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Switched Inductor Based Quadratic Converter

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Abstract:- Nowadays the requirement of high frequency dc-dc converters is steadily increasing in many application areas such as portable electronics equipment, telecommunication systems, energy storage systems and uninterruptible power supplies. Photovoltaic (PV) power systems is the major renewable energy resource. But, the output voltage of the PV system is very low and high dc voltage is necessary for various applications. So inorder to maximise the voltage gain, a switched inductor concept is introduced to enhanced gain buck-boost converter. Here a switched inductor based quadratic converter is analysed. This converter is the combination of inverting boost followed by restructured ZETA converter. This converter has two active switches and two diodes and features a quadratic conversionratio. The device stresses are evaluated and compared to a classical buck-boost, it exhibits, lower input and output current ripples along with positive output voltage polarity and high gain. It also exhibits common ground and non-inverting output voltage. The operation principles and steady-state characteristics analysis of the converter is discussed in detail. Results are obtained by simulating the converter in MATLAB/SIMULINK R2017b. The simulation results shows that the converter has high voltage gain and achieves a peak efficiency of 84% . The converter is controlled using TMS320F28335 microcontroller.

Keyword:- *Boost Inverter, Transformerless, Gain, Effi-Ciency, THD*

I. INTRODUCTION

The photovoltaic (PV) power systems have become very popular among the renewable energy sources during last decade. Solar photovoltaic technology was introduced by various PV markets globally by replacing the conventional energy resources. PV modules may be operated as isolated system (standalone system) or grid connected. The output voltage of the PV systems is generally low. Consequently, converters need to be connected to boost the output voltage of PV in order to maintain a stable voltage for the load. The traditional buck-boost converter(TBBC)is used for bucking/boosting from source voltage. However, achieving high voltage transformation ratio(VTR)at very high duty ratio is not a feasible solution because it will cause high voltage stress on switching devices. Moreover this topology has inverted load voltage polarity and a higher magnitude of source current ripple. Though the input L- C filter is able to mitigate the ripple content problem but it is at the expense of additional damping network without which the system is more prone to instability issues. To overcome issues associated with BBC, some fourth order converter topologies have been reported such as SEPIC converter, CUK converter, and ZETA converter [3][5]. Though some of these converters are effective in ripple mitigation but the VTR is same as BBC. A switching capacitor based buckboost converter reported in [7] which overcomes the drawbacks of discontinuous input current as well as output current but its gain is same as BBC. A quadratic type buckboost converter with non-inverting load voltage polarity has been reported in [1]. However, its input and output currents are discontinuous and high stress on output capacitor. A single switch buckboost converter reported in [2] is able to overcome some of the shortcomings mentioned. However, there is no common ground and peak voltage stress on power switch is high. To eliminate the above stated limitations while keeping the benefits offered by them like 1) quadratic type buckboost conversion 2) minimal ripples like in CUK converter at input and output sides and 3) common ground or positive output voltage polarity. It is customary to adopt cascading of structures to realize quadratic type buck-boost conversion. Input and output ports of the proposed converter must have inductances to realize minimal ripples. To ensure common ground with positive output voltage polarity, the upstream side of topology must be similar to buck converter with no inductance, capacitance and diode in the return path. The possible options are boost or quadratic boost converter in the front-end side, while buck, SEPIC, and ZETA type converters should be on the upstream side[8]. Cascading of these topology along with a switched inductor circuit will result in the formation of switched inductor based quadratic converter. Switched inductor is the combination of a pair of equal valued inductors and multiple passive (diodes) elements. Thus this switched inductor concept is added to the quadratic converter converter so that it has characteristics of high gain, high integration, few power devices, less switching losses and easy to control. Switched inductor is introduced at the inputside mainly to increase the

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voltage gain. So the proposed converter have a high voltage gain compared to other typical boost converters.It also possess many desired features such as common ground, minimal ripples at input and output side and positive output voltage polarity

II. METHODOLOGY

The switched inductor (S-L) based quadratic converter is a is a combination of inverting boost converter and ZETA converter. It consists of 2 power switches S_1 S_2, seven energy storage components, inductance L_1 L_4 and capacitance C_1 C_3, diode D_1 D_5 and load resistor R_0. Figure 3.5 shows the switched inductor based quadratic converter. Fig. 1 shows the switched inductor (S-L) based quadratic converter.

