IJCRT.ORG ISSN : 2320-2882
INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

SWITCHED INDUCTOR BASED SINGLE STAGE TRANSFORMERLESS BUCK-BOOST INVERTER WITH VIRTUAL GROUNDING

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Abstract: Single stage inverters are gaining more popularity in the applications like electric vehicles, micro grids, uninterrupted power supplies and photovoltaic. Compared to the conventional isolated inverters, the transformerless inverter topologies are becoming a new trend due to its compact size, reduced weight and higher efficiency. Generally transformerless inverters have a missing in galvanic isolation, which may raise grounding and protection concerns, in turn results in the common mode leakage current. In order to reduce the leakage current and to improve the gain, a switched inductor based single stage transformerless buck-boost inverter with virtual grounding is introduced. The inverter can perform both buck and boost functions so that the output can be kept constant. High conversion efficiency can be realized because only one switch is operated at high frequency. Through a simple SPWM technique the control of inverter topology is simulated using MATLAB/Simulink R2017b for an output power of 500W. The inverter is controlled using TMS320F28027F. The experimental results obtained from a 6.5W inverter prototype confirm the theoretical considerations and the simulation results.

***Index Terms* - Virtual grounding, Buck-boost inverter, Switched inductor.**

I. INTRODUCTION

In this era of environmental crisis caused due to the excessive use of conventional sources, is now constantly calling for higher usage of eco-friendly and sustainable means for producing electricity. Problems due to the fossil fuels based electricity generation techniques demand new sources of energy for an alternative way of electricity generation [9]. The use of renewable energy sources has an advantage of non pollution, high reserve etc. Photovoltaic inverters are now widely used in both residential and industrial applications like uninterrupted power supplies, static frequency changers and variable speed drives. The output voltage of renewable energy sources may vary greatly. The dc output voltages from the PV panels are normally low, fluctuating and are not sufficient to drive the system. It can be either high or low depending upon the climatic condition and amount of energy received. Therefore, to compensate for the variance of renewable energy source voltage, the inverter systems need to have buck-boost dc-ac power conversion capability [4]. For this purpose single stage or multi-stage inverters have been introduced. In case of multi-stage inverters the boost converters are cascaded with the voltage source inverters. This cascading leads to bulkier system, whereas in single stage inverters both boosting and DC to AC conversion is done in a single stage thereby reducing the overall size.

As the output from the renewable energy sources changes in a wide range, in order to regulate an inverter output voltage in systems having wide input dc voltage variation, a buck-boost power conditioning system is preferred [2]. As the conversion ratio of the system increases, the number of input sources to be used can be reduced. For this purpose of improving gain many topologies are emerging. Z source inverter [7] with impedance network provides an efficient means of power conversion between source and load in a wide range of electric power conversion applications. Improvements to the impedance networks are made by introducing coupled magnetic to provide higher voltage boosting. The other method to improve the gain is interleaving inverters [5] parallel or in series to achieve system-level objectives and cost reductions. This method provides the benefits of low distortion in ac output current, reduction in filtering component, higher efficiency.

With reference to the above mentioned papers a switched inductor based single stage transformerless buck boost inverter is introduced which can realize a higher quality AC output with improved gain. The inverter provides both buck and boost operation in order to make it applicable for photovoltaic applications. The inverters avoids the leakage current by making use the concept of virtual grounding [1] in which the capacitors provides a low impedance path and are virtually connected to the negative terminal of the source to the grounding of load. The proposed topology can achieve features like lower switching stress, absence of shoot through problem, lower THD and higher efficiency.

II. CIRCUIT TOPOLOGY OF PROPOSED INVERTER

The switched-inductor based single stage transformerless buck-boost inverter consists of a gain enhancement circuit in the input side. In order to improve the gain the inductors are charged parallel and discharged in series. The inverter consists of five active switches. Switch S_1 operates in high frequency and all other switches operate in line frequency. Fig. 1 shows the switched-inductor based single stage buck-boost inverter.

