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Switched Inductor Based Transformer less Buck-Boost Converter For Renewable Energy Application

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Abstract:- In recent years DC-DC converters have found wide applications in industry which have taken a special place with the expansion of the use of renewable energy sources. DC-DC converters with step-down/step-up voltage are required in many applications like electronic products, fuel cell systems, battery powered systems, portable devices, light emitting diode (LED) and electric vehicle. Therefore converters with high voltage con-version ratio, high efficiency, low cost and small size are needed. A switched inductor based converter achieves, high voltage ratio for applications that needs of high voltage, improves the effi-ciency and reduces voltage stress. The Switched Inductor based Transformerless Buck-Boost converter has continuous input and output current. The output voltage ripple of this converter is low and the voltage stress across switch and diodes are slight and lower than the converters output voltage. Results are obtained by simulating the converter in MATLAB/ SIMULINK R2021b. The simulation results shows that the Switched Inductor based Transformerless Buck-Boost converter has high voltage gain and achieves a peak efficiency of 96%.

Keywords:- *Buck-Boost Converter, Transformerless, Gain, Efficiency, Switched inductor.*

I. INTRODUCTION

The DC-DC converter systems have become very popular among the industries which have taken a special place with the expansion of the use of renewable energy sources. Renewable energy applications was introduced by various industries and markets globally by replacing the conventional energy resources. The use of renewable energy is gaining attention nowadays. Therefore converters[1] with high voltage conversion ratio, high efficiency, low cost and size are needed. Number of energy sources like PV and FC have low output voltage which requires high gain converters to regulate their output voltage. High gain DC-DC converters are classified into two groups isolated and non-isolated. A method to get high conversion ratios is to use isolated converters which they can be implemented utilizing coupled inductor or transformer. The traditional buck-boost converter is simplest buck-boost converter. The Cuk, ZETA[2], SEPIC[3] converters are the other basic buck-boost converters. Among these converters, the Cuk converter is special for its continuous output and input current and negative output voltage, the last option is used directly for audio amplifiers, signal generators and data transmission interfaces in applications needing a negative voltage source. In a transformerless buck-boost converter based on SEPIC converter is presented where one main switch is utilized in this converter but the number of storage elements is high. In a ZETA based non-isolated converter is suggested. It has a simple structure and high efficiency. Discontinuous input current is disadvantage of this converter. In a buck-boost converter based on Cuk is proposed. The voltage gain is high and the CCM operation mode is different from the proposed converter. In a multilevel Cuk converter is presented. The voltage gain of the converter is suitable for photovoltaic applications but the number of elements is high and implementation of converter will be difficult.

The conventional boost converter is not suitable for a very high voltage gain as it achieves high voltage gain at a high value of the duty cycle. A higher value of duty cycles mounts the problems for transient response [4], [5]. And Another demerit of the converters operation at extreme duty cycle is that enough time is not provided to transfer the stored energy of inductor and capacitor for a diode with reverse recovery time. The conventional boost converter (CBC) is reduced significantly at higher duty ratios because of voltage drops across diodes, switches, and equivalent series resistance of capacitors and inductors [6]. The converters efficiency depends on the number of the components present in the circuit, their conduction time as well as on switching frequency [7].

A switched inductor based transformerless[8] buck-boost converter is proposed in this paper. 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 transformerless buck-boost converter so that it has characteristics of high gain, high efficiency, high integration, few power devices, less switching losses and easy to control. In the proposed converter, there is only one switch that reduces stress of the components in the converter. Moreover, the proposed converter provides high gain with low ripple. This buck-boost converter can work in a wide input voltage range.

II. METHODOLOGY

The switched inductor (S-L) based transformerless buck-boost converter can be derived from the basic transformerless buck-boost converter by adding a switched inductor concept to increase the output voltage and thus by increasing the gain and efficiency of the converter. The switched inductor (S-L) based transformerless buck-boost converter consists of one power switch S, four inductors L_{11}, L_{12}, L_2 & L_3, four capacitors C_1, C_2, C_3 & C_0, load resistor R, five diodes D_{11}, D_{12}, D_{13}, D_1 & D_2. Figure 1 shows the switched inductor based transformerless buck-boost converter.

