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Switched Inductor based Quadratic Following Boost Converter

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ABSTRACT: *High step-up gain DC-DC converters are becoming increasingly important as the use of renewable energy grows. When circuit complexity taken into account, the quadratic boost converter provides the best trade-off in the cascade boost family. At a moderate duty ratio, this converter can step up a low source voltage to a high voltage, which is more than a conventional boost converter. The quadratic following boost converter in between the source and load appears like a cascaded connection of Switched L-C and Charge pump effect from boosting point of view. The operating principle and the mathematical model of the converter in continuous conduction mode (CCM) are given. In order to provide improved gain, the converter is employed with switched inductor concept. The converter's superiority is mostly based on the low magnetic field energy, which reduces the size and cost of the inductors and lessens the current stress on the switching elements, resulting in minimal conduction losses that can raise the converter's efficiency. Besides to illustrate the advantages of designed converter, a comparison with quadratic boost converter is carried out. The performance study and analysis of switched-inductor based quadratic following boost converter is carried out with MATLAB/SIMULINK 2020b for an output power of 500W. The experimental validations for the performance and working of the 3W designed prototype are presented.*

KEYWORDS: Boost Converter, Transformer less, Gain, Efficiency, DC-DC converters, Switched inductor

I. INTRODUCTION

A DC-to-DC converter is referred to as a boost converter if the output voltage is higher than the source voltage. A boost converter is sometimes called a step-up converter because it increases the source voltage. The boost converter can be powered from any suitable DC source, such as batteries, solar panels, rectifiers, and DC generators. The process of converting one DC voltage to another DC voltage is called DC to DC conversion. Boost topologies are more frequently used for high voltage realization, and their range of applications is substantially greater. Enhanced battery pack voltage is necessary in many applications. Due to its ease of operation and ease of construction, the step-up boost topology is a crucial choice for achieving this objective. But if the battery pack voltage is increased excessively, efficiency decreases. The functioning of traditional boost topologies at high duty ratios is the primary cause of this low efficiency. Due to the non-ideal resistance present in the converter system, such operation results in increased dissipation losses. Raising the battery pack voltage has the overall effect of decreasing device efficiency and increasing thermal loading, which necessitates improved heat sink heat extraction systems. Due to the short transistor switch OFF time, the high duty ratio also restricts the converter's switching frequency. Since the diode has less time to conduct due to the high duty cycle, the diode current is reduced to a narrow pulse with a high instantaneous value. In turn, this high diode current results in disconnected reverse recovery loss and an EMI issue. Several no isolated DC-DC converter topologies have been reported in order to address these problems, which still exist in conventional converters belonging to the boost topology class. A novel dual-stage boost converter known as a quadratic boost converter offers the same voltage gain as connecting two boost converters in series. However, compared to basic boost converters, these systems feature additional L-C elements, which are primarily utilized to store more energy, allowing for higher boost voltages, as well as to reduce ripple content at heavy loads. A high step-up converter [3] consisting of an integrated quadratic boost converter and a voltage double. The integration of the quadratic boost converter makes the system easier to lift up its voltage gain through slightly increasing the duty ratio of the single switch. The voltage double further increases the voltage gain of the system as the turn ratio rises. The voltage stresses on the switch and the diodes are decreased for such cascaded topology. The leakage inductance contributes to realizing zero current switching of the diodes in the second boost stage and the double and the energy can be recycled to the load. But it has complicated design. A wide voltage gain DC-DC converter [4] to increase and equalize the relatively low voltage of fuel cell stacks with DC link bus or energy storage devices, such as supercapacitors or batteries. This introduces two new non-isolated DC-DC converters suitable for such applications, which can be extended to other electric vehicles as well. The converters combine the main characteristics of both quadratic boost and cuk converters, offering high step-up voltage and control simplicity using only one ground referenced active power switch. Additionally, the topologies present reduced voltage stress across the active power switch when compared to other boost converters. A novel step-up converter [5] with stackable switching stages that is suitable for renewable energy applications. On the one hand, the converter gain corresponds to that of the traditional quadratic boost converter, achieving an arbitrary exponential gain in extended configurations. On other hand, the converter requires a single switch, while the output voltage is partitioned among several capacitors. As argued in this work, the features of this topology represent a significant contribution with respect to standard topologies that exhibit greater voltage stress. A non-isolated quadratic boost converter [6] featuring low output voltage ripple compared to CQBC. This advantage differs from other topologies that require high amounts of stored energy capacitors to achieve the same output voltage ripple specification.