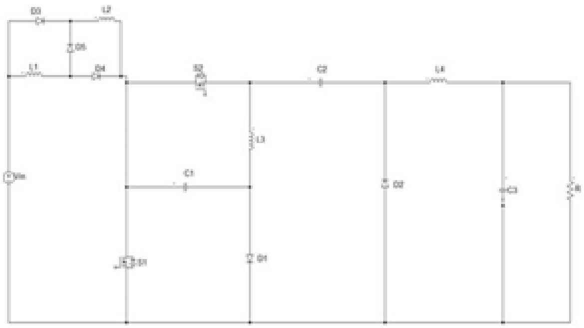

Fig. 1. Switched Inductor Based quadratic converter

A. *Modes of Operation*

The proposed converter operates in continuous current mode. There are two operating modes in one switching cycle. Both modes provide positive output voltage. Both switches turn on and turn off simultaneously. In switched inductor concept, when the inductors charges then the current flows in parallel direction and when the inductors discharges then the current flows in series direction.

- *Mode 1 (t_0 t_1):* At t = t_0, the switches S_1 and S_2 are turned on and diodes D_1 and D_2 are turned off. At thismoment, the inductors L_1,L_2 and L_4 are charged through the source. Capacitor C_1 charges inductor L_3. Current in all inductors increases linearly. The capacitors C_1, C_2 and C_3 discharges. Fig. 3 shows the operating circuit of mode 1.

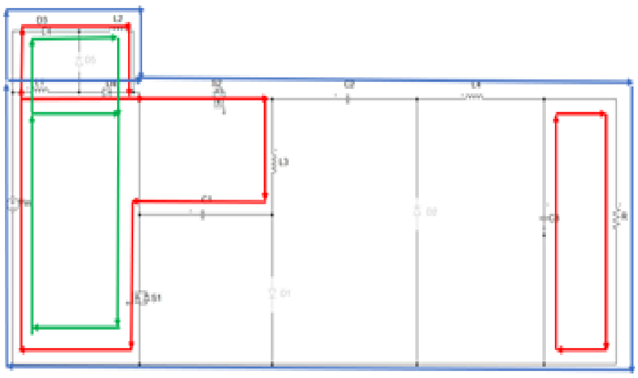

Fig. 2. Operating Circuit of Mode 1

- *Mode 2 (t_1 t_2):* At t = t_1, the switch S_1 and switch S_2 are turned off. Diodes D_1 and D_2 are turned on. At this moment, the stored energy of inductor L_1, L_2 charges capacitor C_1 , while inductor L_3 charges capacitor C_2. Inductor L_4 supplies energy to capacitor C_3 and load. Fig. 4 shows the operating circuit of mode 2.

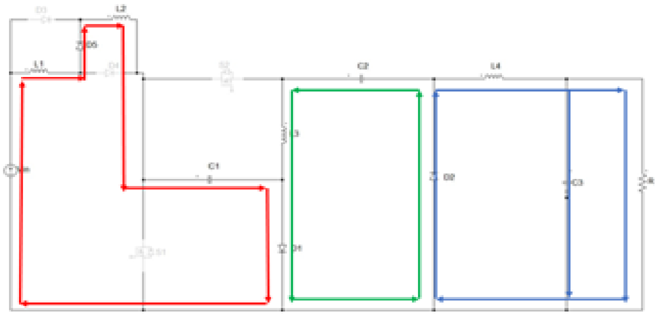

Fig. 3. Operating Circuit of Mode 2

- Figure 4 shows the theoretical waveforms for mode 1 and mode 2.