- Mode 1: At $t = t_0$, the switch S is turned on and diodes D_1 and D_2 are off. At this moment, the input DC power V_{in} charges the inductors L_{11} & L_{12} through diodes D_{11} & D_{13} and power switch S. The capacitor C_1 discharges and charges inductors L_2,L_2 and capacitors C_2, C_3. Thus supplies power to the load R. Figure 3.6 shows the operating circuit of mode 1.
- Mode 2: At $t = t_1$, the switch S is turned off and diode D_1 and D_2 are conducting. At this moment, both inductors L_{11} & L_{12} discharges and the capacitors C_2, C_3 charges. Figure 3.7 shows the operating circuit of mode 2.

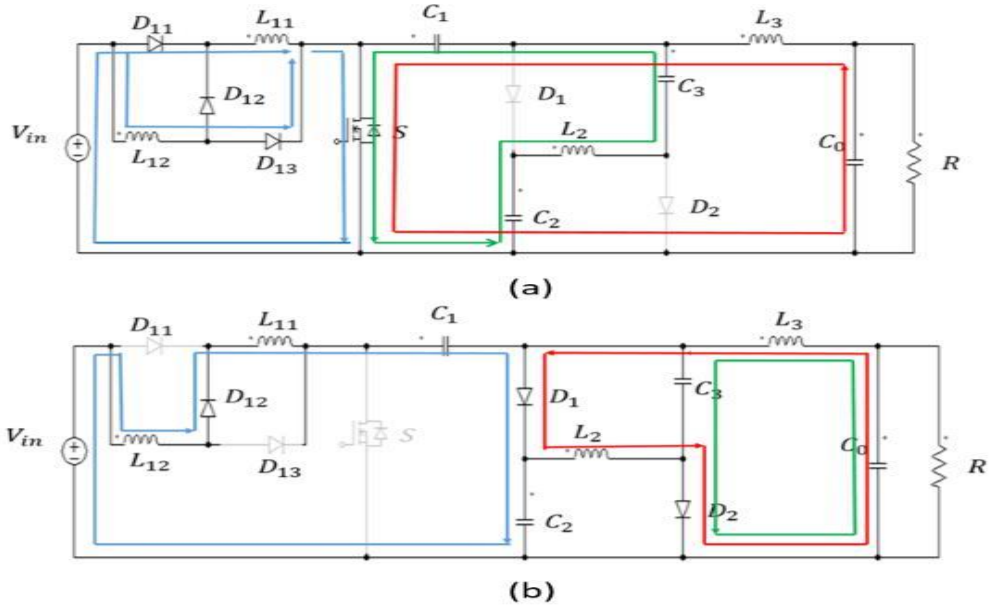

Fig. 1: S-L based Transformerless Buck-Boost Converter

A. Modes of Operation

The proposed converter operates in continuous current mode of boost inductor. There are two modes of operation. 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.

