by varying duty cycle.

A PID controller repeatedly determines an error value by comparing the obtained output voltage (Vo) and reference voltage and applies closed loop control based on three main terms: i) proportional, ii) integral and iii) derivative terms. The major advantage of PID controller is its feasibility and it can be easily implemented. The PID controller ensures satisfactory closed loop operations of the buck-boost converter system.

In the proposed system, it always produces a positive output voltage and its voltage gain is high. Wider range of positive output voltage is obtained by this proposed system. Hence this proposed buck-boost converter with PID controller used to overcome the drawbacks of the conventional ones for satisfying the industrial oriented requirements is very valuable and important.

Operating principle:

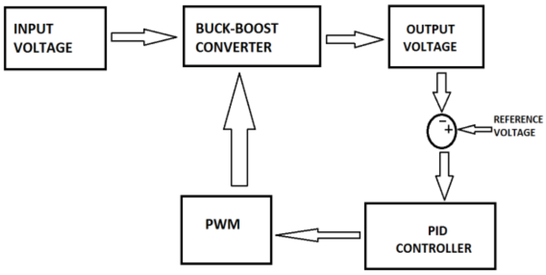

Figure.2. Closed loop control of Buck-boost converter

A control system is a procedure or system, which regulates the characteristics of other systems to obtain desire results. The most important type of control system is a closed loop system, whose main feature is feedback mechanism (i.e) the output obtained from the control system is used to adjust the input signal. PID controller is a feedback mechanism which is used in the closed loop control system. It delivers its output based on the measured error and the three controller gains namely proportional gain Kp, integral gain Ki, and derivative gain Kd. So, the well-designed feedback system has an ability to produce output with increased accuracy.

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau + k_d \frac{de(t)}{dt}$$

The operation of the closed loop control of proposed buck-boost converter begins from the point, where output voltage is obtained. The obtained output voltage (Vo) is compared with the reference voltage in the comparator, which produces an error signal which is send as input to PID controller. The PID controller tries to decrease the error over time by adjusting the control variable and in end of this process a new value is determined. The output signal from the PID controller is used as reference signal in PWM control.

The fundamental principle involved in working of this converter is creating a square pulse to control the switching of the MOSFET. This square pulse is called the duty cycle and this duty cycle (D) controls the output voltage. The switching is controlled by the duty cycle. Here, the reference signal obtained from the PID controller is compared with carrier signal (in this paper a triangular wave is taken as carrier signal), which produces the square pulses. The obtained signal from PWM generator is used to control the switching of switches.

The main characteristics of this closed loop control are to reduce errors, to improve stability of the system, to increase the systems sensitivity and to produce a performance which is more reliable. The main advantage of this closed loop control system is that it has the ability to adjust its output voltage automatically by feeding its output signal to the switches to control duty cycle. Thus, the closed loop control is employed for efficient operation of converter which gives high voltage gain.

Buck-boost operation: Buck-boost converter generally steps up or step down the input voltage so that the output voltage (Vo) will be greater than or less than the input voltage (Vin). Buck-boost converter combines the principle of buck converter and boost converter. In buck converter produced output voltage is less than the input voltage. Boost converter produces output voltage higher than the input voltage. It is generally used in the battery power systems, self-regulating power supplies, USB applications where input required varies and so on.

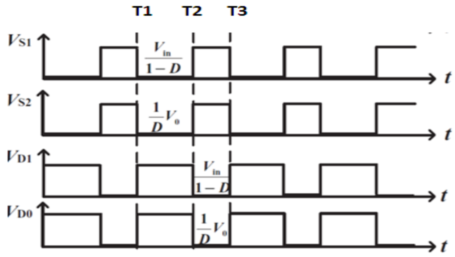

Figure.3. Key waveform

CASE1: (T1 < t< T2): The switches namely S1 & S2 were turned on, during this period interval and diode D1 and D0 are reverse biased.