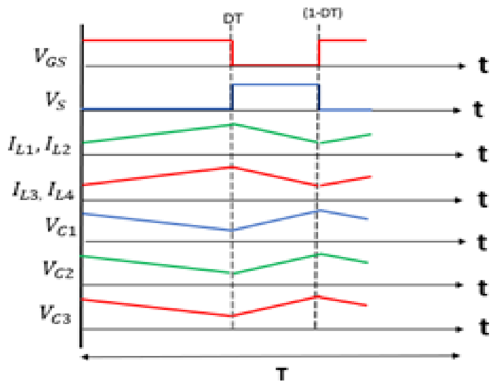

Fig. 4. Theoretical Waveforms

B. *Design of Components*

In order to operate a converter properly, its components should be designed appropriately. It consists of design of load resistance, inductors L_1, L_2, L & L_4 and the capacitors C_1, C_2 & C_3. Some assumptions are taken for the designof switched inductor based quadratic converter. Here, in switched inductor concept the pair of inductor values (ie, L_1 & L_2) are taken as same. The input voltage is taken as V_{in}= 15V. The output power and output voltage are taken as P_0 = 82W and V_0 = 111V. The duty cycle, D = 0.69 and switching frequency, f_s = 75kHz. So time period, $T_s = \frac{1}{f_s}$ =0.000013sec.

$$I_o = \frac{P_o}{V_o} \qquad (1)$$

- Duty Ratio can be found by (2) which is taken as 0.69. Thevalue of load resistor is set as 150Ω in (3).

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

$$R_o = \frac{{V_o}^2}{P_o} \quad (3)$$

- The inductors L_1 & L_2 are obtained by taking current rippleas 10% of I_{L1}.

$$I_{L1} = \frac{D^2 * I_0}{(1-D)^2} \quad (4)$$

- The inductors L_3 & L_4 are obtained by taking current rippleas 39.9% of I_{L3} & L_{L4}.

$$I_{L3} = \frac{D * I_0}{(1-D)} \quad (5)$$

$$I_{L4} = I_0 \quad (6)$$

- By substituting values to (7), (8) & (9) it is approximated 0.6mH for L_1 & L_2, 0.9 mH for L_3 and 1.1 mH for L_4.

$$L_1, L_2 >= \frac{D * V_{in}}{\Delta I_{L1} * f_s} \quad (7)$$

$$L_3 >= \frac{D * V_{in}}{(1-D) * \Delta I_{L3} * f_s} \quad (8)$$

$$L_4 >= \frac{D^2 * V_{in}}{(1-D) * \Delta I_{L4} * f_s} \quad (9)$$

- The design of the capacitor mainly considers the voltage stress and maximum acceptable voltage ripple across it. The capacitance C_1 is obtained by taking voltage ripple as 0.8%of V_{C1}

$$V_{C1} = \frac{V_{in}}{(1-D)} \quad (10)$$

- The capacitance C_2 is obtained by taking voltage ripple as0.2% of V_{C2}.

$$V_{C2} = \frac{D * V_{in}}{(1-D)^2} \quad (11)$$

- The capacitance C_3 is obtained by taking voltage ripple as0.01% of V_{C3}.

$$V_{C3} = \frac{D^2 * V_{in}}{(1-D)^2} \quad (12)$$

- By substituting values to (13), (14) & (15) capacitor values are approximated to 47μF for C_1 & C_2 and 100μF for C_3.

$$C_1 = \frac{D^2 * I_0}{(1-D)\Delta V_{C1} * f_s} \quad (13)$$

$$C_2 = \frac{D * I_0}{\Delta V_{C2} * f_s} \quad (14)$$

$$C_3 = \frac{(1-D) * R * I_0}{8 * L_3 * \Delta V_{C3} * {f_s}^2} \quad (15)$$

III. SIMULATIONS AND RESULTS

The switched inductor based quadratic converter is simulated in MATLAB/SIMULINK by choosing the parameters listed in Table 1. The switches are MOSFET with constant switching frequency of 75kHz. MATLAB is a high-performance language for technical computing. It integrates computation, visualization and programming in an easy way to use environment where problems and solutions are expressed in familiar mathematical notation. SIMULINK is a software package for modeling, simulating, and analysing dynamical systems.