The switches S_1, S_4, S_5 have unidirectional voltage blocking capability and can flow current in both direction. The switches S_2 and S_3 flows current in single direction. Therefore it is implemented with power MOSFET in series with diode. In order to avoid the leakage current, the capacitor provides a low impedance path and virtually connects the negative terminal of source to the ground of load.

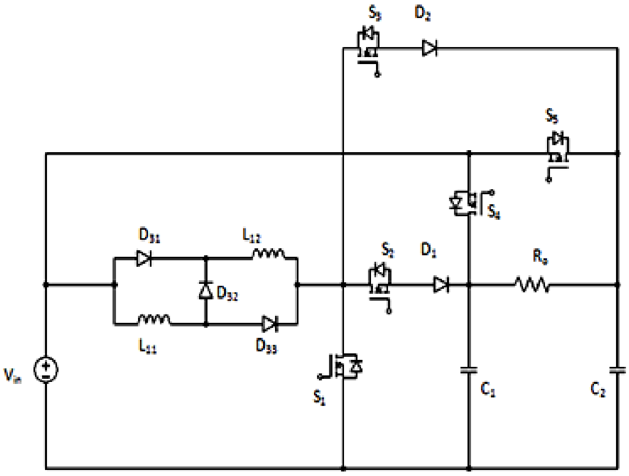


Fig.1 Switched-Inductor Based Transformerless Buck-Boost Inverter

2.1 Modes of Operation

The switched-inductor based single stage buck-boost inverter consists of five switches. The switch S_1 operates in high frequency and switches S_2, S_3, S_4, and S_5 operates in line frequency. The switches S_2 and S_5 are turned ON during positive half cycle whereas S_3 and S_4 turned ON at negative half cycle.

Mode 1 operation

In this mode, switches S_1, S_2 and S_5 are ON. Voltage across capacitor C_2 is clamped to V_{IN}. The capacitor C_1 supplies energy to the load. At the time the inductors are connected to the source and are charged parallel through the diodes D_{31} and D_{33}. Fig. 2(a) shows the equivalent circuit diagram of the inverter and current paths for this mode.

Mode 2 operation

In this mode, switches S_2 and S_5 remains ON and S_1 is turned OFF. Voltage across C_2 is clamped to V_{IN}. The inductors L_{11} and L_{12} connected in series through diode D_{32} transfers the stored energy to C_1 and load. Fig. 2(b) shows the equivalent circuit diagram of the inverter and current paths for this mode.