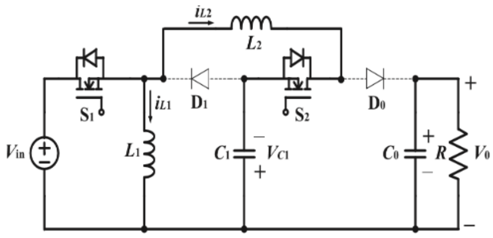

Figure.4. (a) Mode 1

From Fig. 4(a), it is shown that inductor L1 is charged from the input voltage (Vin) alone, while inductor L2 is charged from the input voltage Vin and the capacitor C1. The output capacitor (C0) supplies the output energy. Thus, the equations are described as

$$V_{L1} = V_{in} \ldots\ldots\ldots\ldots (1)$$

$$V_{L2} = V_{in} + V_{C1} \ldots\ldots\ldots (2)$$

CASE2: (T2 < t < T3):

$$V_o = \frac{V_s}{(1-D)}$$

$$D = 1 - \frac{Vs}{Vo} = 1 - \frac{18}{40.5} = 0.6*100 = 60\%$$

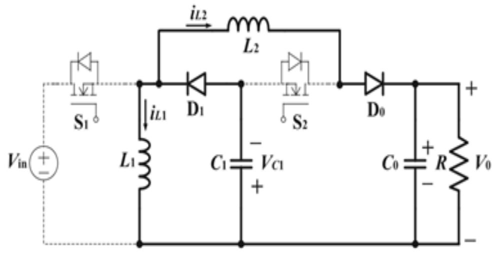

Figure.4(b) MODE 2

The switches namely (S1, S2) which are turned on in the case 1, are turned off during this period of time interval, and diodes (D1, D0) are forward biased. From Fig. 4(b), it is clearly shown that the energy stored in the inductor L1 is discharged to the capacitor C1 through the diode D1. At the same time, the energy stored in the inductor L2 is discharged to the capacitor C1, the output capacitor C0, and the resistive load R through the diodes D0 and D1. Thus, the equations of the state 2 can be established as follows

$$V_{L1} = -V_{C1} \ldots\ldots\ldots\ldots (3)$$

$$V_{L2} = -(V_{C1} + V_0) \ldots\ldots (4)$$

The voltage across the capacitor C1 is obtained from (1) and (3) as

$$V_{C1} = \frac{D}{1-D} V_{in} \ldots\ldots\ldots (5)$$

Here, D is the duty cycle. The voltage gain of the proposed buck–boost converter can be obtained from the above equation

$$M = \frac{V_0}{V_{in}} = \frac{D2}{(1-D)2} \ldots\ldots (6)$$

From this above equation, it is clear that when the duty cycle is bigger than 0.5, the proposed buck–boost converter can step-up the input voltage and when the duty cycle is smaller than 0.5, the input voltage gets stepped down.

Design Consideration: In this section, the design of inductors and capacitors are taken into account. A brief analysis on switches and diodes also carried out in this section. To explain the design of the parameters the output voltage is taken as 40.5V.

Duty Cycle Calculation:

$$D = \frac{T_{ON}}{T} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

Inductor Design: Inductors values are designed with the help of following equations

$$L_1 = \frac{DV_{in}}{f * IR_{L1}} = \frac{0.6*18}{20000*0.54} = 1mH \quad \ldots (8)$$

$$L_2 = \frac{DVo}{(1-D)F * IR_{L2}} = \frac{0.6*40.5}{0.4*20000*1.01} = 3mH \quad \ldots\ldots\ldots (9)$$

$$I_{L1} = \frac{D^2(2D-1)V_{in}}{(1-D)^4 R} \ldots\ldots\ldots\ldots (10)$$

The current stress of the inductors can be given by

$$I_{L1} = \frac{D^2(2D-1)V_{in}}{(1-D)^4 R} \quad I_{L2} = \frac{D^2 V_{in}}{(1-D)^3 R} \quad \ldots\ldots\ldots\ldots\ldots (11)$$

