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Design and Implementation of KY Buck-Boost Converter with Voltage Mode Control

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Abstract— This paper presents a simple voltage mode analog controller for an improved KY buck-boost converter. The improved KY buck-boost converter comprises of a KY boost converter and a synchronous buck converter. The voltage mode analog control is designed by using a PI controller to regulate the output voltage of the converter. An experimental prototype of KY buck-boost converter of 30 Watt, 12 V output voltage, 10 kHz with discrete analog controller is designed and developed for an input voltage 10V-16V. The functionality of the converter with the controller under closed loop is demonstrated for the variation in input voltage.

Index Terms—buck–boost converter, KY converter, Synchronous buck converter, PI controller.

1 Introduction

In general, batteries are used as a power source in portable applications and they are variable in nature. DC-DC switch mode converters are widely being used in low power portable applications because of their very high efficiency and small size. Many new topologies of DC-DC converters have been explored to meet the growing demand in the area of switch mode power supplies. They are boost converter [1], dual boost converter [2], Luo converter [3], buck converter [4], buck–boost converter [5], Zeta converter [6], SEPIC [7], Cuk converter [8] and KY converter [9] etc.

The boost converter [1], dual boost [2] converter and Luo converter [3] which boosts the input voltage, have right-half plane zeros in the continuous conduction mode (CCM) that reduces the system stability at high frequencies. The KY boost converter [10] is introduced to overcome this problem that always operates in CCM making the corresponding current ripples small and has no RHP zero.

In literature [11], an improved KY boost converter is constructed mainly by one charge pump capacitor and one central tapped coupled inductor. The KY converter is combined with the synchronously rectified (SR) boost converter to make a new voltage-boosting converter, KY boost converter [12] for low power applications.

The buck converter [4] that steps down the input voltage gives considerable amount of output voltage ripple and conduction loss. So synchronous technique [13], [14] is used to reduce the conduction losses and raise the efficiency. However, at high frequency the switching losses increase thus decrease the efficiency.

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The KY buck-boost converter reported in [15] has many good features when compared to other DC-DC converters for portable applications. The KY buck-boost converter uses only two switches, which are operated in synchronous way. This reduces the cost and size of the circuit and can operate in bidirectional mode. The polarity of the output voltages of buck–boost [5], Zeta [6], SEPIC [7], Cuk [8], and single-switch buck–boost [16] converters are opposite in polarity with input voltage whereas the KY buck - boost converter provides the output voltage of same polarity with input voltage. The KY buck-boost converter does not have RHP zero that increases stability and transient response [17]. A simple voltage mode analog controller is proposed in this work for the KY buck-boost converter to regulate the output voltage.

The structure of this paper is as follows: Section II discusses the principles of operation of the KY buck-boost converter. The functionality of the converter with the controller is verified using MATLAB/ SIMULINK and the simulation results are presented in section III. Section IV demonstrates the functionality of the controller with experimental results. The conclusion of the paper is discussed in section V.

2 KY Buck-Boost Converter

This section explains the principle of operation of the KY buck-boost converter under steady state to obtain voltage conversion ratio.

2.1 Principle of Operation

The topology of the KY buck-boost converter [15] is shown in Fig 1. This combines a synchronous buck converter formed by two power switches S_1, S_2, capacitor C_1, inductor L_1 and the KY boost converter formed by two power switches S_1, S_2, power diode D, output inductor L_2, capacitor C_2 and output capacitor C_o with the common output load R_o, respectively. The principle of operation of the converter is explained based on volt-second balance and charge balance of the inductors and capacitors over a switching time period respectively. It is assumed that the components used in the circuits are ideal. There are mainly two operating modes, Mode I (switch S_1 is ON and S_2 is OFF) and Mode II (switch S_1 is OFF and S_2 is ON) respectively. The functionality of the circuit under two operating modes is discussed below.

