IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

DUAL OUTPUT QUADRATIC GAIN BUCK-BOOST CONVERTER

[1]Anagha E B, [2]Dr. Siny Paul, [3]Kiran Bobby, [4]Meenu Gibi, [5]Dinto Mathew

[1]PG Scholar, [2,3,4,5]Professors

[1]Department of EEE, Mar Athanasius College of Engineering, Kothamangalam, Kerala, India

Abstract: The high gain DC-DC converters have played a vital role in industrial electronics applications. The dual output quadratic gain buck-boost converter is a combination of quadratic boost followed by buck converter. The non-isolated DC-DC converter topology exhibit quadratic buck-boost voltage transformation ratio together with common ground feature and a positive output load voltage polarity. The dual output DC-DC converter with single input reduce size and cost of the high gain converters in modern power electronics with advantage of multilevel boost outputs and eliminates the requirement of individual converters for each voltage level. The boost applications are more prevalent in harvesting renewable energy so the converter topology is designed to provide multiple boost outputs with high gain and high efficiency. The DC-DC converter performs buck operation below a duty ratio of 40% to obtain quadratic buck-boost gain. The input and output side inductors ensures continuous input current with minimal ripple at input and output sides. The converter topology producing 67W and 150W output powers, at a switching frequency of 75kHz is analysed and the performance study of the DC-DC buck-boost converter is carried out with MATLAB/SIMULINK R2017b. It is observed that the converter attained 100V and 150V for boost operation and 8V for buck operation for an input of 15V with an efficiency of 94% for R and RL loads. The switching pulses for the control circuit is generated using PIC16F877A microcontroller. The experimental results obtained from a 7W and 16W converter prototype designed with a 5V DC input and 75KHz switching frequency confirm the theoretical considerations and the simulation results.

Index Terms **- Buck-Boost Converter, Quadratic Gain, Multilevel Boost Outputs, Microcontroller**

I. INTRODUCTION

The evolution of power electronic devices in renewable energy application and portable electronics resulted in fast development of DC-DC converters. The need for DC-DC conversion for different voltage levels from a single DC source emerged. The DC-DC converter that converts DC voltage to different levels with low losses and high efficiency became tremendously popular in recent times. These converters are able to increase or decrease the DC voltage levels and invert its polarity. Many applications require step-down, step-up and multiple outputs from the same power supply. The conventional buck-boost converter is preferable only when input supply voltage fluctuations are over smaller ranges. The conventional converter has limitations in efficiency and voltage transformation ratio at moderate duty cycles. In many applications, non-inverting voltage and continuous input current with low ripple content are key considerations. The input L-C filter is able to eliminate the ripple content problem, but the need of additional damping network causes instability issues.

The quadratic type single switch buck-boost converter [2] with non-inverting load voltage polarity maintains continuous input and output currents. The transformerless quadratic voltage transformation ratio-based buck-boost converter [3] attains wide voltage conversion ratio with minimal ripples but encounters high voltage and current stress on the capacitors. The non-isolated ZETA-based buck-boost converter [4] with low output capacitor current ripple exhibits discontinuous input current. These converters are effective in ripple reduction but lacks voltage gain improvements. The limitations related with conventional BBC is overwhelmed by some fourth-order converter topologies such as SEPIC converter, CUK converter, and ZETA converter [5-9]. The switched-capacitor-based buck-boost converter [10] overcomes the drawbacks of discontinuous input and output current. The two-switch and four-switch version of buck-boost DC-DC converters [11-15] produces continuous output current.

The converter topologies that yield buck-boost voltage gain with a greater number of L-C elements, discontinuous input or output current are also studied. By eliminating the above-mentioned limitations and preserving the benefits, the following DC-DC converter is introduced. The basic aim of new non-isolated enhanced gain buck-boost topology [1] is to achieve quadratic type buck-boost conversion with minimal voltage and current ripples in input and output sides. The topology is then modified into dual output quadratic gain buck-boost converter. The structure has a quadratic boost converter in front-end side that is modified to improve the gain of the converter and the ZETA converter in output side emulates like a buck converter also ensures minimal ripple. The series combination of output capacitors provides the new high gain boost output along with the existing buck-boost outputs.

The structure retains common ground and positive output voltage polarity. The quadratic boost followed by buck converter is feasible to yield quadratic buck-boost gain with low current stress.

II. METHODOLOGY

The dual output quadratic gain buck-boost converter is developed by cascading of quadratic boost followed by buck converter. The converter can obtain quadratic type buck-boost conversion with minimal current stress. The buck converter ensures low ripple at output side. The converter topology posses common ground structure and ensures positive output load voltage polarity in both bucking as well as boosting operation. The two switches in the buck-boost converter operates with a single PWM drive signal and duty cycle for both the switches S_1 and S_2. The diodes turn ON/OFF operation is complementary to the switches S_1 and S_2 operation. The two switch-based buck-boost converter consist of three inductors and four capacitors. The converter has only two switching states. The dual output quadratic gain buck-boost converter is shown in Fig. 1.