This property allows for a compact converter design where the size of the capacitors is proportional to their energy storage rating. Solution for photovoltaic module partial shading: boost converter [7] with high DC gain. By substituting a switched inductor branch for the boost converter's inductor, the switched inductor boost converter is created. The conversion gain ratio might be raised as a result. In order to connect the PV system and the load, this converter is used.

Additionally, having more L-C components allows for greater duty ratio adjustment flexibility, which is necessary for the converter to operate reliably. Additionally, lower duty ratios are adequate to achieve high voltage lifting. In the current work, a boost converter is introduced that closely tracks the voltage gain of a quadratic converter. A Switched Inductor based Quadratic Following Boost Converter is introduced for applications that require high-voltage gain as in the case of renewable energy applications. In order to provide improved gain, the converter is employed with switched inductor concept. The converter's superiority is mostly based on the low magnetic field energy, which reduces the size and cost of the inductors and lessens the current stress on the switching elements, resulting in minimal conduction losses that can raise the converter's efficiency.

II. METHODOLOGY

Switched inductor based quadratic following boost converter can boost a lower input DC voltage to greater values at the load side at trade-off duty ratios than the conventional boost converter. From a boosting perspective, the quadratic following boost converter situated between the source and the load resembles a cascaded connection of Switched L-C and Charge pump effect. In order to provide improved gain, the converter is employed with switched inductor concept. Switched inductor based quadratic following boost converter consist of two switches S_1&S_2 five diodes D_1, D_2, D_3, D_4 &D_5 three capacitors C_1, C_2 &C_3 and three inductors L_1, L_2& L_3 for transferring of power along with load voltage boosting action. V_{in} is the input voltage. output voltage is denoted as V_0. Fig. 1 shows a circuit of typical arrangement of switched inductor based quadratic following boost converter. The converter performance is analyzed under the steady state and continuous conduction mode conditions.

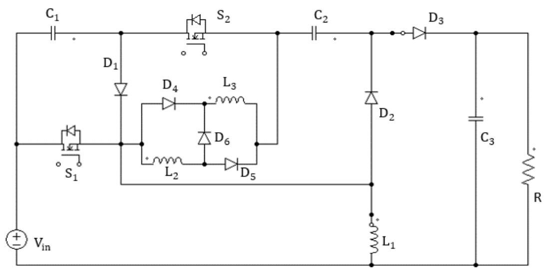


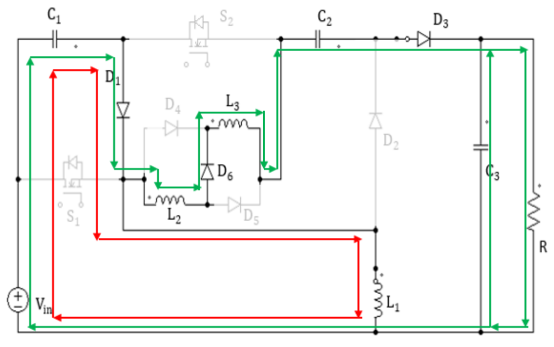
Fig. 1 Switched Inductor based Quadratic Following Boost Converter

2.1 Modes of Operation

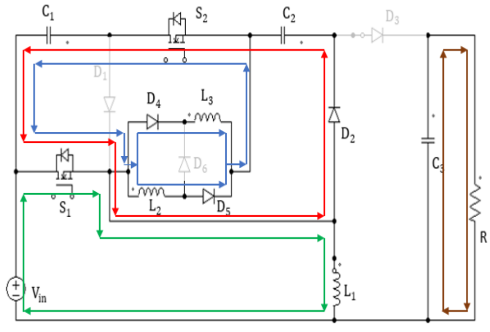
The working of the circuit can be explained by two modes of operation.