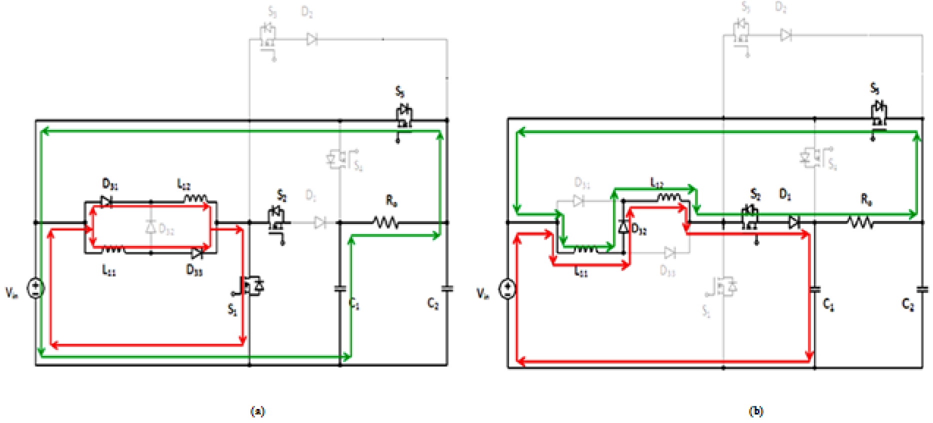


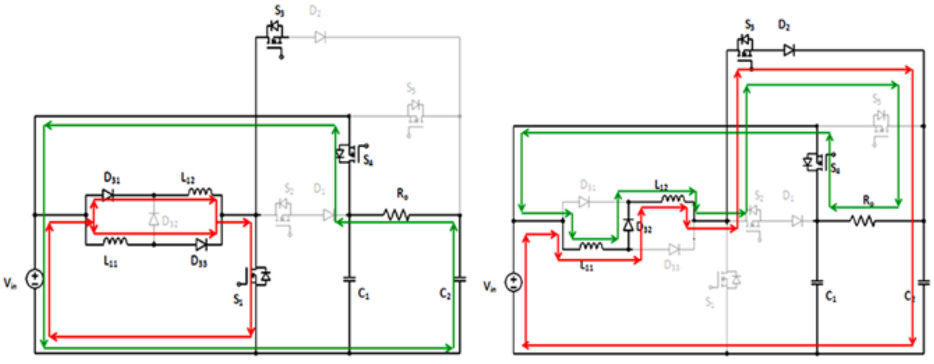
Fig.2 Operating Modes (a) Mode 1 (b) Mode 2

Mode 3 operation

During this mode, the switches S_1, S_3 and S_4 are turned ON. Voltage across the capacitor C_1 is clamped to V_{IN}. The capacitor C_2 supplies energy to the load. At the time the inductors are connected to the source and are charged parallel through the diodes D_{31} and D_{33}. Fig. 3(a) shows the equivalent circuit diagram of the inverter and current paths for this mode.

Mode 4 operation

During this mode, the switches S_3 and S_4 remain ON. S_1 is turned-OFF. Voltage across the capacitor C_1 is clamped to V_{IN}. The inductors L_{11} and L_{12} connected in series through diode D_{32} transfers the stored energy to C_2 and load. Fig. 3(b) shows the equivalent circuit diagram of the inverter and current paths for this mode.



(a) (b)

Fig.2 Operating Modes (a) Mode 3 (b) Mode 4

2.2 Design of Components

For operating the inverter efficiently, its components must be designed properly. The input voltage of 42V-250V is taken. The pulses of switch S_1 are switched at the rate of 50 kHz and all other switching pulse is at 50Hz. The duty ratio of switch S_1 is denoted as D. Through the proper gate pulse generation, the duty ratio is obtained as in eqn.1.

$$D = \frac{V_o \sin\omega t}{V_{in} + V_o \sin\omega t} \qquad (1)$$

Thus the maximum duty ratio of switch S_1 is eqn.2.

$$D_{max} = \frac{V_o}{V_{in} + V_o} \qquad (2)$$

Voltage gain, G is given as eqn.3.

$$G = \frac{V_o}{V_{in}} \qquad (3)$$

From eqn.2 and eqn.3 the conversion ratio can be derived as eqn.4

$$G = \frac{D_{max}}{1 - D_{max}} \qquad (4)$$

The filter capacitance are designed in such a way to reduce the voltage ripple and keep leakage current low. Therefore the output voltage ripple can be taken as 6% of output voltage. During the positive cycle of V_O and for duty ratio D, the current through the filter capacitor C_1 equals to the output current I_O. Similarly, during the negative cycle of V_O and for duty ratio D, the current through the filter capacitor C_2 equals to the output current I_O. A the duty ratio is varied with respect to time, the capacitance value can be taken in terms of maximum duty ratio as eqn.5,

$$C_1 = C_2 \geq \frac{V_o * D_{1max}}{\Delta V_o * f_s * R_o} \qquad (5)$$

From mode analysis, the inductors are charged in parallel through input source and hence depend on the duty ratio, current ripple and frequency. The current ripple can be taken as 10\% of the inductor current. Hence the value of inductors can be taken as eqn.6

$$L_{11} = L_{12} = \frac{V_o}{\Delta I_L * f_s * (1+G)} \qquad (6)$$

2.3 Pulse Generation

The switch S_1 operates at high frequency and other switches operate at line frequency. During the positive half cycle of V_O, the switches S_2 and S_5 are turned ON and turned OFF at negative half cycle. Similarly, during the negative half cycle of V_O, switches S_4 and S_3 are turned ON and turned OFF at positive half cycle. Fig. 4 shows the block diagram for gate pulse generation. The power switches of the inverter are based on sinusoidal pulse width modulation technique. The reference signal is initially rectified and added with a constant resulting in a DC biased rectified signal. This signal is compared with the repeating carrier to generate the gate pulse of switch S_1.