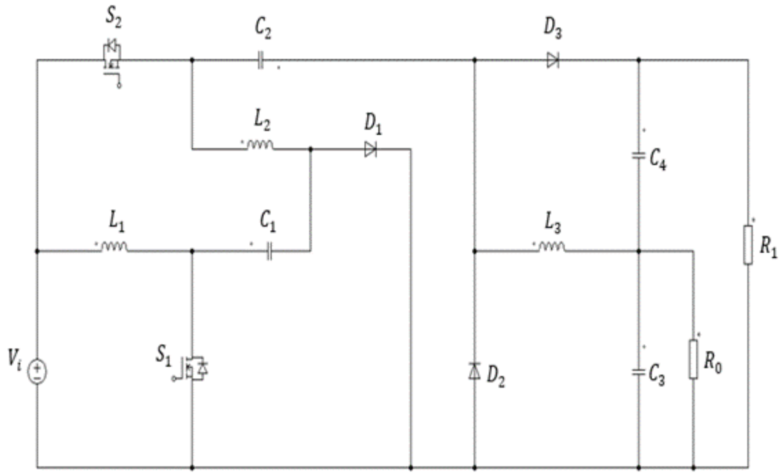


Fig. 1 Dual Output Quadratic Gain Buck-Boost Converter

2.1 Modes of Operation

The dual output quadratic gain buck-boost converter has two switches. According to switching states of power switches, there are two operating states in terms of either turn-on or turn-off state of the active power switches S_1 and S_2. The switching times of S_1 and S_2 are same and diodes turn ON/OFF operation is complementary to the switches. The theoretical waveforms of the operating modes of the buck-boost converter are shown in Fig. 3.

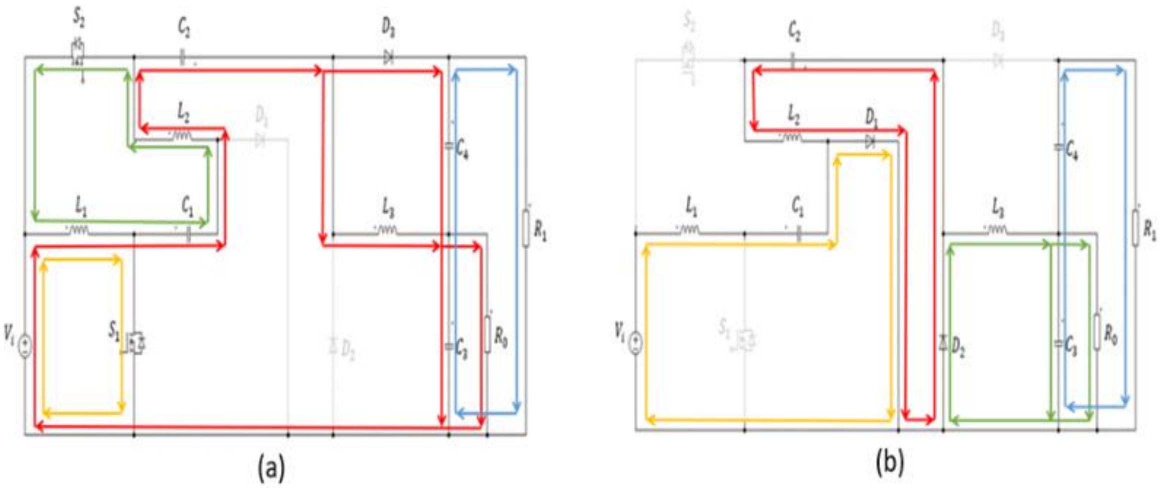


Fig. 2 Operating Modes. (a) Mode I; (b) Mode II

Mode I: In this mode shown in Fig. 2(a), switches S_1, S_2 are turned ON and diode D_3 forward biased. The diodes D_1 and D_2 are reverse biased and four current loops appear in the circuit. The input voltage source V_i charges the inductor L_1 through switch S_1. The inductor L_3 is charged by input voltage source V_i and the capacitor C_2, while the inductor L_2 is charged by the capacitor C_1. The capacitor C_3 maintains load voltage V_{01} in the load R_0. The series combination of capacitors C_3 and C_4 maintains constant load voltage V_{02} in the load R_1.

Mode II: In this mode shown in Fig. 2(b), switches S_1, S_2 are turned OFF and diode D_3 reverse biased. The diodes D_1 and D_2 are forward biased and four current loops appear in the circuit. The inductor L_1 charges the capacitor C_1, while the inductor L_2 is charges the capacitor C_2 through D_1 and D_2. The stored energy in inductor L_3 transfered to the capacitor C_3 and the load R_0. The series combination of capacitors C_3 and C_4 maintains constant load voltage V_{02} in the load R_1.