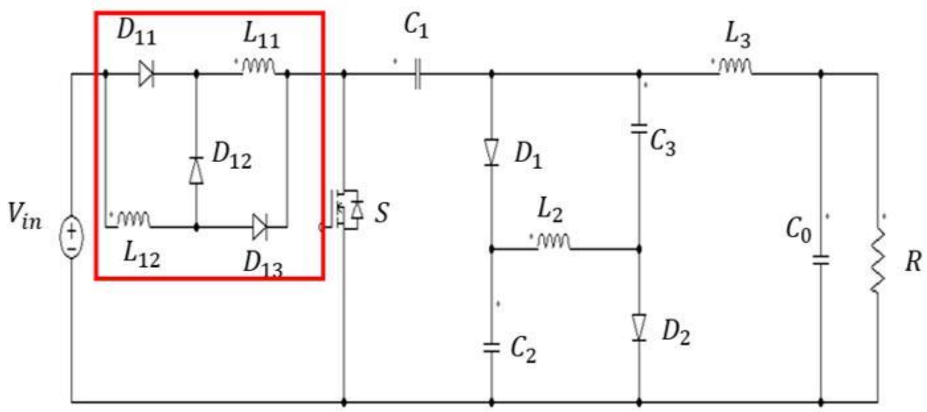

Fig. 2: Operating Modes. (a) Mode 1; (b) Mode 2

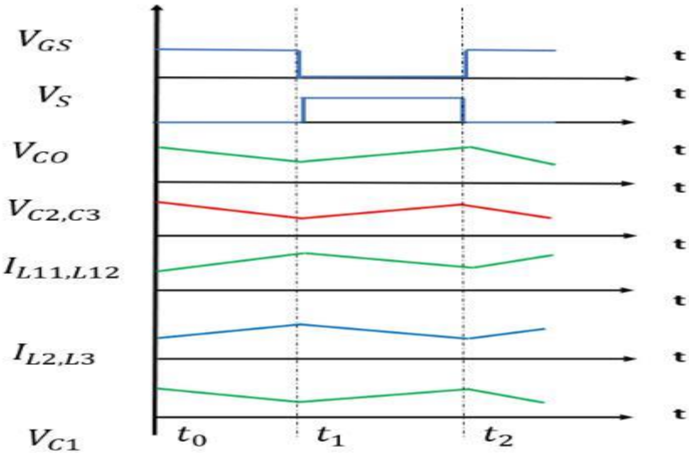

Fig. 3: Theoretical Waveforms of S-L based Buck-Boost Converter

B. Design of Components

In order to operate a converter properly, its components should be designed appropriately. Some assumptions are taken for the design of S-L based transformer less buck-boost con-verter. It consists of design of load resistance, inductors L_{11}, L_{12}, L_2 & L_3 and the capacitors C_1, C_2, C_3 & C_0. The input voltage is taken as 25V. The output power and output voltage are taken as 340W and 103.5V. Switching frequency is 40kHz. On solving (1) output current is obtained as 3.28A.

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

Duty Ratio can be found by (2) which is taken as 0.67. The

value of load resistor is set as 30 in (3).

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

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

The inductors L_{11} & L_{12} are obtained by taking current ripple as 40% of I_{L11}.

$$I_{L1} \ 1 = \frac{2DI_0}{1 \ D} \quad (4)$$

The inductors L_2 & L_3 are obtained by taking

$$I_{L2;L3} = I_0 \quad (5)$$

By substituting these values to (6) & (7) it is approximated 500 H for L_{11} & L_{12} and 800 H for L_2 & L_3

$$L_{11} >= \frac{D \ V_{in}}{f_s \ \ i_{L11}} \quad (6)$$

$$L_{2;3} >= \frac{D \ V_{in}}{f_s \ \ i_{L2;L3}} \quad (7)$$

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The design of the capacitor mainly considers the voltage stress and maximum acceptable voltage ripple across it. The capacitors C_1, C_2, C_3 & C_0 are obtained by taking voltage ripple as 1% of voltage across corresponding capacitors. By substituting values to (8), (9) & (10) capacitor values are approximated to 100 F for C_1,C_2,C_3 & 500 F for C_0.

$$C_1 >= \frac{D \; I_{C1}}{f_s \quad V_{C1}} \tag{8}$$

$$C_{2;3} >= \frac{D \; I_{C2;C3}}{V_{C2;C3} \; f_s} \tag{9}$$

III. SIMULATIONS AND RESULTS

The switched inductor based transformerless buck-boost converter is simulated in MATLAB/SIMULINK by choosing the parameters listed in Table 1. The switch is MOSFET with constant switching frequency 40kHz. 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 ex-pressed in familiar mathematical notation. SIMULINK is a software package for modelling, simulating, and analysing dynamical systems.

A dc input voltage of 25V gives an dc output of 103.5V. Figure 4 shows the input voltage and current. Figure 5 shows the output voltage and current. Figure 6 shows the gate pulse and voltage stress across switch S. The voltage stress of switch S is 90V.