The ripples of the inductor current iL1 and iL2 can be given as

$$\Delta i_{l1} = \frac{V_{L1}}{L_1} DT_S = \frac{DV_{in}}{L_1 f_x} \ldots\ldots (12) \quad i_{l2} = \frac{V_{L2}}{L_2} DT_S = \frac{DV_{in}}{(1-D)L_2 f_x} \ldots\ldots (13)$$

Capacitor Design:

Capacitors values are designed with help of following formulas

$$C1 = \frac{DV_o}{(1-D) f * R * VR_{c1}} = \frac{0.6*40.5}{0.4*20000*149*.2} = 10\mu F \quad \ldots (14)$$

$$C0 = \frac{DV_o}{f * R * VR_{C0}} = \frac{0.6*40.5}{20000*149*0.4} = 20\mu F \quad \ldots (15)$$

The ripples of the voltage (ΔvC1 and ΔvC0) across the capacitors C1 and C0

$$\Delta v_{c1} = \frac{\Delta Q}{C} = \frac{DV_0}{(1-D)RC_1 f_x} \ldots\ldots (16) \quad \Delta v_{c0} = \frac{\Delta Q}{C} = \frac{DV_0}{RC_0 f_x} \ldots\ldots\ldots (17)$$

The voltage value across the capacitor C1 is given by

$$V_{C1} = \frac{D}{1-D} V_{in} = \frac{1-D}{D} V_0 \quad \ldots\ldots\ldots\ldots\ldots (18)$$

Diode Characteristics: The product name of the diodes (D1 and D2) used in proposed converter is MUR810. The voltage stress of the two diodes (D1 and D0) can be derived

$$V_{D1} = \frac{D}{1-D} V_{in} = \frac{1-D}{D^2} V_0 \quad \ldots\ldots (19) \quad V_{D0} = \frac{D}{(1-D)^2} V_{in} = \frac{1}{D} V_0 \quad \ldots (20)$$

The current stress of the two diodes (D1 and D0) can be derived

$$I_{D1} = (1-D)(I_{L1}+I_{L2}) = \frac{D^3 V_{in}}{(1-D)^3 R} \ldots(21) \qquad I_{D0} = (1-D)I_{L2} = \frac{D^2 V_{in}}{(1-D)^2 R} \ldots(22)$$

Switch Characteristics: The product name of the power switches (S1 and S2) is HEXFET power MOSFET IRFP264. The voltage stress of the two power switches (S1 and S2) can be derived

$$V_{S1} = \frac{1}{1-D}V_{in} = \frac{1-D}{D^2}V_0 \ldots(23) \qquad V_{S2} = \frac{D}{(1-D)^2}V_{in} = \frac{1}{D}V_0 \ldots(24)$$

The current stress of the two power switches (S1 and S2) can be derived

$$I_{S1} = D(I_{L1}+I_{L2}) = \frac{D^4 V_{in}}{(1-D)^4 R} \ldots(25) \qquad I_{S2} = DI_{L2} = \frac{D^3 V_{in}}{(1-D)^3 R} \ldots(26)$$

3. RESULT AND ANALYSIS

Based on the above analysis, it is expected that the proposed Buck Boost converter should obtain more voltage gain than conventional converters. In order to analyze and verify the circuit operation and characteristics of the proposed buck boost converter, MATLAB software is used for simulation.

The parameters of the components in circuit is given in the table.1.

Table.1. Circuit Parameters

Parameters	Values
Inductors L1	1mH
Inductor L2	3mH
Capacitors C0	20µF
Capacitors C1	10µF
Input Voltage	18V
Input Current	2.4A
Switching frequency	20 kHz
Load Resistance	150

Simulation Results: Figure.6, shows that the overall circuit diagram of the simulation conducted on proposed converter with Matlab software tool. The simulation circuit shown in fig.2, consists of circuit components like power switches (S1, S2), PID controller for controlling unit, diodes (D1, D2), blocking capacitor, output capacitors.

The complete Simulink model is shown in fig.5.