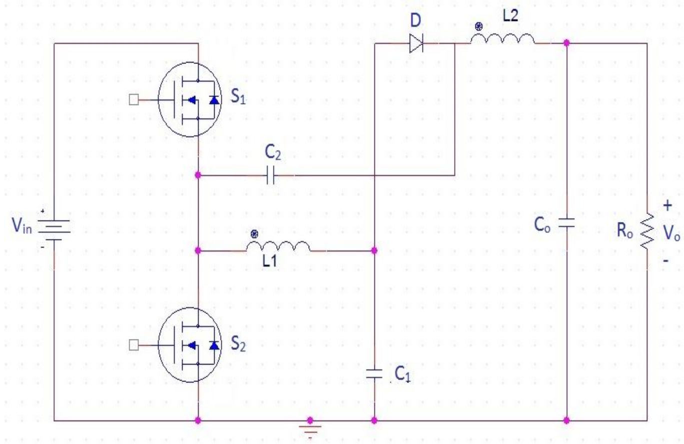

Fig 1: Circuit diagram of the KY buck-boost Converter

2.1.1 Mode I (S_1 ON, S_2 OFF):

In this mode the input voltage provides energy for C_1 and L_1 making C_1 getting charged and L_1 to be magnetized as shown in equivalent circuit diagram, Fig 2. At the same moment, the input voltage along with capacitor C_2 supplies the energy for inductor L_2 and to the output which causes C_2 to be discharged and L_2 getting magnetized.

The associated equations in Mode I are

$$v_{L1} = V_{in} - v_{C1} \quad (1)$$

$$v_{L2} = V_{in} + v_{C2} - V_o \quad (2)$$

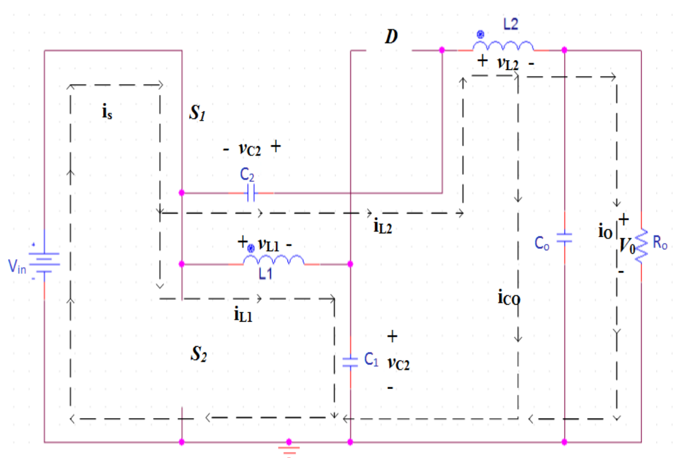

Fig 2: Equivalent Circuit Diagram under Mode I

2.1.2 Mode II (S_1 OFF, S_2 ON):

The equivalent circuit diagram during this mode of operation is shown in Fig 3. The energy stored in inductor L_1 and capacitor C_1 are released to capacitor C_2 and to the output via inductor L_2 causing C_1 to be discharged and L_1 to be demagnetized. At the same moment, the voltage across L_2 is v_{C2} minus V_o, thus making C_2 to be charged and L_2 being demagnetized.

The associated equations in Mode II are

$$v_{L1} = -v_{C1} \quad (3)$$

$$v_{L2} = v_{C2} - V_o \quad (4)$$

$$v_{C1} = v_{C2} \quad (5)$$

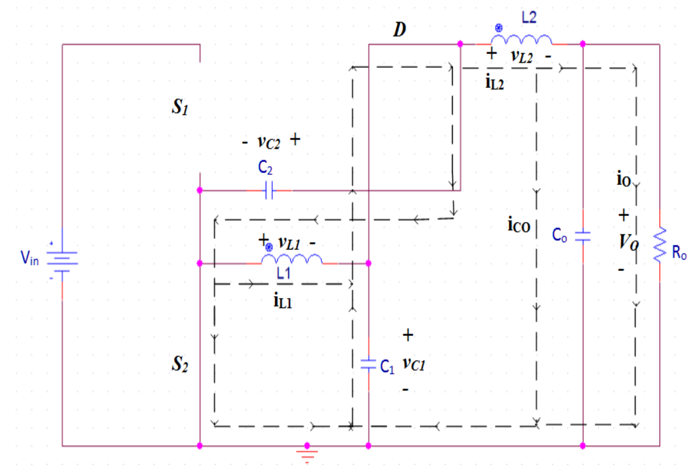

Fig 3: Equivalent Circuit Diagram under Mode II

By applying volt-sec balance for inductor L_1 over a switching period from eqn (1) and (3) we get,

$$\left(V_{in} - v_{C1}\right).D.T + \left(-v_{C1}\right).\left(1-D\right).T = 0$$

$$v_{C1} = DV_{in} \quad (6)$$

By applying volt-sec balance for inductor L_2 over a switching period from eqn (2) and (4) we get,

$$\left(V_{in} + v_{C2} - V_o\right).D.T + \left(v_{C2} - V_o\right).\left(1-D\right).T = 0 \quad (7)$$