Parameters	Specification
Input voltage V_{in}	25 V
Output voltage V_o	103.5 V
Inductor L_{11}, L_{12}	500µH
Inductor L_2, L_3	800 µH
Capacitor C_1	100 µH
Capacitor C_2 , C_3	100 µF
Capacitor C_O	500 µF
Switching frequency	40 kHz
Output load	30 Ω
Duty ratio (buck mode)	25 %
Duty ratio (boost mode)	60 %

Table 1: Simulation Parameters Of S-L Based Transformerless Buck-Boost Converter

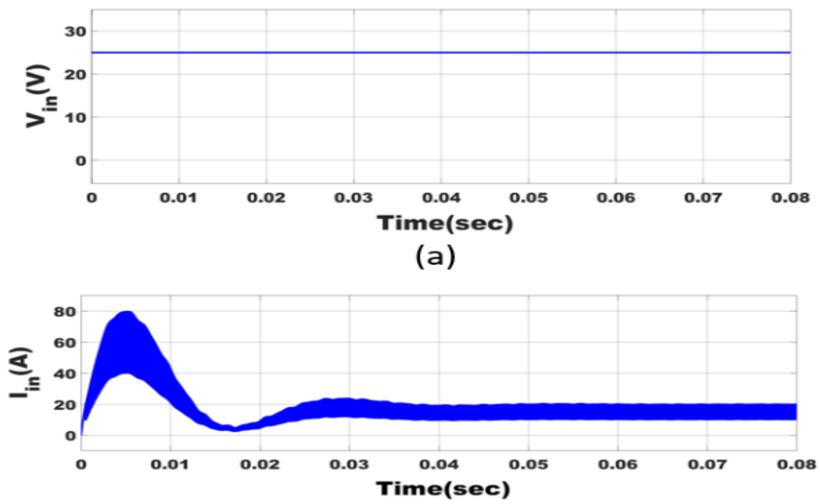

Fig. 4: (a) Input Voltage (V_{in}) and (b) Input Current (I_{in})

$$C_0 = \frac{V_0 \quad (1 \quad D)}{16\, L_3 \quad V_{C0} \quad (f_s)^2} \qquad (10)$$

The voltage across capacitors V_{C1} is 139.7V ,V_{C2} & V_{C3} is obtained as 50.3V each which is shown in Figure 7. Figure.8 shows the current across inductances L_{11}, L_{12}, L_2 & L_3. It can be seen that the current across inductances I_{L11}=I_{L12} is 9.74A, I_{L2} is 2.834A & I_{L3} is 2.94A