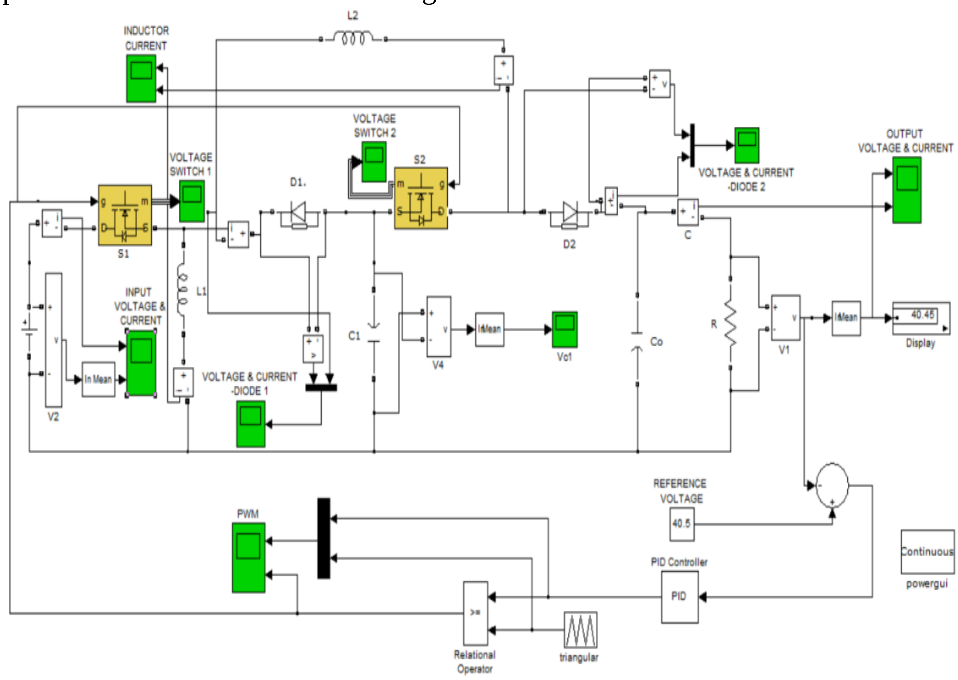

Figure.5. Simulation Circuit

The complete Simulation waveforms are shown in fig 6.

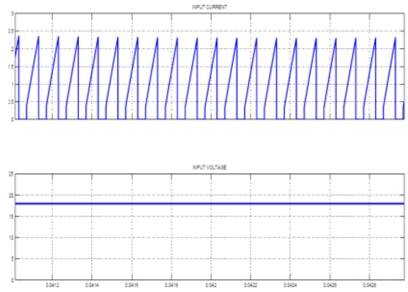

Figure.6a.Input Current and Voltage Waveforms

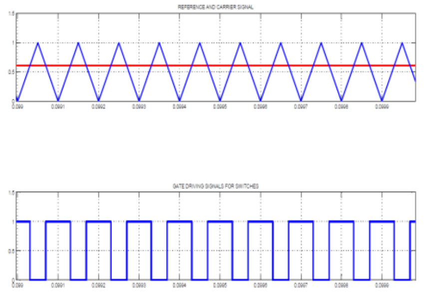

Figure.6b. Switching Signals

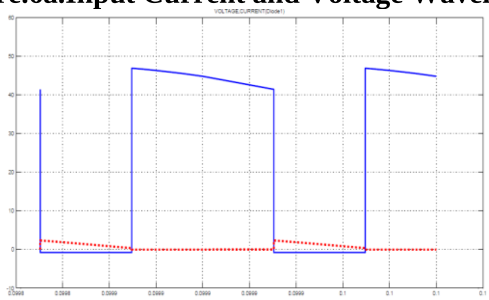

Figure.6c(i)

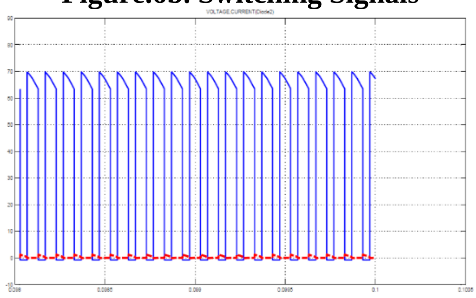

Figure.6c(ii)