Mode 1: In this mode, switch S_1&S_2 is turned on. At the same time diode D_2, D_4 &D_5 is turned on and diodes D_1, D_3 &D_6 are turned off. The input voltage charges the inductor L_1. The capacitor C_1 is discharge to charge inductor L_2& L_3. The capacitor C_3 is discharge to supply load R. Fig. 3(a) shows the equivalent circuit diagram of the converter and current paths for this mode is also shown.

Mode 2: In this mode, switch S_1&S_2 is turned off. At the same time diode D_2, D_4 &D_5 is turned off and diodes D_1, D_3 &D_6 are turned on. The input voltage charges the capacitor C_1. The capacitor C_2, L_2& L_3 discharge to charge capacitor C_3 and to supply load R. Fig. 3(b) shows the equivalent circuit diagram of the converter and current paths for this mode is also shown.



(a)



(b)

Fig. 3 Operating Modes. (a) Mode I; (b) Mode II

2.1 Design of Components

In order to operate a converter properly, its components should be designed appropriately. Some assumptions are taken for the design of switched inductor based quadratic following boost converter. It consists of design of load resistance, inductors L_1, L_2& L_3 and the capacitors C_1, C_2, &C_3. The input voltage is taken as 42V. The output power and output voltage are taken as 500W and 250V respectively. Switching frequency is 100kHz. So, the ripple of inductor current is taken as ΔI_{L1} < 30% of I_{L1}, ΔI_{L2} < 15% of I_{L2}, and ΔI_{L3} < 15% of I_{L3}

Duty Ratio can be found by (1) which is taken as 0.54. The value of load resistor is set as 300Ω in(2).

$$\frac{V_o}{V_{in}} = \frac{1 - D - D^2}{(1 - D)^2} \tag{1}$$

$$R = \frac{V_O^2}{P_O} \tag{2}$$

The inductors L_2 & L_3 are obtained by taking current ripple as 15% of I_{L2} and I_{L3}. By substituting values to (4) & (5) it is approximated to 800μH.each. For inductor L_1 the current ripple is 30% of I_{L1}. It is given in (3) and value chosen to be 150μH

$$L_1 = \frac{V_{in} * D^2}{\Delta i_{L1} * f_s} \tag{3}$$

$$L_2 = \frac{V_{in} * D}{\Delta i_{L2} * (1-D) * f_s} \tag{4}$$

$$L_3 = \frac{V_{in} * D}{\Delta i_{L3} * (1 - D) * f_s} \tag{5}$$

The design of the capacitor mainly considers the voltage stress and maximum acceptable voltage ripple across it. By substituting values to (6) capacitor values are approximated to C1, C2 = 66μF. To ensure sufficient energy and hold up time provided for the post stage, the output capacitor is selected (7) as 100μF

$$C_1,\ C_2 = \frac{(I_{L1}-I_{L1})*(1-D)}{\Delta V_C * f_s} \tag{6}$$

$$C_3 = \frac{V_0 * D}{\Delta V_o * f_s} \tag{7}$$

III. SIMULATIONS AND RESULTS

The quadratic following boost converter is simulated in MATLAB/SIMULINK by choosing the parameters listed in Table 1. The switches are MOSFET with constant switching frequency of 100 kHz. The duty cycle of switch is taken as D=0.54. Fig. 4(a) shows that the input voltage V_{in} is 42V and the input current I_{in} is 6.1A. The ripple content in input current is 0.003A. Fig. 4(b) shows the output voltage V_0 and current I_0, V_0 measured as 251.8V and voltage ripple is 0.06V. The output current I_0 is 0.83A.