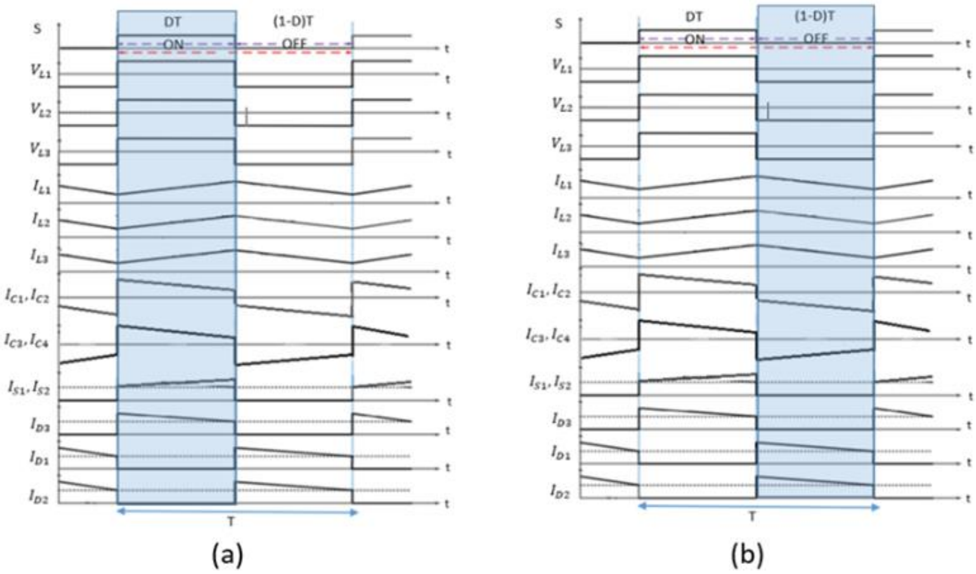


Fig. 3 Theoretical Waveforms. (a) Mode I; (b) Mode II

2.2 Design of Components

In order to operate the DC-DC converter, its components should be designed approximately. It consists of design of inductors and capacitors. For designing purpose, the input voltage V_i is taken as 15V to obtain output voltages V_{01} and V_{02} for as 100V and 150V for boost operation and 10V for buck operation. The load resistance is taken as 150Ω for both loads and switching frequency f_s is taken as 75kHz. The duty ratio D for switches S_1 and S_2 are taken as equal and fixed as 0.69 for boost operation and 0.35 for buck operation. The Conversion ratio is obtained as in equation (1).

$$\text{Conversion ratio } M = \frac{V_o}{V_i} \tag{1}$$

The output powers P_{01}, P_{02} and output voltages V_{01}, V_{02} for boost operation are 67W,150W and 100V,150V. Therefore, the maximum output currents I_{01}, I_{02} is obtained as 0.5A and 1A. The load resistance R_{01}, R_{02} are approximated as 150Ω from equations (4) and (5).

$$I_{01} = \frac{P_{01}}{V_{01}} = 0.5A \tag{2}$$

$$I_{02} = \frac{P_{02}}{V_{02}} = 1A \tag{3}$$

$$R_{01} = \frac{{v_{O1}}^2}{P_{01}} \tag{4}$$

$$R_{02} = \frac{{V_{02}}^2}{P_{02}} \tag{5}$$

By applying Kirchhoff's Current Law (KCL) in operating circuits of mode 1 and mode 2 in Fig. 2. The inductor currents I_{L1}, I_{L2} and I_{L3} are obtained in (6), (7) and (8).

$$I_{L1} = \frac{D^2 * I_o}{(1-D)^2} \tag{6}$$

$$I_{L2} = \frac{D * I_o}{(1-D)} \tag{7}$$

$$I_{L3} = I_o \tag{8}$$

By applying Kirchhoff's Voltage Law (KVL) in operating circuits of mode 1 and mode 2 in Fig. 2. The capacitor voltages $V_{C1}, V_{C2}, V_{C3}, V_{C4}$ and V_{C5} are obtained in (9), (10), (11) and (12).

$$V_{C1} = \frac{V_i}{(1-D)} \tag{9}$$

$$V_{C2} = \frac{D * V_i}{(1-D)^2} \tag{10}$$

$$V_{C3} = \frac{D^2 * V_i}{(1-D)^2} \tag{11}$$

$$V_{C4} = \frac{D * V_i}{(1-D)^2} \tag{12}$$

Consider the inductor ripple current $\Delta I_L < 40\%$ of I_L. The maximum output current I_0 is taken as 1A. The values of inductors are obtained in (13), (14) and (15). The value of inductor L_1 is obtained as 1.2mH, L_2 as 0.9mH and L_3 as 1.1mH respectively.

$$L_1 \geq \frac{D * V_i}{\Delta I_{L1} * f_s} \qquad (13)$$

$$L_2 \geq \frac{D * V_i}{(1-D) * \Delta I_{L2} * f_s} \qquad (14)$$

$$L_3 \geq \frac{D^2 * V_i}{(1-D) * \Delta I_{L3} * f_s} \qquad (15)$$

The capacitor ripple voltage is taken as $\Delta V_c < 1\%$ of Vc. By solving the equation in (16), (17), (18) and (19) the values of capacitors C_1, C_2, C_3 and C_4 obtained. The value of capacitors C_1 & C_2 are taken as $47\mu F$ and C_3 & C_4 are taken as $100\mu F$ respectively.

$$C_1 \geq \frac{D^2 * Io}{(1-D) * \Delta V_{C1} * f_s} \qquad (16)$$

$$C_2 \geq \frac{D * Io}{\Delta V_{C2} * f_s} \qquad (17)$$

$$C_3 \geq \frac{(1-D) * R * Io}{8 * L_3 * \Delta V_{C3} * {f_s}^2} \qquad (18)$$

$$C_4 \geq \frac{D * Io}{\Delta V_{C4} * f_s} \qquad (19)$$

In the following chapters, the simulation results and performance analysis of dual output quadratic gain buck-boost converter is discussed in detail. Further a detailed comparison between proposed converter and other converters are also given.