By placing equation (5) and (6) into (7), the final voltage conversion ratio under steady is obtained as

$$\frac{V_o}{V_{in}} = 2D \quad (8)$$

It can be observed that the converter can generate the output voltage less than input voltage (buck operation) for duty ratio less than 0.5 and produce the output voltage more than input voltage (boost operation) for duty ratio greater than 0.5.

Under steady state the DC voltages across capacitors C_1 and C_2 are equal and given as,

$$v_{C1} = v_{C2} = 0.5V_o$$

2.2 Design Specifications of the Converter

The KY buck –boost converter is designed based on the design

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specifications, which are listed in Table 1.

TABLE 1

Design Specifications of the Converter

S.No.	COMPONENT	VALUE
1	Input voltage	10V - 16V
2	Output voltage	12V
3	Full Load Current	2A
4	Switching frequency	10kHz
5	Inductor L_1 L_2	 3000 µH 1000 µH
6	Capacitor C_1 C_2 C_o	 470 µF 220 µF 47 µF

A simple PI controller is designed to regulate the output voltage of the converter based on the following design specification.

3 Design of PI Controller

The transfer function of PI controller is

$$G_C(s) = K_p + \frac{Ki}{S} \tag{9}$$

The values of K_p = 1.389 * 10^-3 and K_i = 40 are obtained from the root locus technique.

3.1 Closed Loop Operation of the Converter in MATLAB

The KY buck-boost converter with the PI controller is simulated in MATLAB/SIMULINK as shown in fig 4. The output voltage when operated in buck and boost mode in MATLAB simulation are shown in Fig 5 and Fig 6 respectively.

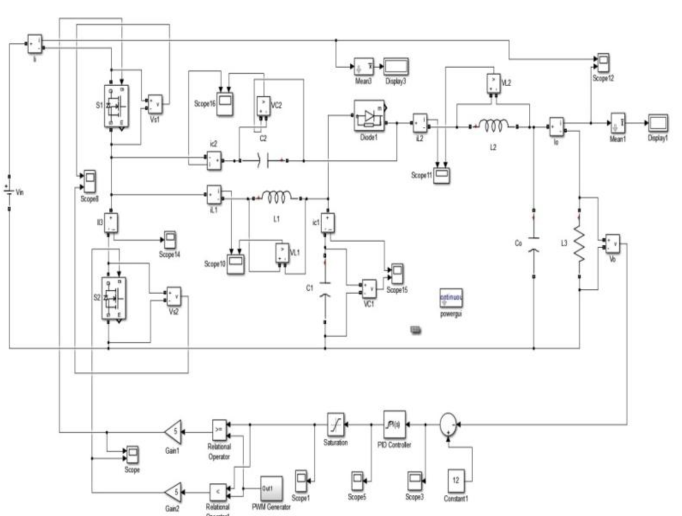

Fig 4: Closed loop converter circuit using PI controller.