Table 1 Simulation Parameters of Switched Inductor Based Quadratic Converter

Parameters	Value
Input Voltage(V_{in})	15V
Output Voltage(V_0)	111.2V
Switching Frequency(f_s)	75kHz
Cpacitor (C_1)	47µF
Capacitor (C_2)	47µF
Capacitor (C_3)	100µF
Inductors(L_1, L_2)	0.6mH
Inductor (L_3)	0.9mH
Inductor (4)	1.1mH
Load Resistance (R)	150Ω
Duty Cycle (D)	69

A dc input voltage of 15V gives a dc output voltage of 111.2V. Fig. 5 shows the input voltage and current. Fig. 6 shows the output voltage and current . Thus, the voltage gainis obtained as 7.4.

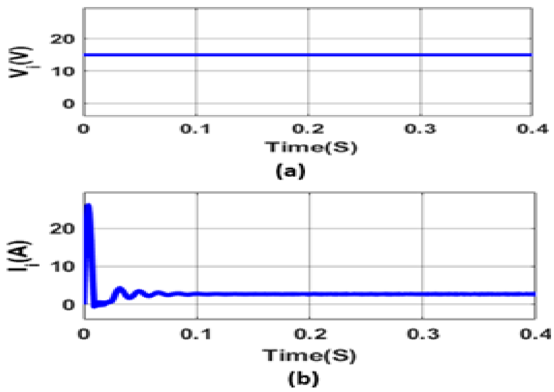

Fig. 5. (a) Input Voltage (V_{in}) and (b) Input Current (I_{in})

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- Switches S_1 and S_2. The voltage stress of V_{S1} is 74V and V_{S2} is 236V .

The voltage across capacitor (V_{C1}) is 73.55V, voltage across capacitor (V_{C2}) is 161.2V and voltage across capacitor (V_{C3}) is 112.2V which is shown in Fig. 9. Fig. 10 shows the currentacross inductance L , L , L and L .It can be seen that the current across inductance I_{L1}, I_{L2} is 6.855A I_{L3} is 1.724A and I_{L4} is 0.531A.

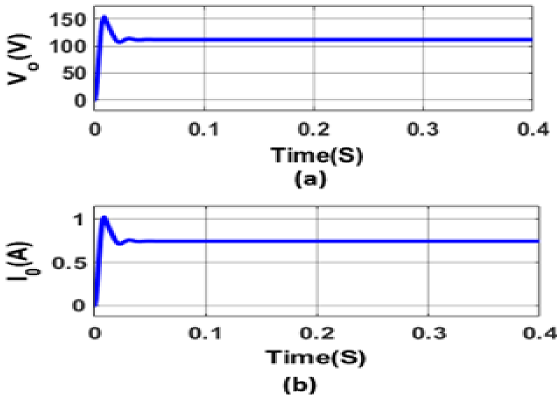

Fig. 6. (a) Output Voltage (V_0) and (b) Output Current (I_0)

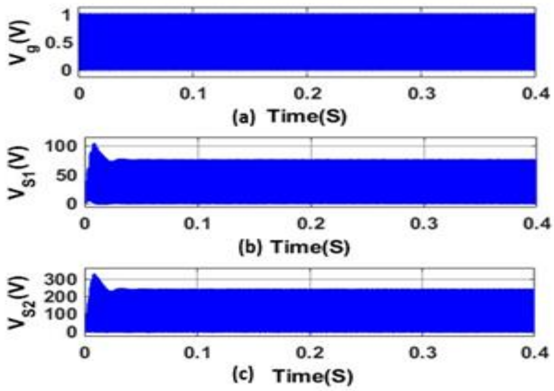

Fig. 7. (a) Gate Pulse of S_1 and S_2 and (b) voltage stress from V_{S1}, (c)Voltage Stress from S_2