III. Simulations And Results

The values of capacitors and inductors are designed using suitable equations. The dual output quadratic gain buck-boost converter is validated using the designed values. The converter is simulated in MATLAB/SIMULINK using the simulation parameters shown in Table 1. The switches are MOSFET/Diode with constant switching frequency of 75kHz. The duty cycle D of switches S_1 and S_2 are taken as 0.69 for boost operation and 0.35 for buck operation. The simulation results of the proposed converter are shown in the following figures.

TABLE I

Simulation Parameters of Quadratic Gain Buck-Boost Converter

Parameters	Specifications
Input voltage (V_i)	15V
Rated Output voltage (V_0)	70V-100V (for Boost operation) 5V-10V (for Buck operation)
Duty ratio	0.69 (for Boost operation) 0.45(for Buck operation)
Switching frequency (f_s)	75kHz
Rated output power (P_0)	37W 5W
Output load resistance (R_0)	150Ω
Inductors L1,L2,L3	1.2mH, 0.9mH,1.1mH
Capacitors C1,C2,C3	47μF, 47μF, 100μF

The input voltage V_i and input current I_i for the boost operation are 15V and 14.5A is shown in Fig. 4. The output voltage V_{01} and V_{02} are obtained as 100V with 0.04V ripple and 150V with 0.1V ripple. The output voltages and the output currents for the boost operation are shown in Fig. 5. The output currents I_{01} and I_{02} are obtained as 0.667A with a ripple of 0.00029A and 0.969A with a ripple current 0.0007A.

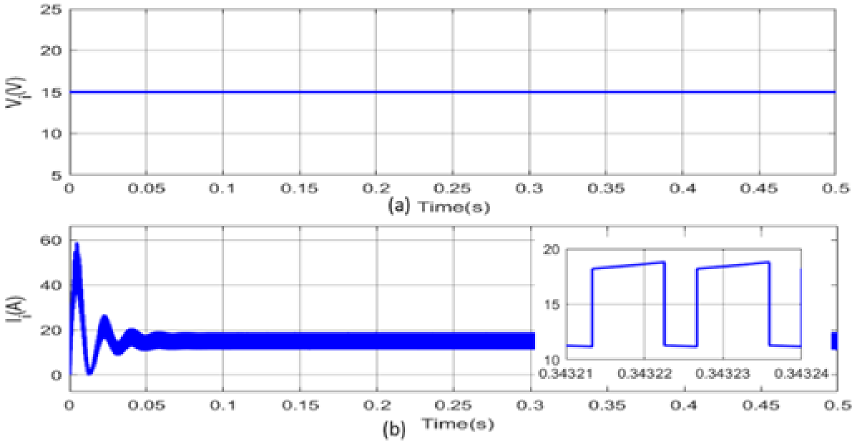


Fig. 4 (a) Input Voltage V_i, (b) Input Current I_i for boost operation

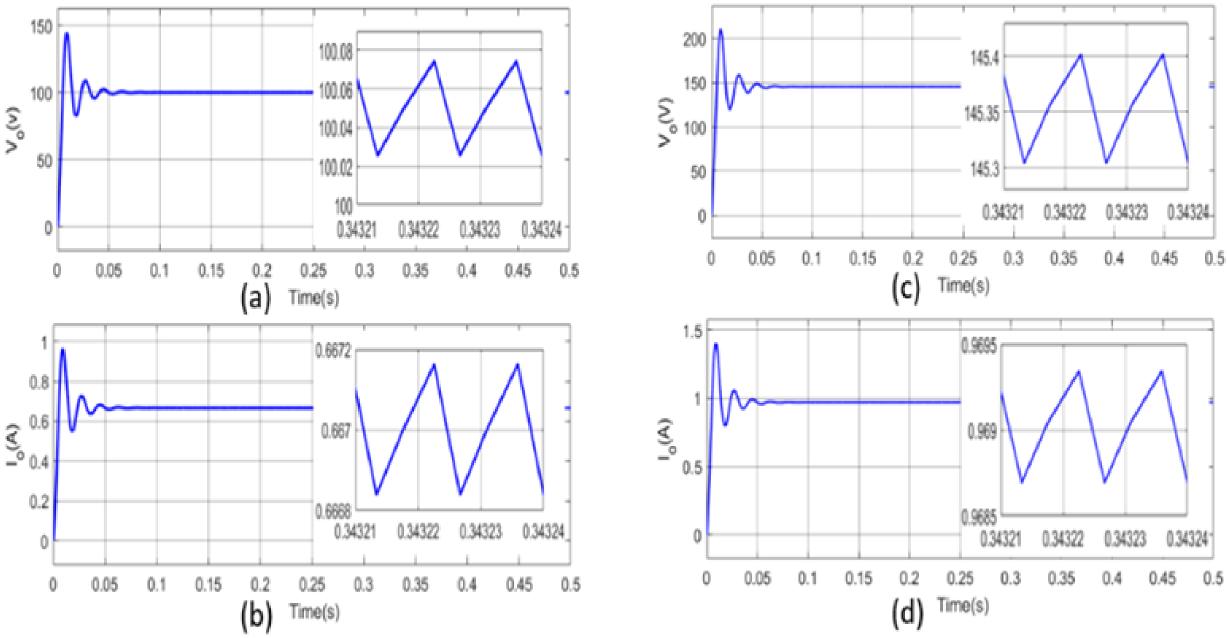


Fig. 5. (a) Output Voltage V_{01}; (b) Output Current I_{01}; (c) Output Voltage V_{02}; (d) Output Current I_{02}

The input voltage V_i is 15V and the input current I_i is 1.25A for buck operation with duty ratio of 0.35 is shown in Fig. 6. The output voltage V_0 is measured as 8.8V with ripple 0.019V and output current I_0 is obtained as 0.0588A with a ripple 0.00013A. The Fig. 7 shows the output voltage and the output current for the buck operation.