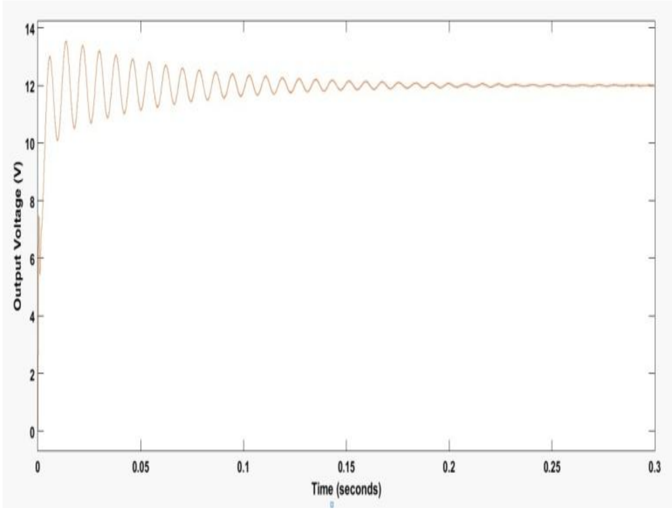

Fig 5: Output voltage in buck operation

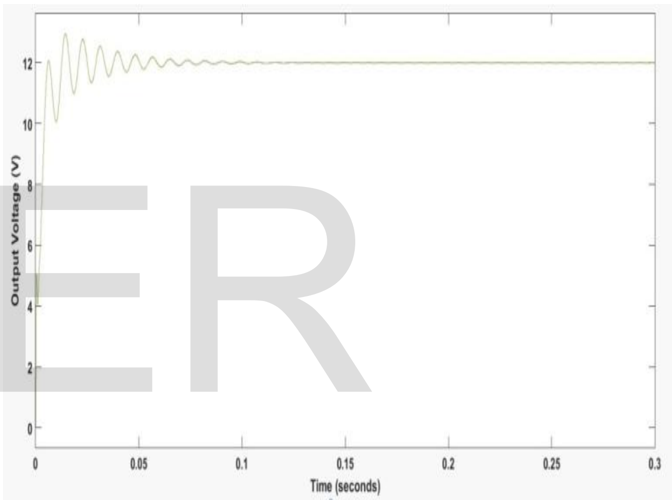

Fig 6: Output voltage in boost operation

It can be observed from the step responses of the converter that the output voltages reach steady state value. Therefore, it can be concluded that the design values of PI controller for the closed loop operation are appropriate. The hardware setup of the converter with PI controller is presented in the next section.

4 Hardware Implementation of the Converter with PI Controller

An experimental prototype of 30Watt, 12V output voltage, 10kHz KY buck-boost converter is designed and developed for an input voltage range 10V-16V. The controller is designed using analog discrete components. The list of all components used in the power circuit and the control circuit are listed in Table 2 and Table 3 respectively.

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TABLE 2

Components used in the Power Circuit

S.No.	COMPONENT	VALUE
1	MOSFET	IRF530
2	Diode	MIC6A4
3	Capacitors	470 µF, 63V – 1 no. 220 µF, 63V - 1 no. 47 µF, 63V - 1 no.
4	Inductors	3000 µH - 1 no. 1000 µH - 1 no.
5	Load Resistor	300 ohm, 5A

TABLE 3

Components used in the Control Circuit

S.No.	COMPONENT	VALUE
1	Op amp	LM741
2	Schmitt trigger inverter	74HC14
3	Transistor	BC557A
4	Zener diode	MILL750
5	Diode	1N4007
6	Not gate	74LS04
7	Driver	TLP250
8	555 timer	1 no.

4.1 Description of the Experimental set up

The complete schematic of the experimental prototype is shown in Fig 7.