- Fig. 7 & 8 shows the gate pulse and voltage stress across

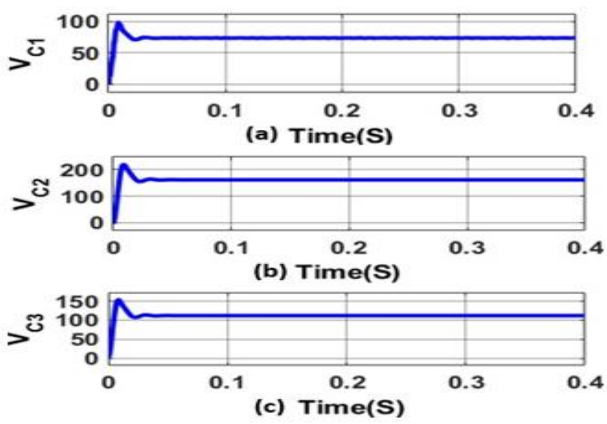

Fig. 8. Voltage across Capacitor (a) V_{C1}, (b) V_{C2} and (c) V_{C3}

IV. PERFORMANCE ANALYSIS

Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. Here the efficiency Vs output power with R load and RL load for S-L based quadratic converter is done and shown in Fig. 12. The maximum converter efficiency for R & RL load are obtained as 87.69% and 86% . The variation of efficiency with power

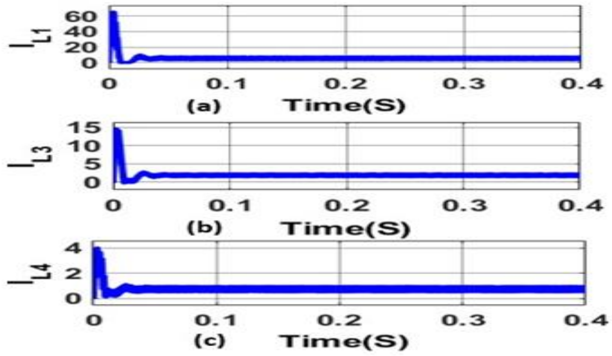

Fig. 9. Current across Inductance (a) i_{L1}, i_{L2} (b) i_{L3} and (c) i_{L4}

- output is medium for both load is about 83W. Thus, the S- L based quadratic converter can be used in medium power applications.

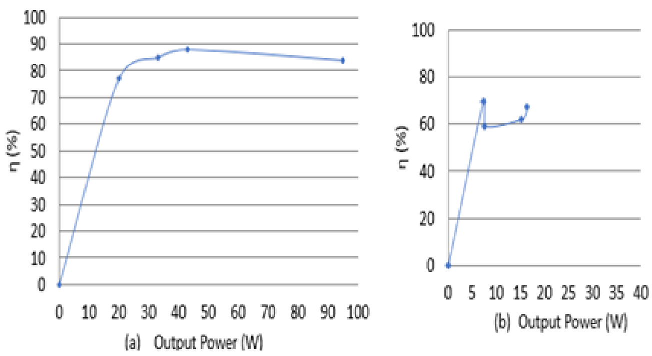

Fig. 10. Efficiency Vs Output Power for (a) R load, (b) RL load

- The plot of voltage gain VS duty ratio is shown in Fig. 11.The plot of output voltage ripple VS duty ratio is shown in Fig. 12. The plot of output voltage ripple VS frequency is shown in Fig. 13.