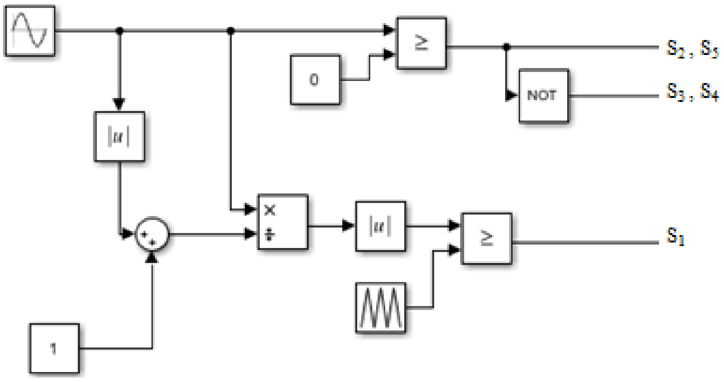


Fig. 4 Pulse Generation Circuit

III. SIMULATION RESULTS

In order to analyze the performance of the switched inductor based buck-boost inverter, simulation in done in MATLAB/SIMULINK for an output power of 500W. The simulation parameters are shown in table.1

Table.1 Simulation Parameters

Parameters	Specification
Input voltage (V_{in})	44 V– 250V
Output voltage (V_0)	155 V
Switching frequency (f_s)	50 kHz
Rated output power (P_0)	500 W
Inductor (L_{11}, L_{12})	0.3 mH
Filter Capacitor (C_1, C_2)	14 µF
Input Capacitor (C_{in})	4.1 mF

Both buck and boost operation is analyzed and the corresponding result are obtained. In boost mode, for an input of 42V, the output of 155.58V with current 6.48A is obtained. In buck mode, for an input of 250V, the output of 155.5V with current 6.45 is obtained. Fig. 5 shows the input and output waveforms in boost mode and Fig. 6 shows the input and output waveforms in buck mode.