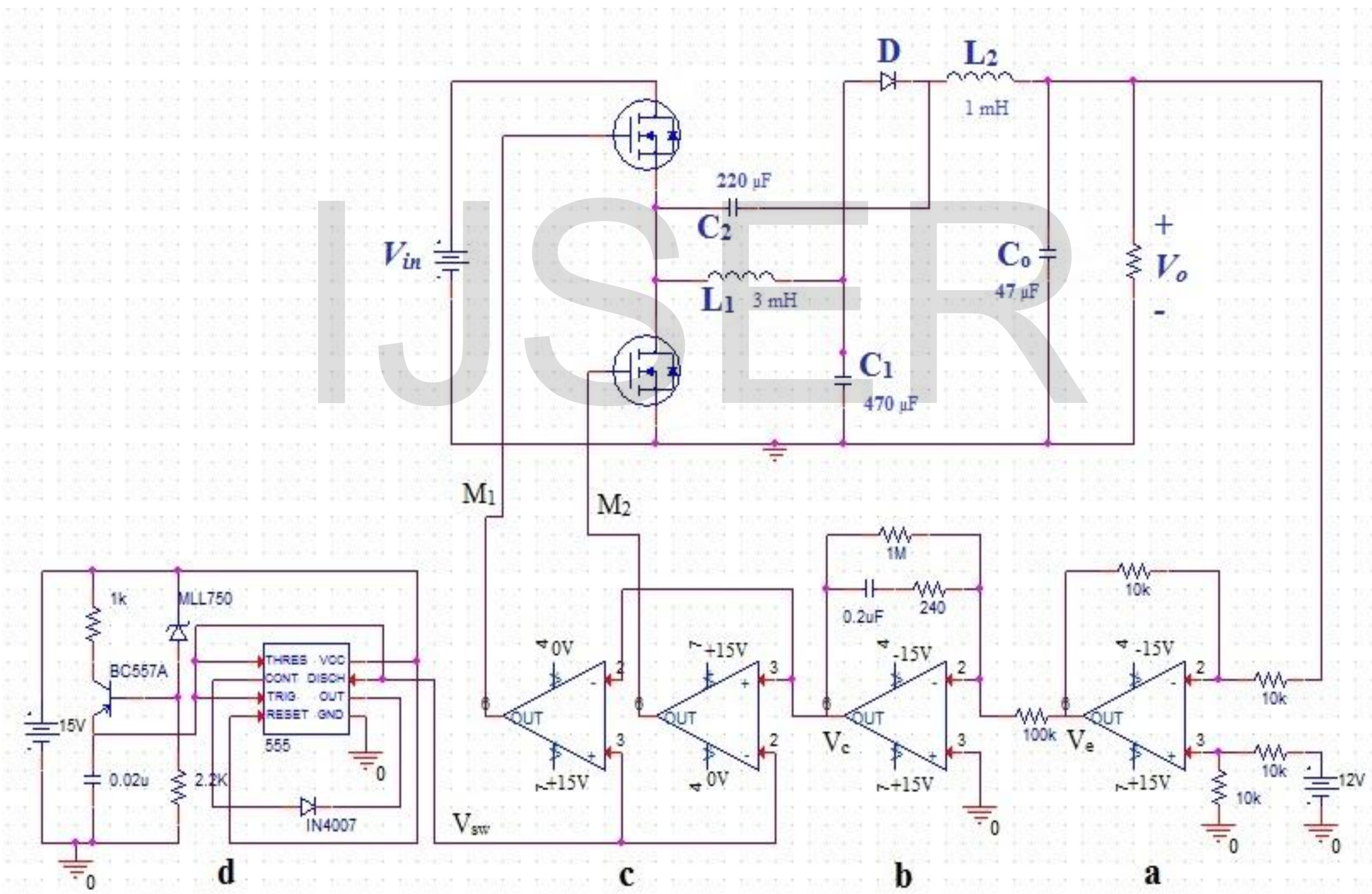

Fig 7: Schematic of the KY buck-boost converter with PI controller under closed loop.

The output voltage V_o is compared with the reference voltage of 12V to get an error voltage (V_e) as shown in Fig 7 part (a). Then this error voltage (V_e) is given as input to the PI controller to get the control voltage (V_c) as shown in Fig 7 part (b). Now the obtained control voltage (V_c) is compared with the saw tooth voltage (V_{sw}) to get the desired switching pulses (M_1, M_2) which are shown in Fig 7 part (c). These switching pulses are applied through a driver circuit (TLP250) to the switches S_1 and S_2. A 555-timer is used for the generation of saw tooth waveform. The saw tooth voltage waveform of 10 kHz obtained from the circuit is shown in Fig 8.

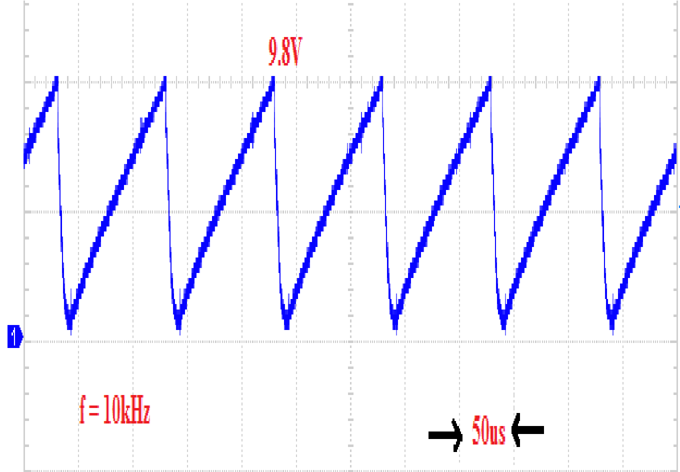

Fig 8: Saw tooth voltage from the 555 timer.