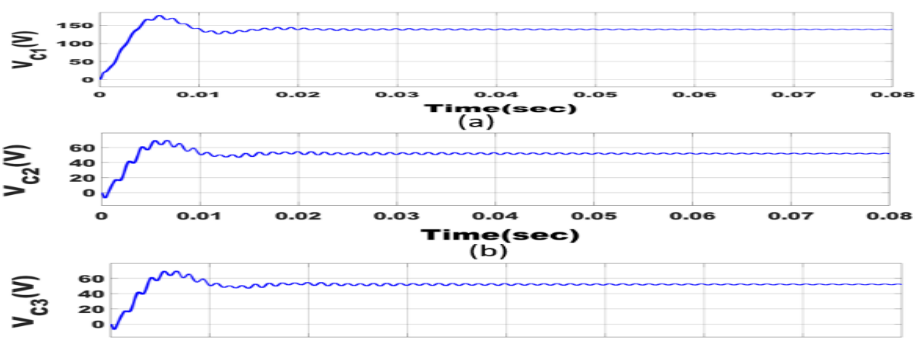

Fig. 5: Voltage across Capacitor (a)VC1, (b)VC2

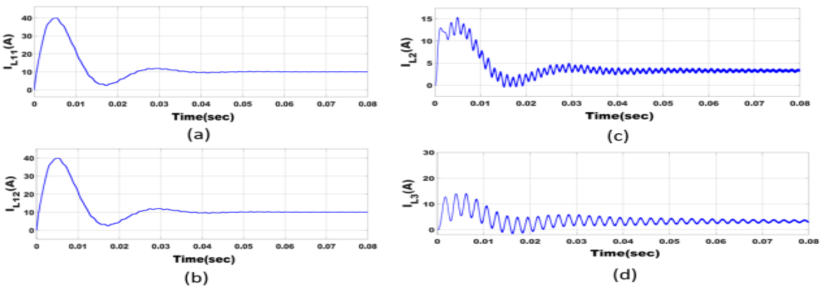

Fig. 6: Current across Inductance (a)I_{L1}, (b)I_{L2}

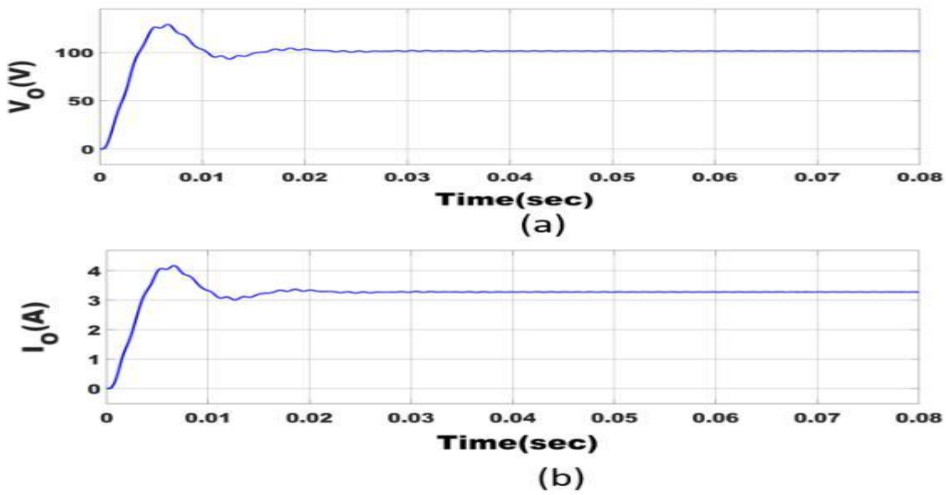

Fig. 7: (a) Output Voltage (V_0) and (b) Output Current (I_0)

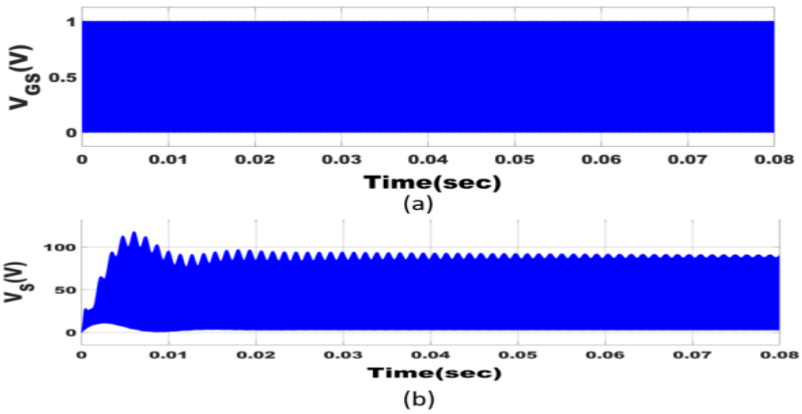

Fig. 8: (a) Gate Pulse of S (b) Voltage Stress of S(V_S)

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 transformerless buck-boost converter is done and shown in Fig. 9. The maximum converter efficiency for R & RL load are obtained as 96% and 97% . The variation of efficiency with power output is medium for both load ie about 350 W.