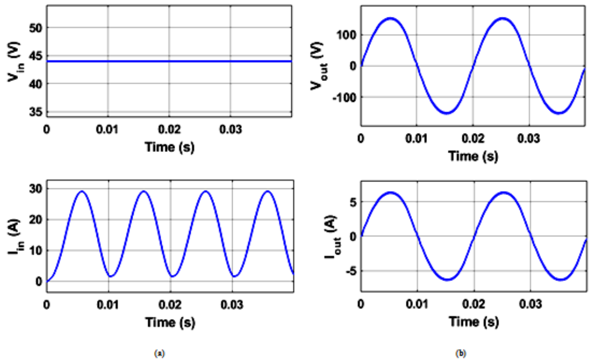


Fig.5 Boost (a) Input voltage and current
(b) Output voltage and current

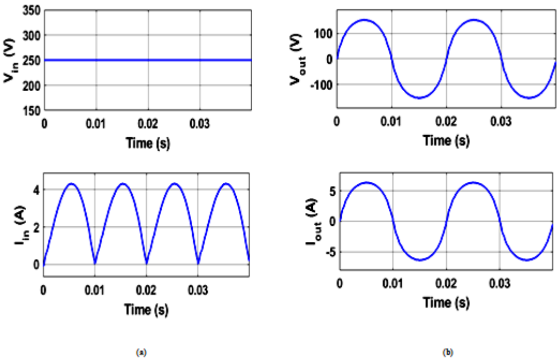
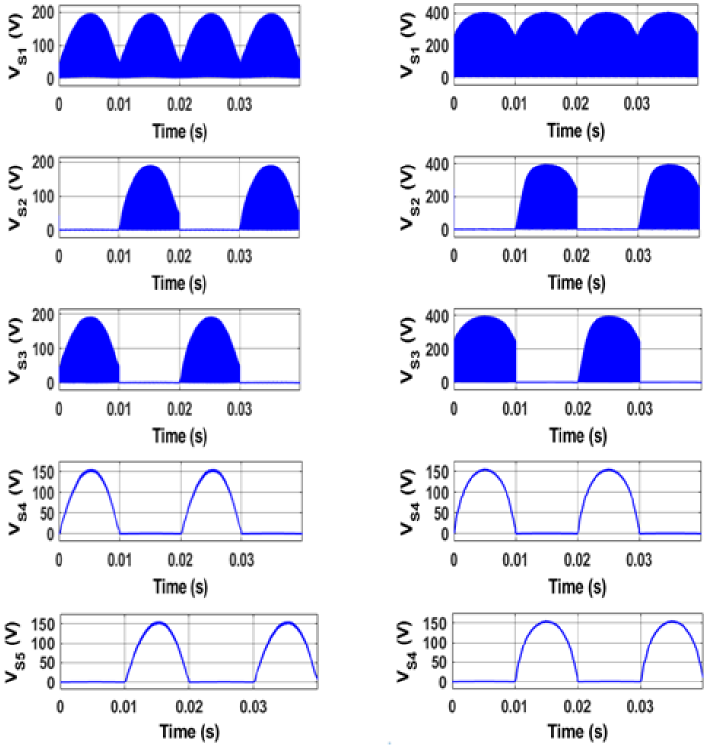


Fig.6 Buck (a) Input voltage and current
(b) Output voltage and current

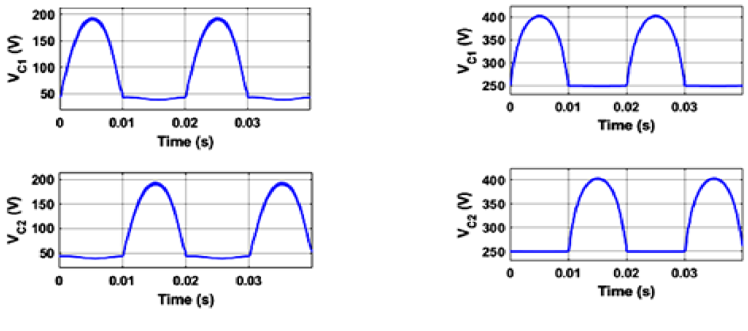
In boost mode, the stress across the switches as nearly equal to 1.24 times the output voltage and in buck mode t is nearly 2.4 times the output voltage. Fig. 7 shows the voltages across switches in both buck and boost mode.



(a) (b)

Fig.7 Voltage across switches (a) Boost mode (b) Buck mode

The voltage across filter capacitors is shown in Fig. 8. The capacitors charges from input voltage to $V_{in} + V_o \sin\omega t$.

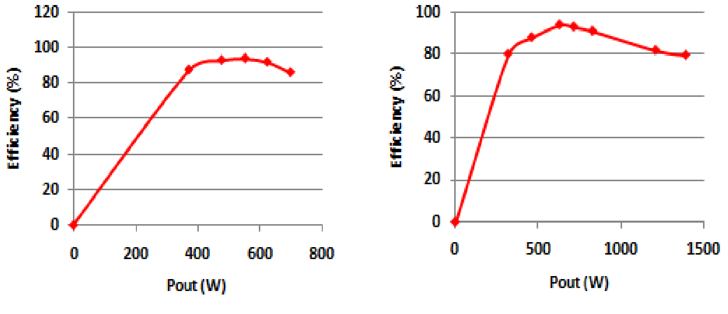


(a) (b)