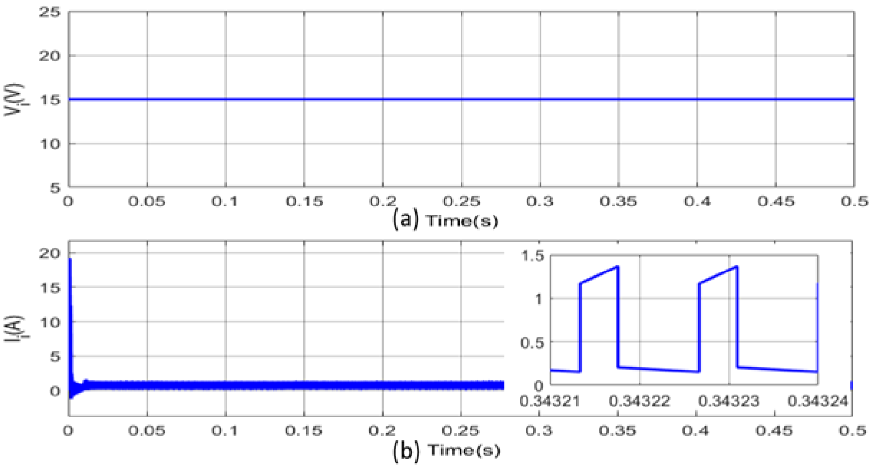


Fig. 6. (a) Input Voltage V_i, (b) Input Current I_i for buck operation

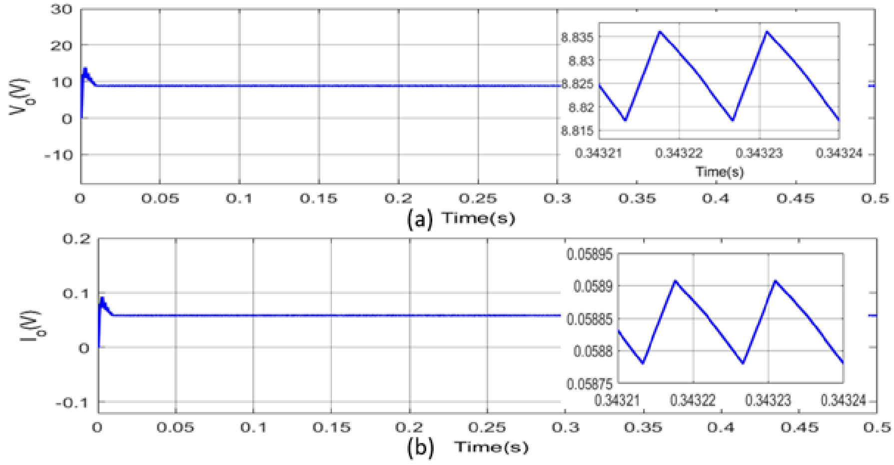


Fig. 7. (a) Output Voltage V_0; (b) Output Current I_0

IV. Performance Analysis

The analysis of dual output quadratic gain buck-boost DC-DC converter is carried out by considering parameters like efficiency, voltage gain, ripple voltage and duty cycle. The efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. The efficiency gives the fraction of the input power delivered to the load. The Fig. 8(a) shows Efficiency Vs Output Power for R Load. The converter efficiency is around 94% for R load and 93.5% for RL load. The output power is about 67W for the boost operation. The efficiency is about 81% for buck operation. The conversion ratio is defined at any load as the ratio of output voltage to input voltage. The Fig. 8(b) shows conversion ratio Vs Duty ratio. The conversion ratio decreases for an increase in the duty cycle from 0.15 to 0.40 for buck operation. The duty ratio is selected as 35% as the converter achieves maximum efficiency with a 1.7 conversion ratio for buck operation. The voltage gain increases when the duty cycle is above 40% and the converter turned into boost operation. The duty ratio is taken as 69% for voltage gains of 6.67 and 9.67 in boost operation. The converter input current shoots at very high level, when duty cycle turned above 75% thus the efficiency also gets reduced.