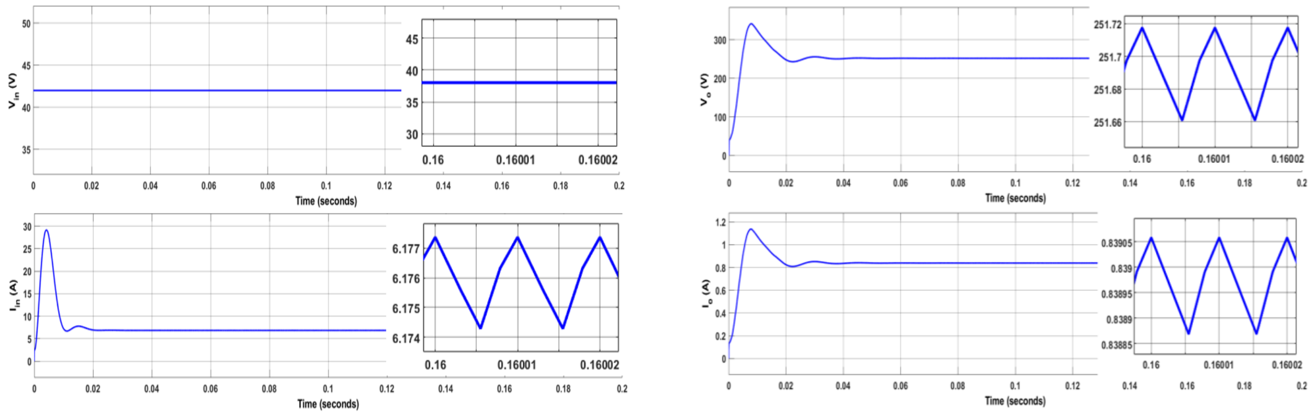
Fig. 5(a) shows gate pulse and voltage stress across the switch S_1. The duty ratio of S_1 is 0.54. The voltage stress across switch S_1 is 92.12V. Fig. 5(b) shows gate pulse and voltage stress across the switch S_2. The duty ratio of S_2 is 0.54. The voltage stress across switch S_2 is 214V. The switching frequency is chosen to be 100kHz for both switches.

Fig. 6 shows current through inductor L. The inductor current I_{L1} is measured as 4.95A, I_{L2} is 1.46A and I_{L3} is 1.46A.

TABLE I

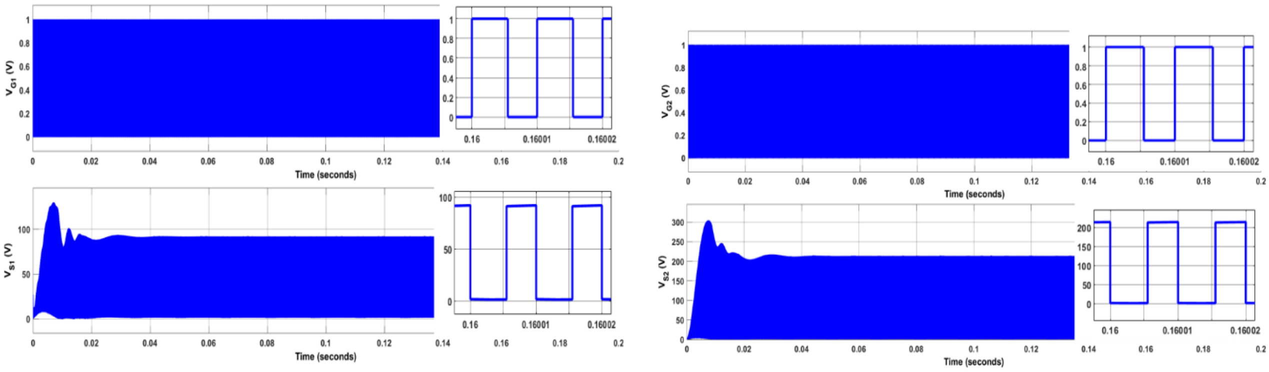
Simulation Parameters of Transformer less Grid- Connected Boost Inverter