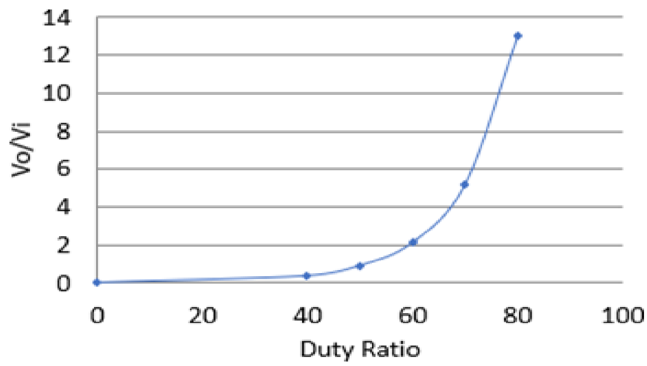

Fig. 11. Voltage Gain Vs Duty Ratio

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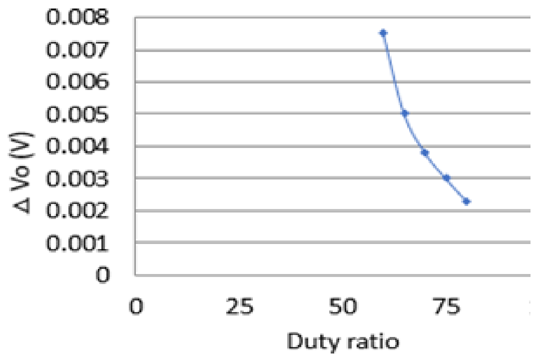

Fig. 12. Output Voltage Ripple Vs Duty Ratio

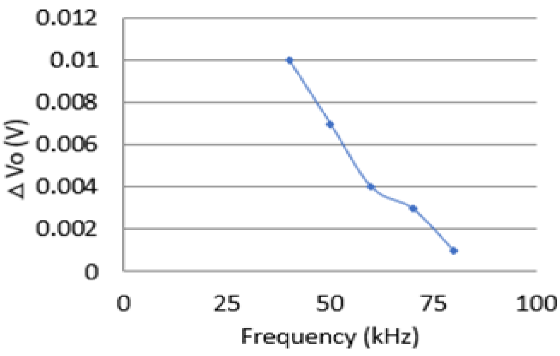

Fig. 13. Output Voltage Ripple Vs Frequency

V. COMPARITIVE STUDY

The comparison between switched inductor based quadraticconverter & enhanced gain buck-boost converter is given in table 2. On the comparison it can be observed that, keeping same values for input voltage 15V & switching frequency as 75kHz, the required output voltage is 111.2V for S-L based buck-boost converter and 75V for enhanced gain buck-boost converter. And voltage stress across switch is more in proposedconverter. Also, proposed converter have low output ripple than other converter.

Table 2 Comparison Between Enhanced Gain Buck-Boost Converter & Proposed Converter

Parameters	Enhanced Gain Buck-Boost Converter	Switched Inductor Based Quadratic Converter
Number of Inductors	3	4
Number of Switches	2	2
Number of Capacitors	3	3
Number of Diodes	2	2
Voltage Gain	5	7.48
Output Voltage Ripple	0.005V	0.003V
Efficiency	87.69	86.53
Output Current Ripple	0.00002A	0.00003A
Output Voltage	75V	111.2V
Voltage Stress Of Switches	48V,150V	74V,236V

- Table 3 shows the component wise comparison between S-L based quadratic converter & other converters. Comparison is based on the components used in the different converters. From table it can be observed that, the number of total components used in S-L based quadratic converter and other converters aresimilar.