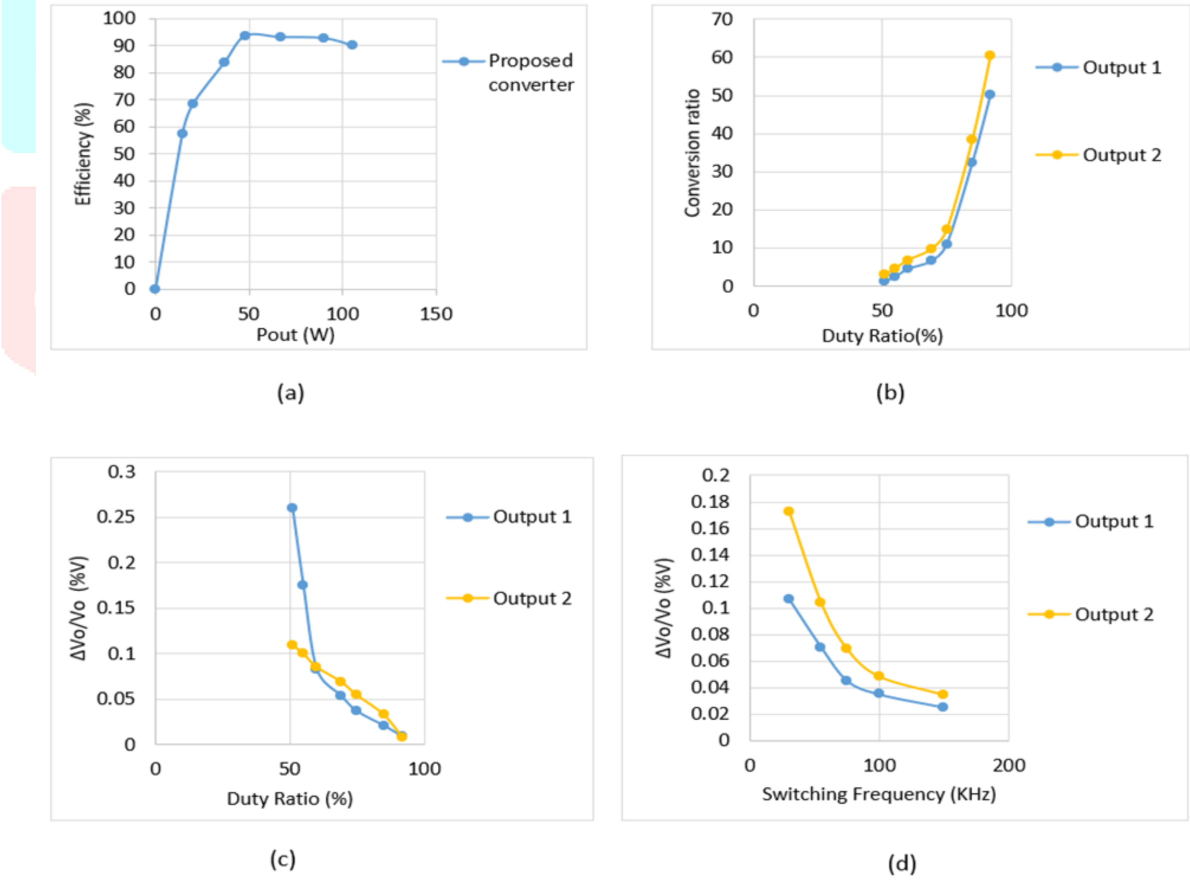


Fig. 8. (a) Efficiency Vs Output Power for R load; (b) Conversion Ratio Vs Duty Ratio; (c) Output Voltage Ripple Vs Duty Ratio; (d) Output Voltage Ripple Vs Switching Frequency

The Fig. 8(c) shows Output voltage ripple Vs Duty ratio. There is a gradual decrease in the output ripple voltage as the duty ratio D is varied from 0.15 to 0.39 for the buck operation. The duty ratio is selected as 35% for minimum ripple below 0.22% for buck operation. The duty cycle of 40% is taken as threshold duty ratio. When the duty ratio is above 60% the converter obtained minimum ripple voltages. For duty ratio above 80% the input current shoots at very high level. Thus, the duty cycle D is taken as 69% for minimum ripple of 0.043% for boost operation. The Fig. 8(d) shows Output voltage ripple Vs Switching frequency. The output ripple voltage and switching frequency are inversely proportional. When the switching frequency increases, ripple voltage reduces. The converter obtained minimum ripple voltage with maximum efficiency for both buck and boost operation for frequency between 50kHz and 100kHz. Thus, the duty ratio is taken as 75kHz for the buck-boost converter.

V. COMPARITIVE STUDY

The comparison between dual output quadratic gain buck-boost converter with two-switch-based enhanced gain buck-boost converter is given in Table 2. From the comparison table, it can be observed that, maintaining same value for input voltage 15V and switching frequency as 75kHz, the output voltage obtained are 100V and 150V for dual output quadratic gain buck-boost converter whereas only 70V obtained by two switch-based enhanced gain buck-boost converter for boost operation. The proposed converter posses higher gain than two-switch-based enhanced gain buck-boost converter but, voltage ripple increased a little bit compared to the other converter. The proposed converter has multiple boost output along with a buck output and also offers higher efficiency than other buck-boost converters.

TABLE II
Comparison Between Two-Switch-Based Enhanced Gain Buck-Boost Converter and Dual Output Quadratic Gain Buck-Boost Converter

Parameters	Two-Switch-Based Enhanced Gain Buck–Boost Converter	Dual Output Quadratic Gain Buck–Boost Converter
No. of Switches	2	2
No. of Diodes	2	3
No. of Inductors	3	3
No. of Capacitors	3	4
Output Voltages V_{01}, V_{02} (Boost mode) V_{01} (Buck mode)	V_0=70.12V V_0=5.6V	V_{01}=100.05V, V_{02}=145.35V V_{01}=8.8V
Conversion ratio V_{01}, V_{02} (Boost mode) V_{01} (Buck mode)	4.67 2.6	6.67, 9.67 1.71
Output Current Ripple I_{01}, I_{02} (Boost mode) I_{01} (Buck mode)	0.004% for I_0 0.17% for I_0	0.043% for I_{01}, 0.072% for I_{02} 0.22% for I_{01}
Output Voltage Ripple V_{01}, V_{02} (Boost mode) V_{01} (Buck mode)	0.004% for V_0 0.08% for V_0	0.039% for V_{01}, 0.068% for V_{02} 0.22% for V_{01}