Parameters	Specifications
Input voltage (V_{in})	42V
Switching frequency (f_s)	100kHz
Inductor (L_1)	150μH
Inductor (L_2)	800μH
Inductor (L_3)	800μH
Resistor (R)	300Ω
Capacitors (C_1, C_2)	66μF
Capacitor (C_3)	100μF
Duty cycle (D)	0.54



(a) (b)

Fig. 4 (a) Input Voltage & Input Current, (b) Output Voltage & Output Current



(a) (b)

Fig. 5. Gate Pulse and Voltage Stress of (a) S_1 (V_{S1}), (b) S_2 (V_{S2})

Fig. 7 shows Voltage across capacitors. V_{C1} is measured as 91.31V, V_{C2} is measured as 87.94V and V_{C3} is measured as 251.8V.

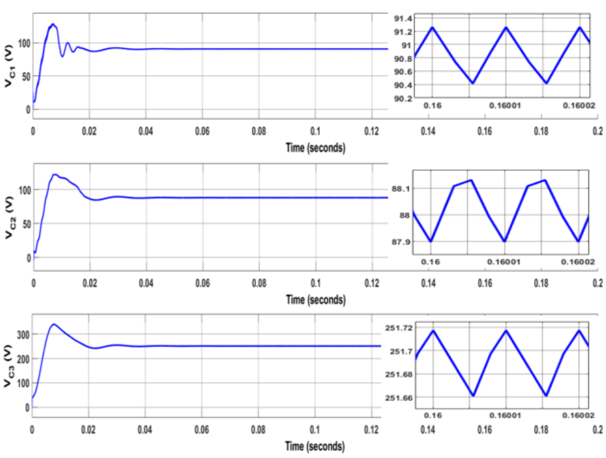


Fig. 6. Voltage across Capacitor V_{C1},V_{C2} & V_{C3}

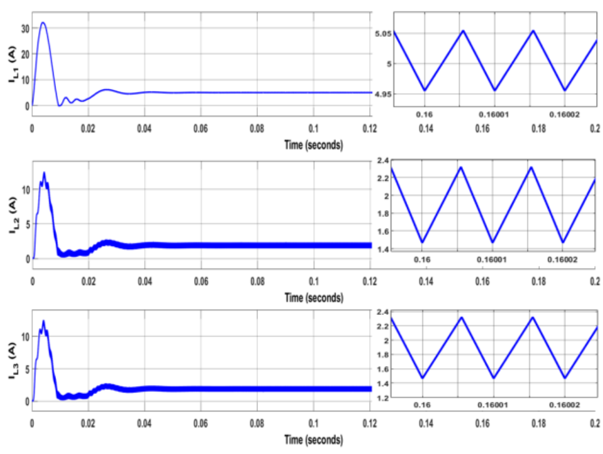
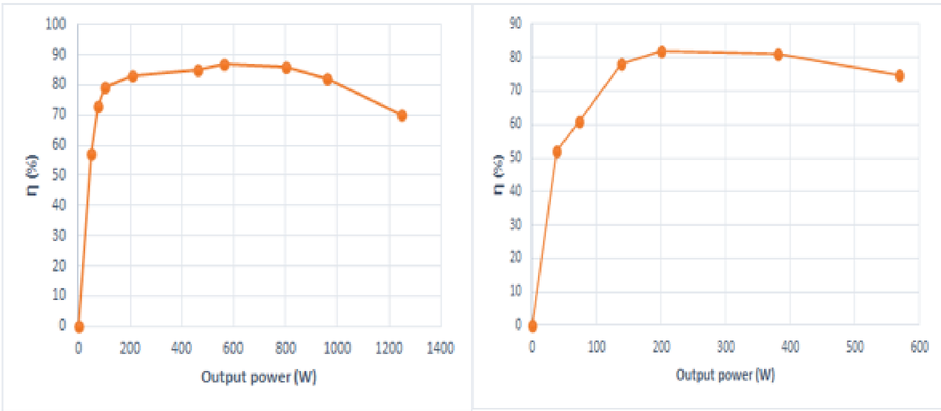