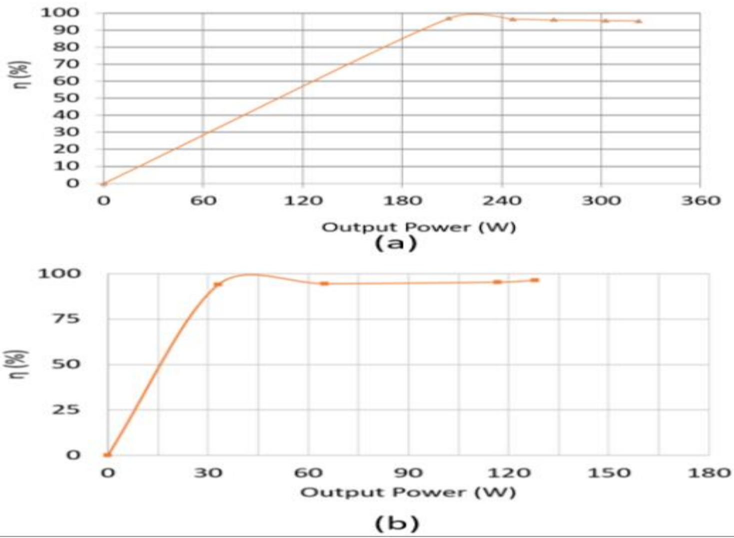

Fig. 9: Efficiency Vs Output Power for (a) R load, (b) RL load

The plot of Voltage gain VS duty ratio is shown in figure 10.The plot of Output voltage Vs duty ratio is shown in figure The plot of Output voltage ripple Vs Frequency is shown in figure 12.

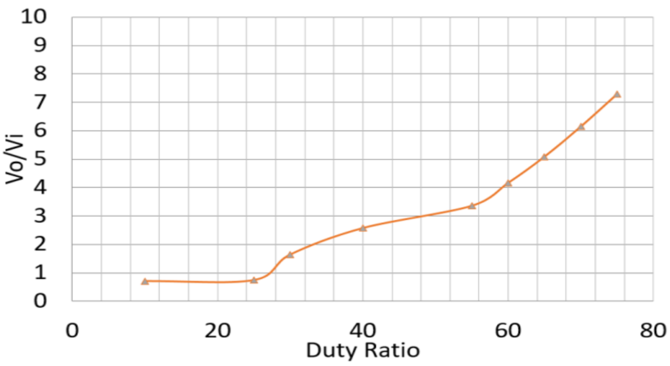

Fig. 10: Voltage Gain Vs Duty Ratio

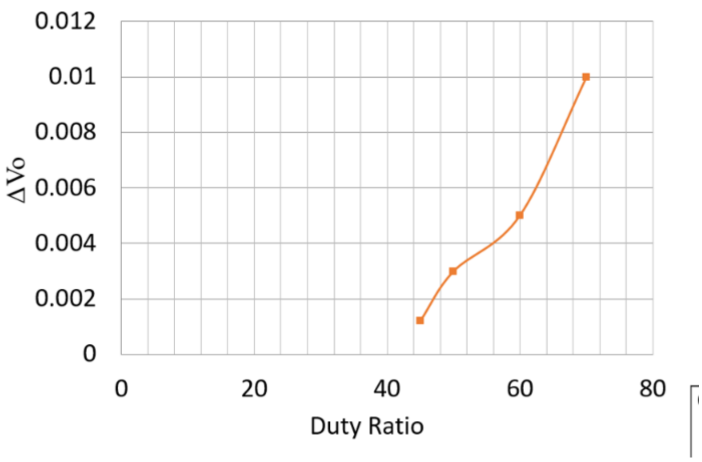

Fig. 11: Output Voltage Ripple Vs Duty Ratio

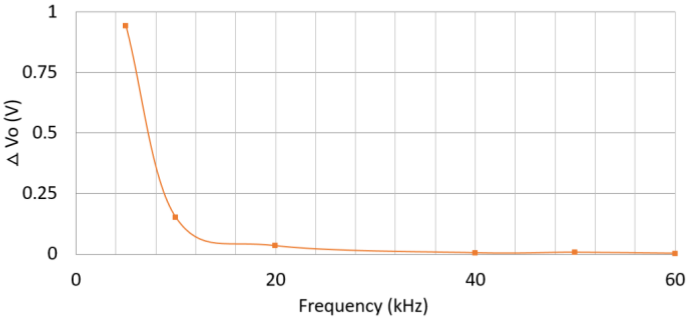

Fig. 12: Output Voltage Ripple Vs Frequency

V. COMPARITIVE STUDY

The comparison between switched inductor based trans-formerless buck-boost converter & transformerless buck-boost converter is given in table 2. On the comparison it can be observed that, keeping same values for input voltage 25V

& switching frequency as 40kHz, the required output volt-age is 103.5V for S-L based buck-boost converter and 70V for transformerless buck-boost converter. And voltage stress across switch is more in proposed converter. Also, proposed converter have low output ripple and high efficiency than other converter.