4.2 Experimental Results

4.2.1 Buck Mode of Operation:

The closed loop operation of the converter in buck mode is conducted with a voltage input of 16V for a reference voltage of 12V. The corresponding output voltage, gate pulses for switch S_1, S_2 and the voltage over the switch S_2 are shown in Fig 9(a), 9(d), 9(c) and 9(b) respectively. It can be observed that the controller generates the control signal for the switch S_1 with an approximate duty ratio of 40% to produce the output voltage 12V.

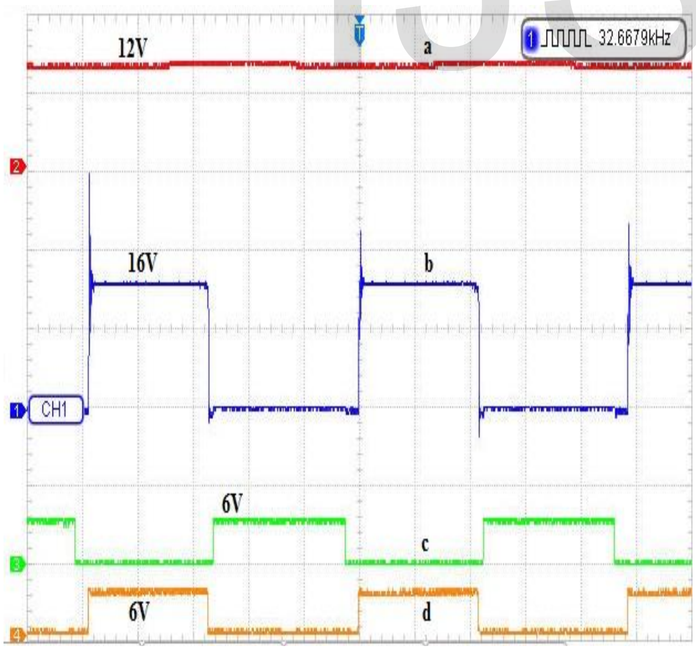

Fig 9: (a) Output Voltage, (b) voltage over switch S_2, (c) M_2, (d) M_1.

4.2.2 Boost Mode of Operation:

The closed loop operation of the converter in boost mode is conducted with a voltage input of 11V for a reference voltage of 12V. The corresponding output voltage, gate pulses for switch S_1, S_2 and the voltage over the switch S_2 are shown in Fig 10(a), 10(d), 10(c) and 10(b) respectively. It can be observed that the controller generates the control signal for the switch S_1 with an approximate duty ratio of 56% to produce the output voltage 12V.

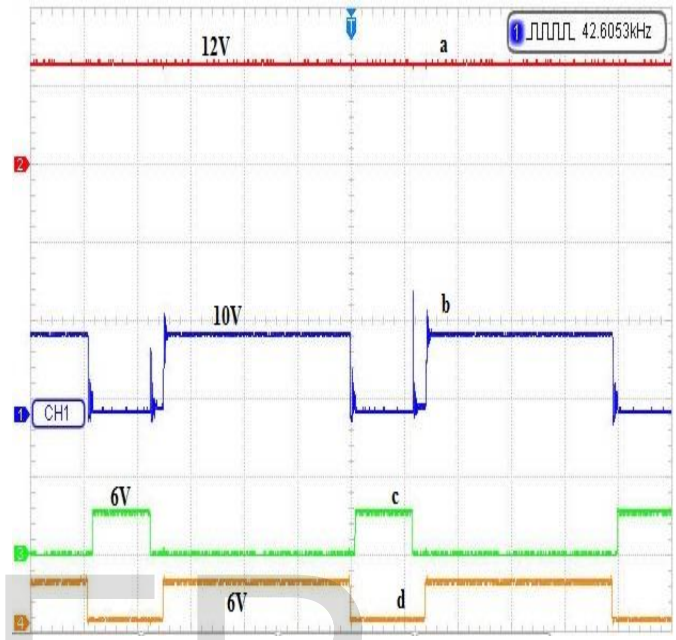

Fig 10: (a) Output Voltage, (b) voltage over switch S_2, (c) M_2, (d) M_1

The experimental results illustrated above for the KY buck- boost converter demonstrate the successful operation of the PI controller under steady state.