Fig. 7. Current across Inductors i_{L1}, i_{L2} & i_{L3}

IV. PERFORMANCE ANALYSIS

Analysis of quadratic boost Converters is carried out by considering parameters like efficiency, voltage gain, ripple voltage and duty cycle. Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. It gives, the fraction of the input power delivered to the load. The quadratic following boost converter has an efficiency of 82 % for R load and 70 % for RL load with an output power of 600W. The new Switched inductor based quadratic following boost converter efficiency is around 90% for R load and RL load is around 80% at 180 W output power. The plot of efficiency Vs output power for R load and RL load is shown in Fig. 8(a) & (b) respectively.



(a) (b)

Fig. 8. Efficiency Vs Output Power for (a) R load, (b) RL load

The plot of voltage gain of the converter and duty ratio shown in Fig. 9(a). By analyzing the graph it is clear that the voltage gain increases with Duty ratio for both the converters. The new switched inductor based quadratic following boost converter has high gain than the quadratic following boost converter for same value of duty ratio. The analysis of output voltage ripple Vs switching frequency is shown in Fig. 9(b). According to the analysis the output voltage ripple decreases with increase in switching frequency for both the converters. As increase in switching frequency the % of ripple is low for switched inductor based quadratic following boost converter than the quadratic following boost converter. The voltage ripple is minimum at 100kHz. From Fig. 10 the duty rato 0.54 gives lowest ripple. So at 0.54 duty ratio the high voltage gain obtained is 6 for switched inductor based quadratic following boost converter.

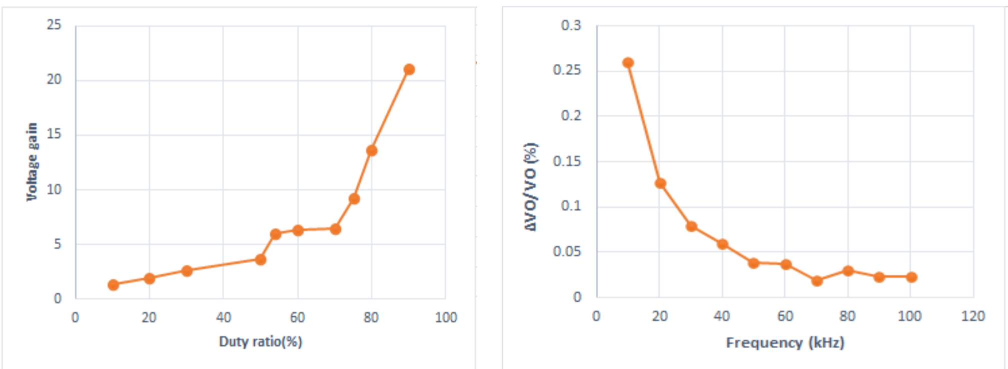


Fig. 9. (a) Voltage Gain Vs Duty ratio, (b) Output Voltage Ripple Vs Switching Frequency