Parameters	Transformerless Buck-boost converter	Switched inductor based transformerless buck-boost converter
No. of switches	1	1
No. of inductor	3	4
No. of capacitor	4	4
Voltage gain	2.799	4.12
Efficiency	94%	96%
Output Voltage Ripple	0.006 V	0.005V

Table 2: Comparison Between Transformerless Buck-Boost Converters Proposed Converter

Table 3 shows the component wise comparison between S-L based transformerless buck-boost 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 transf.

Converters	Transformerless Buck-Boost converters	SEPIC based single switch buck-boost	ZETA Converter based on Buck-Boost Converter	Single-switch buck-boost (SSBB) converter	Two-switch buck-boost (TSBB) converter	Switched inductor based buck-boost converter
Switches	1	1	1	1	2	1
Inductors	3	4	3	1	1	4
Capacitors	4	6	4	1	1	4
Diodes	2	3	2	1	2	5

Table 3: Comparison Between S-L Based Transformerless Buck-Boost Converter & Other Converters

VI. EXPERIMENTAL SETUP

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 transformerless buck-boost converter is shown in Fig. 13. Input 5V with 1.645A 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 16.45V is to be obtained from power circuit. Output voltage of converter will be taken from the DSO oscilloscope.

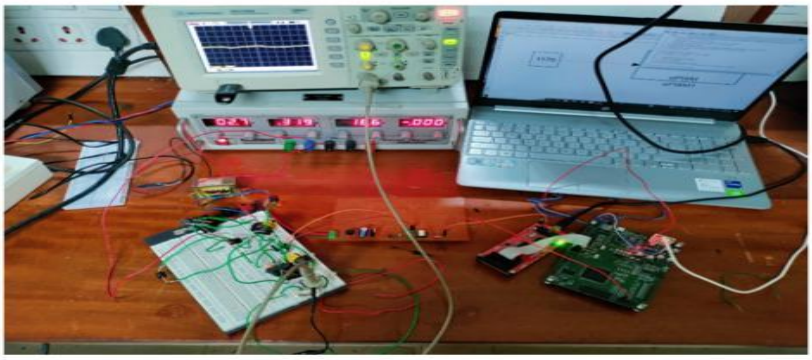

Fig. 13: Experimental Setup

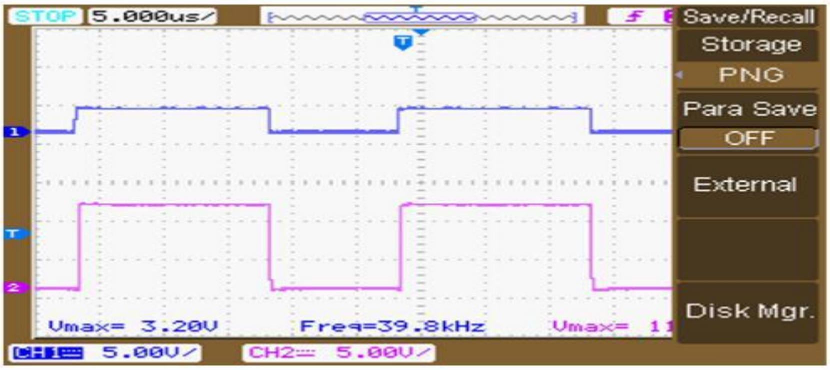

Fig. 14: Switching pulse for S

VII. CONCLUSION

A switched inductor based transformerless buck-boost con-verter is proposed in this report, 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 transformerless buck-boost converter so that it has char-acteristics of high gain, high efficiency, high integration, few power devices, less switching losses and easy to control. In the proposed converter, there is only one switch that reduces stress of the components in the converter. Moreover, the proposed converter provides high gain with low ripple. In addition, val-ues of the boost inductors L_{11} & L_{12} 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 buck-boost converter has characteristics of high gain, high integration, high efficiency and low output voltage ripple. The performance study and analysis of transformerless buck-boost 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 energy applications.

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