Table 3 Comparison Between Switched Inductor Based Quadratic Converter & Other Converters

Parameters	DC-DC Converter [1]	DC-DC CONVERTER[2]	DC-DC CONVERTER[3]	Proposed Converter
Number of Switches	1	1	1	2
Number of Capacitors	2	5	2	3
Number of Inductors	2	3	3	4
Number of Diodes	3	3	4	5

VI. EXPERIMENTAL SETUP WITH RESULT

For the purpose of implementing hardware, the input voltage is reduced to 5V and the switching pulses are generated using TMS320F28335 controller. The switches used are MOSFET IRF540 & diodes are IN 5817. Driver circuit is implemented using TLP250H, which is an optocoupler used to isolate and protect the microcontroller from any damage and also to provide required gating to turn on the switch..

Experimental setup of S-L based transformer less buck-boost converter is shown in Fig. 13. Input 5V with 1.785A DC supply is given from DC source. Switching pulses are taken from TMS320F28335 connector panel to driver circuit. The switching pulse is shown in figure 14. Thus, according to analysis an output voltage of 31.29V is to be obtained from power circuit. Output voltage of converter will be taken from the DSO oscilloscope. .

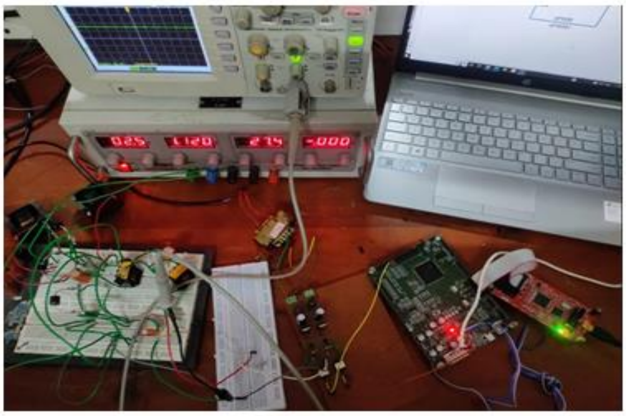
Fig. 14. Experimental Setup

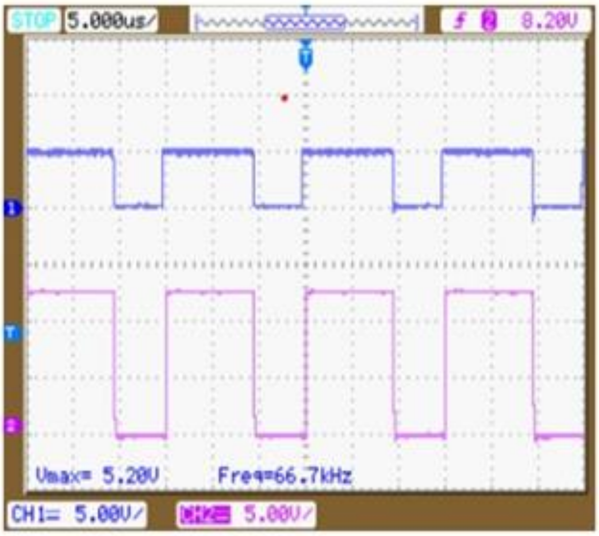

Fig. 15. Switching Pulse for switches

VII. CONCLUSION

A switched inductor based quadratic converter is proposed in this paper, which can work in a wide input voltage range. Switched inductor is the combination of a pair of equal valued inductors and multiple passive (diodes) elements. Thus this switched inductor concept is added to the quadratic converter so that it has characteristics of high gain, high integration, less switching losses and easy to control. The quadratic converter was derived by Cascading of inverting boost followed byrestructured ZETA converter. Moreover, the values of the boostinductors L1 & L2 and the capacitors can be designed to be very small so that the volume and the cost of the circuit are reduced. The S-L based quadratic converter has characteristicsof 1) high gain 2) minimal ripples at input and output side, and 3) common ground or positive output load voltage polarity The performance study and analysis of switched inductor based quadratic converter is carried out. From the simulation results the voltage gain & efficiency are improved and by using the SPWM strategy the modulation of switches is very simple and thus switching losses is reduced. Thus, these features make the presented topology an excellent interface for renewable energyapplications

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