Figure.6C. Voltage & Current Waveforms of Diodes(D1,D2)

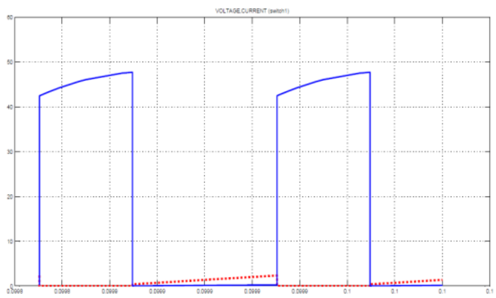

Figure.6d(i)

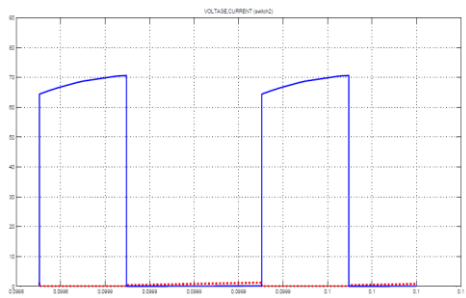

Figure.6d(ii)

Figure.6d. Voltage & Current Waveforms of Switches (S1,S2)

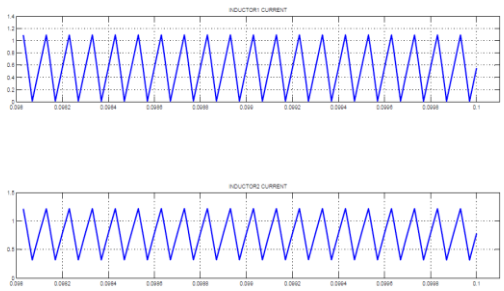

Figure.6e. Inductor Current Waveform (IL1, IL2)

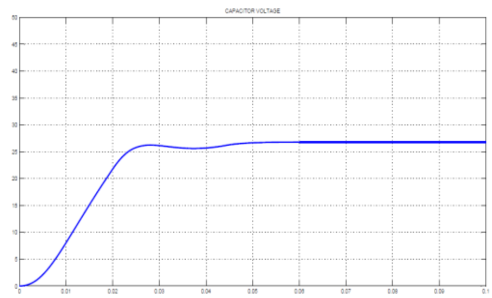

Figure.6f. Capacitor Voltage Waveform

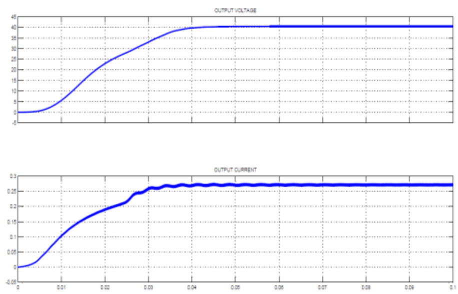

Figure.6g. Output Voltage (Boosted Voltage) & Output Current

Fig.6a, shows the waveform of Input voltage (18v) and Input current respectively. In Fig 6b, red line indicates reference signal, blue line indicates carrier signal. These two waves for produce Gating signal to turn ON and OFF switches (S1,S2). The red dotted line in Fig.6c and Fig.6d, indicates the current waveform in Diode and Switch respectively, while the blue line indicates voltage waveforms.The inductor current of inductors L1 & L2 is clearly indicated in figure 6e. The volatge acrosss the capacitor C1 is shown in the Fig.6f. The boosted output voltage waveform and output current waveform is shown in Fig.6g.

4. CONCLUSION

This paper proposed a new closed loop control of buck-boost converter with PID controller, which has better construction technique and higher voltage gain compared to traditional step-up and step-down converters. The analyses, operating principles and their comparisons are presented. From the analyses, simulation results and the circuit, it is shown that the buck-boost converter with PID control has several merits such as simple construction, simple control strategy, high step-up and step-down voltage gain and positive output voltage. Hence it can be employed in industrial electronics for better buck and boost conversions.

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