The dynamic performances of the controller are presented with step changes in input voltage. The dynamic output voltage waveforms when the input is switched from 0-16 V and 0-11V at 1A are shown in Fig 11 and Fig 12 respectively.

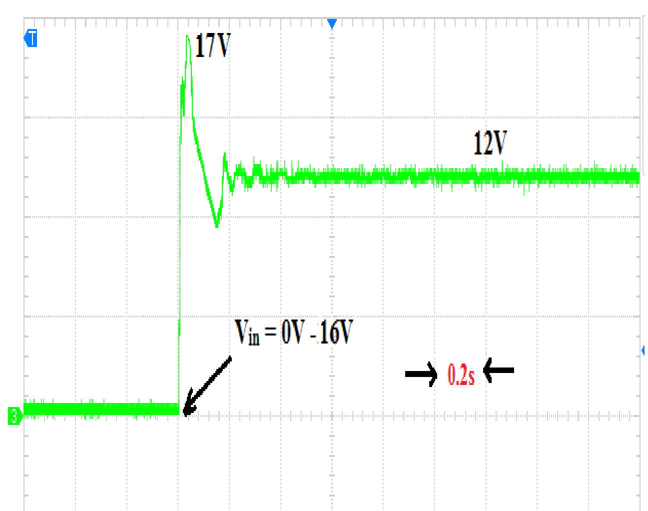

Fig 11: Output Voltage for step change in input from 0 - 16V.

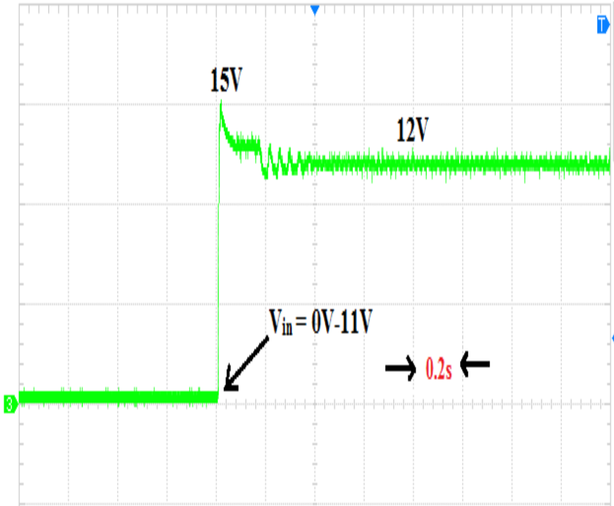

Fig 12: Output Voltage for step change in input from 0 - 11V.

The complete hardware setup of the KY buck-boost converter using PI controller is shown in Fig 13.

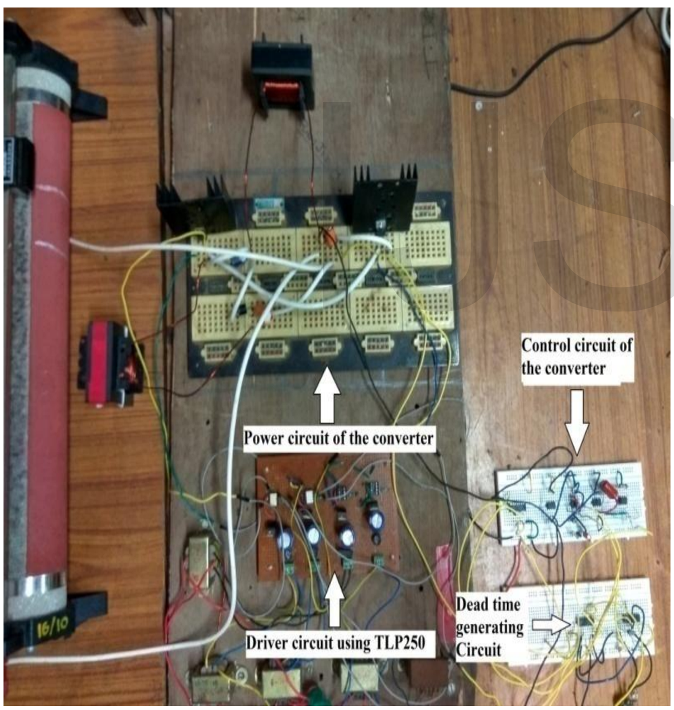

Fig 13: Complete hardware setup of the KY buck-boost converter using PI controller.