The component wise comparison between dual output quadratic gain buck-boost converter and other buck-boost converters are shown in Table 3. The comparison is based on the components used in the different buck- boost converters that produces similar output voltage conversion ratio. The buck-boost converters producing multiple high gain boost output with similar duty ratio range is taken for comparison. From the table it can be observed that, the number of total components used in dual output quadratic gain buck-boost converter and other buck-boost converters are almost same. Hence, all the converters posses similar size. But the dual output quadratic gain buck-boost converter produces higher efficiency outputs with high gain for the same cost compared to other DC-DC converters.

TABLE III
Comparison Between Proposed Converter and Other Buck-Boost Converters

Parameters	Two-Switch-Based Enhanced Gain Buck–Boost Converter [1]	Non-isolated buck-boost converter based on ZETA converter [2]	Quadratic buck-boost converter with zero output voltage ripple [3]	Single-switch quadratic buck-boost converter [4]	Non-Isolated Buck-Boost DC-DC Converter with Single Switch [5]	Zeta-Buck-Boost Converter with Multiple-Outputs [6]	Dual Output Quadratic Gain Buck–Boost Converter
No. of switches	2	1	2	1	1	1	2
No. of Diodes	2	2	2	5	5	2	3
No. of Inductors	3	3	2	3	3	2	3
No. of Capacitors	3	4	2	3	3	3	4

VI. EXPERIMENTAL SETUP WITH RESULTS

The hardware is implemented for the purpose of testing. For that a prototype designed with the input voltage reduced to 5V to produce rated boost output voltages between 30-50V. The switching frequency maintained as 75kHz and duty ratio is also taken as 0.69 with all similar inductor and capacitor values. The switching pulse for both switches are generated using PIC16F877A micro-controller. The switches used are MOSFET IRF640N along with its driver TLP250H, which is an opto-coupler used to isolate and protect the micro-controller from power circuit and also used to provide required gating pulses to turn on the switches.

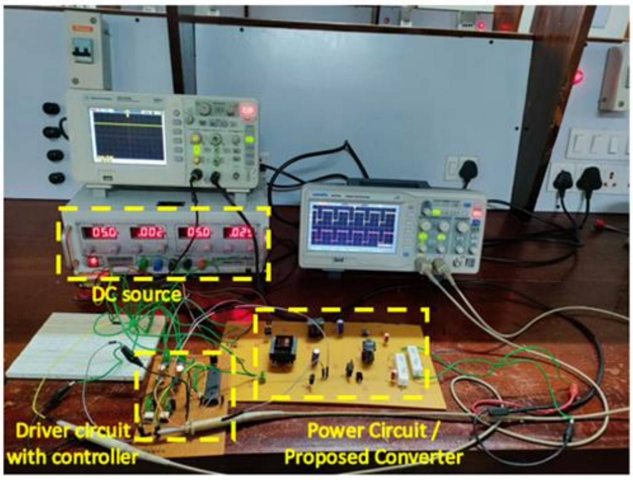
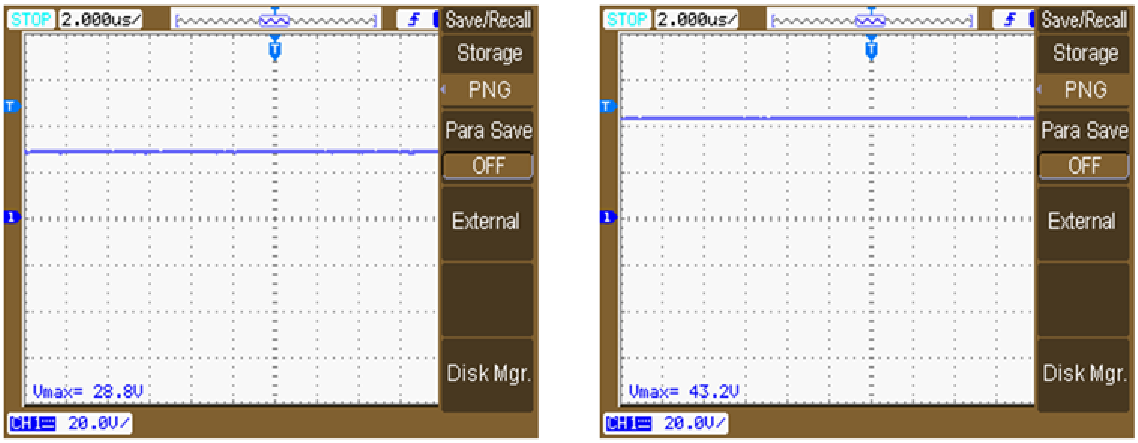


Fig. 9. Experimental Setup For Prototype Using PIC Controller



(a) (b)

Fig. 10. Output Voltages (a) V_{01}, (b) V_{02} for boost operation

The Fig. 9 shows the experimental setup for dual output quadratic gain buck-boost converter. The input voltage 5V DC supply is given from DC source. The switching pulses are taken from interfacing circuit, that consists of PIC16F877A micro-controller and its driver circuit. Thus, an output voltage of 28.8V and 43.2V at 75kHz switching frequency is obtained from power circuit of the converter. The output voltages of converter taken from the DSO oscilloscope are shown in Fig. 10.