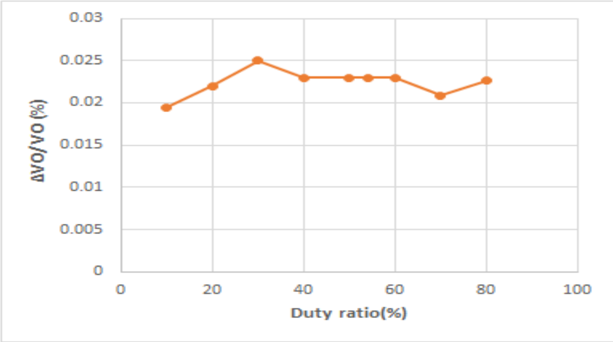


Fig. 10. Output Voltage ripple Vs Duty Ratio

The bode plot of system is shown in the Fig. 11. The system has a continuous-time transfer function which is given in (9). The obtained Phase cross over frequency (W_{pc}) is 754 rad/s and gain cross over frequency (W_{gc}) is 156 rad/s. Thus, it can be seen that both poles are lying on left half of s plane. Also, both gain margin (Gm) and phase margin (Pm) are 1.72 dB and 15.2deg. So both are positive values and the $W_{pc} > W_{gc}$. Hence, the system is stable.

$$G(s) = \frac{(25.88)\,S^4 + (2.592)\,S^3 + (1.709)\,S^2 - (1.712)\,S + 4.5}{S^5 - (226.1)\,S^4 - (6.622)\,S^3 + (1.287)\,S^2 + (1.71)\,S - (3.004)} \quad (9)$$

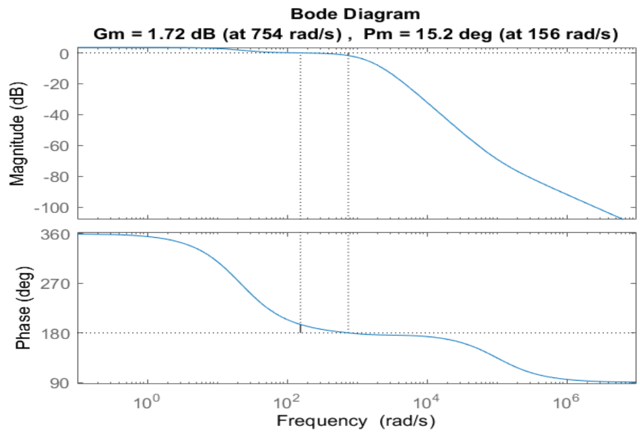


Fig. 11. Bode Plot of Transfer Function

V. COMPARITIVE STUDY

The comparison between quadratic following boost converter and switched inductor based quadratic following boost converter is given in Table 2. From the comparison table it is clear that the switched inductor based quadratic following boost converter has high efficiency than quadratic following boost converter. The number of components higher for modified converter because of the addition of switched inductor in quadratic following boost converter. And thereby the voltage gain of the converter increased from 3.57 to 6. The output voltage of the converter increased to 251.8 V from 150.3 V. Input and output current also increased. Output voltage and output current ripple for both the converters are nearly same. The voltage stress across switch in modified circuit is slightly higher than that of the non-isolated converter. Table 3 shows the components wise comparison between switched inductor based quadratic following boost converter and other quadratic boost converter topologies.

TABLE II

Comparison Between Quadratic Following Boost Converter & Proposed Converter

Parameters	*Quadratic following Boost converter (QFBC)*	*Switched inductor QFBC*
Number of inductors	2	3
Number of capacitors	3	3
Number of switches	2	2
Voltage gain	3.57	6
Output voltage ripple	0.03%	0.02%
Output current ripple	0.07%	0.04%
Output voltage	150.3V	251.8V
Output current	0.5A	0.83A
Input current	2.54A	6.1A
Voltage stress across switches	V_{S1} = 61% of V_o (91.6V) V_{S2} = 73% of V_o (109.7V)	V_{S1} = 36% of V_o (90.6V) V_{S2} = 82% of V_o (210V)