From all the above experimental results it can be concluded that the design of the proposed controller for the KY buck-boost converter satisfy the closed loop operation under steady state and dynamic conditions.

The conclusion of the work is discussed next.

5 Conclusion

This paper presents design and implementation of the KY buck boost converter. A simple PI controller is proposed and designed to regulate the output voltage of the converter. Simulation and hardware results are presented to verify the functionality of the converter with the controller under steady state and dynamic conditions.

References

[1] Bryant, B., and Kazimierczuk, M. K., “Voltage loop of boost PWM DC-DC converters with peak current-mode control,” IEEE Trans. Circ. Syst. I: Reg. Papers, Vol. 53, No. 1, pp. 99–105, 2006.

[2] Sayed, A., Abdel-Salam, M., Ahmed, A., and Ahmed, M., “New high voltage gain dual-boost DC-DC converter for photovoltaic power systems,” Electr. Power Compon. Syst., Vol. 40, pp. 711–728, 2012.

[3] Luo, F. L., and Ye, H., “Voltage-lift converters,” in Essential DC/DC Converters, New York: Taylor & Francis, Chap. 2, 2006.

[4] Wei, X., Tsang, K. M., and Chan, W. L., “DC/DC buck converter using internal model control,” Electr. Power Compon. Syst., Vol. 37, pp. 320–330, 2009.

[5] Lo, Y. K., Chen, J. T., Lin, C. Y., and Qu, S. Y., “Improved control-to-output characteristics of a PWM buck–boost converter,” Int. J. Circ. Theor. Appl., Vol. 39, pp. 203–209, 2011.

[6] Vuthchhay, E., and Bunlaksananusorn, C., “Dynamic modeling of a Zeta converter with state-space averaging technique,” Proc. 2008 5th International Conference on Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology, pp. 969–972, Krabi, 14–17 May 2008.

[7] Wong, L. K., and Man, T. K., “Small signal modeling of open loop SEPIC converters,” IET Power Electron., Vol. 3, No. 6, pp. 858–868, 2010.

[8] Fuad, Y., De Koning, W. L., and van der Woude, J. W., “On the stability of the pulse width-modulated Cuk converter,” IEEE Trans. Circ. Syst. II: Express Briefs, Vol. 51, No. 8, pp. 412–420, 2004.

[9] Hwu, K. I., and Yau, Y. T., “KY converter and its derivatives,” IEEE Trans. Power Electron., Vol. 24, No. 1, pp. 128–137, 2009.

[10] K. I. Hwu and Y. T. Yau, “A novel voltage-boosting converter: KY Converter,” in Proc. IEEE APEC Conf., 2007, pp. 368-372.

[11] K.I. Hwu and W. Z. Jiang, H. M. Chen, "Voltage Gain Enhancement of KY Converter", TENCON 2013-2013 IEEE Region 10 Conference (31194), 2014, IEEE, doi: 10.1109/T ENCON.2013.6718838.

[12] K. I. Hwu, and Y. T. Yau,” A KY Boost Converter”, IEEE Transactions on Power Electronics, vol.25, pp. 2699 -2703, Nov. 2010

[13] Wang, Jian-Min, Sen-Tung Wu, and Gwan- Chi Jane. "A Novel Control Scheme of Synchronous Buck Converter for ZVS in Light-Load Condition", IEEE Trans. Power Electronics, vol. 26, pp. 3265 - 3273, April 2011.

[14] R.M. Amarsagar Reddy and N. Lakshminarasamma, "Analysis, design and implementation of soft switching in a synchronous converter", power and energy systems (ICPS), 2012, ©IEEE, doi: 10.1109/ICPES.2011.6156619.

[15] Hwu, K. I., and Peng, T. J., “A novel buck–boost converter combining KY and buck converters,” IEEE Trans. Power Electron., Vol. 27, No. 5, pp. 2236–2241, 2012.

[16] Banaei, M. R., Ardi, H., and Farakhor, A., “Analysis and implementation of a new single-switch buck–boost DC/DC converter,” IET Power Electron., Vol. 7, No. 7, pp. 1906–1914, 2014.

[17] Jose and Pramelakumari, K., “A Positive Output Buck Boost Converter Combining KY and SR-Buck Converters" IEEE International Conference on PICC, IEEE 2015, and doi: 10.1109/PICC.2015. 7455775.