VII. Conclusion

The non-isolated dual output quadratic gain DC-DC buck-boost converter can achieve quadratic type buck-boost conversion. The two-switch-based buck-boost converter developed by cascading quadratic boost followed by buck converter developed into multiple output buck-boost converter. The converter is modified in the front end of quadratic boost converter to obtain additional current loop from source through the inductors to increase the gain in the boost outputs to improve the overall performance and efficiency of the converter. The output voltage and current ripples increased little bit compared to existing circuit but maintained much below the standard ripple limits. The new series combination of capacitors in output side produced the additional high gain boost output along with the existing buck-boost output. The duty cycle of 40% is taken as threshold duty ratio. The converter topology retains common ground structure and produces non-inverting output voltage in both bucking as well as boosting operation. The converter offers low current stress and high efficiency operation. The operation and control of the converter is simple and flexible. The hardware implementation for prototype is designed and implemented successfully using PIC microcontroller. The hardware outcomes confirmed the simulation results. The converter can be used in portable electronic appliances, car electronics devices, solar power conditioning and renewable energy systems.

References

[1] Mummadi Veerachary, Malay Ranjan Khuntia, "Design and Analysis of Two-Switch-Based Enhanced Gain Buck-Boost Converters," IEEE Trans. Ind. Electron., vol. 69, no. 4, pp. 3577-3587, Apr. 2022.

[2] N. Zhang, G. Zhang, K. W. See, and B. Zhang, "A single-switch quadratic buck-boost converter with continuous input port current and continuous output port current," IEEE Trans. Power. Electron., vol. 33, no. 5, pp. 4157-4166, May. 2018.

[3] J. C. Mayo-Maldonado, J. E. Valdez-Resendiz, P. M. Garcia-Vite, J. C. Rosas-Caro, M. D. R. Rivera-Espinosa, and A. Valderrabano-Gonzalez, "Quadratic buck-boost converter with zero output voltage ripple at a selectable operating point," IEEE Trans. Ind. Appl., vol. 55, no. 3, pp. 2813-2822, May. 2019.

[4] M. R. Banaei and H. A. F. Bonab, "A high efficiency non-isolated buck-boost converter based on ZETA converter," IEEE Trans. Ind. Electron., vol. 67, no. 3, pp. 1991-1998, Mar. 2020.

[5] E. Duran, S.P. Litran2, M.B. Ferrera, and J.M. Andujar, "A Zeta-Buck-Boost Converter Combination for Single-Input Multiple-Output Applications," IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society., vol. 16, no. 1, pp. 5090-3474, Dec. 2016.

[6] A. Sarikhani, B. Allahverdinejad, and H. Torkaman, “A Non-Isolated Buck-Boost DC-DC Converter with Single Switch,” 2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC)., vol. 18, no. 1, pp. 5386-4699, Apr. 2018.
[7] G. Chen, Z. Jin, Yan Deng, Xiangning He, Xinlin Qing, “Principle and Topology Synthesis of Integrated Single-Input Dual-Output and Dual-Input Single-Output DCDC Converters,” IEEE Trans. Ind. Electron., vol. 65, no. 5, pp. 3815-3825, May. 2018.
[8] M. Forouzesh, Y. P. Siwakoti, S. A. Gorji, F. Blaabjerg, and B. Lehman, “Step-up DC-DC converters: A comprehensive review of voltage boosting techniques, topologies, and applications,” IEEE Trans. Power Electron., vol. 32, no. 12, pp. 9143-9178, Dec. 2017.
[9] S. Ding and F. Wang, “A new negative output buck-boost converter with wide conversion ratio,” IEEE Trans. Ind. Electron., vol. 64, no. 12, pp. 9322-9333, Dec. 2017.
[10] M. Veerachary and V. Khubchandani, “Analysis, design and control of switching capacitor based buck-boost converter,” IEEE Trans. Ind. Appl., vol. 55, no. 3, pp. 2845-2857, May. 2019.
[11] M. R. Banaei and S. G. Sani, “Analysis and implementation of a new SEPIC based single-switch buck- boost dc-dc converter with continuous input current,” IEEE Trans. Power Electron., vol. 33, no. 12, pp. 10317- 10325, Dec. 2018.
[12] K. I. Hwu and T. J. Peng, “A novel buck-boost converter combining KY and buck converters,” IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2236-2241, May. 2012.
[13] A. Ajami, H. Ardi, and A. Farakhor, “Design, analysis and implementation of a buck-boost converter,” IET Power Electron., vol. 12, no. 7, pp. 2902-2913, Mar. 2014.
[14] J. Li and J. Liu, “A novel buck-boost converter with low electric stress on components,” IEEE Trans. Ind. Electron., vol. 66, no. 4, pp. 2703- 2713, Apr. 2019.
[15] S. A. Gorji, A. Mostaan, H. T. My, and M. Ektesabi, “Non-isolated buck-boost dc-dc converter with quadratic voltage gain ratio,”IET Power Electron., vol. 12, no. 6, pp. 1425-1433, Feb. 2019.