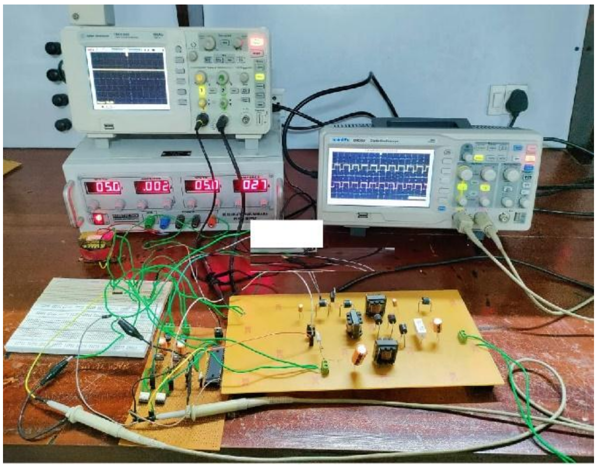
TABLE III

Comparison Between Switched Inductor based Quadratic Following Boost Converter & Other Inverters

Converters	*Switched inductor QFBC*	*Quadratic following boost converter (QFBC)[1]*	*Quadratic high step-up boost converter [2]*	*Non-inverting high gain DC-DC converter[6]*	*High step-up coupled-inductor cascade boost DC-DC converter[4]*	*Non-isolated topology for high step-up DC-DC converters[7]*
Switch	2	2	1	1	1	2
Diode	6	3	7	6	6	5
Inductor	3	2	2	2	2	3
Capacitor	3	3	5	5	4	6

VI. EXPERIMENTAL SETUP WITH RESULT

For implementing hardware, the input voltage reduced to 5V to obtain the output of 29.7V with output power of 2.9W. The switches are MOSFET with constant switching frequency of 100kHz. The duty cycle of switch is taken as D=0.54. The experimental setup of switched inductor based quadratic following boost converter is done through two stages. First the program is written in micro-C for generating gate pulses for switching devices. The program is verified and frequency is checked by simulating it in the Proteus software. The program is burned to the microcontroller (PIC16F877A) using the software micro programming suit for PIC. The switches used are MOSFET IRF540 along with its driver TLP250. Experimental setup of switched inductor based quadratic following boost converter is shown in Fig. 11(a). The output of 28.8V is obtained by drawing an input current of 0.008A. Fig. 11(b) shows the output waveform of the proposed converter.



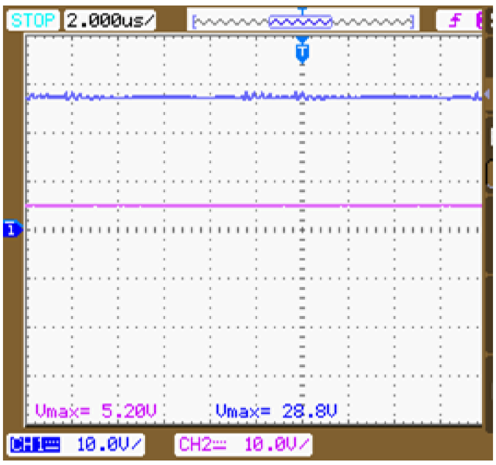


Fig. 11. (a) Experimental Setup, (b) Output Voltage of Proposed Inverter

VII. CONCLUSION

A switched inductor based quadratic following boost converter and considerable conversion ratio is presented. Switched inductor concept is adopted in order to improve the gain. By charging the inductors in parallel and discharging in series the gain is improved to 6. The converter's superiority is mostly due to the low magnetic field energy, which reduces the size and cost of the inductors and reduces the current stress on the switching parts, resulting in minimal conduction losses. which can improve the efficiency of the converter. Lower voltage and current stress across the switches when compared with other topologies aids the converter advantage. For a power of 500W, the system provides an efficiency of 90% . The control of the proposed converter is implemented using PIC16F877A microcontroller. The converter prototype of 3W provides the expected performance with an output voltage of nearly 28.8V, considering the drop across the components. This transformer less topology is suitable for applications that require high-voltage gains as in the case of renewable energy applications.

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