Fig.8 Voltage across capacitors (a) Boost mode (b) Buck mode

IV. PERFORMANCE ANALYSIS

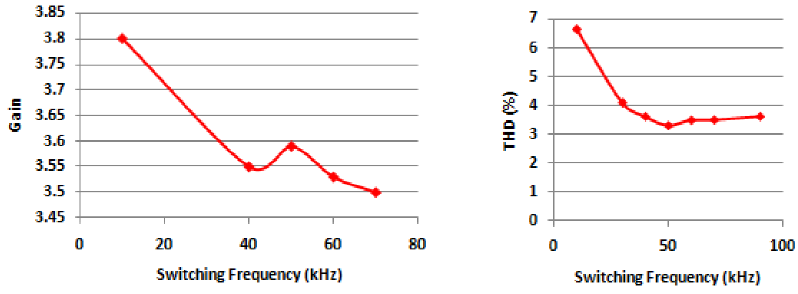
The analysis of the switched inductor based single stage buck boost inverter is carried out by considering the parameters like efficiency, total harmonic distortion and switching frequency. Efficiency of power equipment is defined at any load as the ratio of the power output to the power input. The efficiency tells us the fraction of the input power delivered to the load. Fig. 9 shows the graph between efficiency and output power for R load and RL load.



(a) (b)

Fig.9 Efficiency vs output power (a) RL load (b) R load

The maximum efficiency attained by the proposed inverter is around 94.5% for an output power of 500W for R load and 94.8% for RL load for an output power of 470W. The plot for gain for various switching frequency is shown in Fig.10 (a). It is observed that the switched inductor based buck boost inverter has a higher range of gain values for different switching frequencies. The plot of total harmonic distortion for various switching frequency is shown in Fig. 10 (b). The total harmonic distortion decreases as the switching frequency is varied. The inverter has an THD of 3.42% for a frequency of 50kHz. Even though there is slight increase in the THD, the value of is within the specified IEEE standard. The obtained THD with filters in buck mode is 12.08%. Absence of DC component has added the quality of inverter output.



(a) (b)

Fig.10 (a) Gain vs switching frequency (b) THD vs switching frequency

V. STABILITY ANALYSIS

For the analysis of the stability of the proposed inverter, the transfer function of the inverter is obtained by considering the four modes and the corresponding mathematical equations. For the open loop system, the transfer function is obtained as eqn.7.

$$G(S) = \frac{-0.828s^3+3.714e^8s^2+1.827e^{12}s+2.239e^{15}}{s^4+9838s^3+3.626e^7s^2+5.932e^{10}s+3.635e^{13}} \qquad (7)$$

A fourth order equation with 3 zeros and 4 poles are obtained. The poles lie on the left half of s-plane. Hence the system is said to be stable. Fig. 11 shows the bode plot for eqn.7

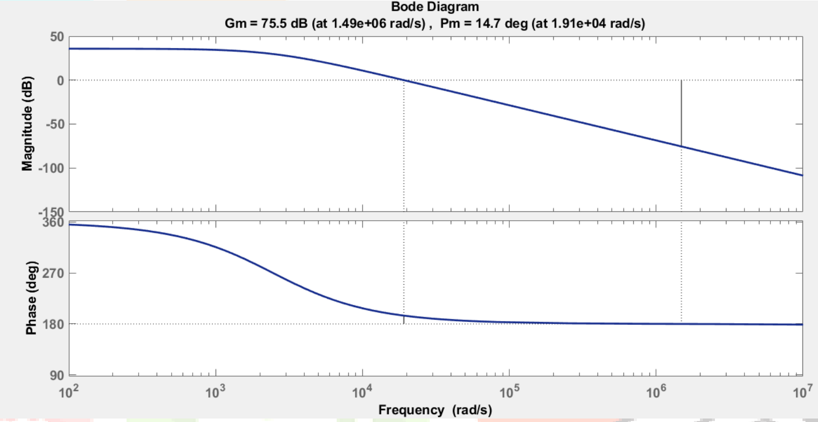


Fig.11 Bode Plot of Proposed Inverter

From the bode plot, it can be inferred that the system offers a gain margin of 75.5dB and phase margin of 14.7 degree. Also the gain crossover frequency is less than phase crossover frequency. Hence it is evident that the system is stable.

VI. COMPARITIVE ANALYSIS

Table.2 Comparison between Transformerless Inverter and Proposed Inverter

Parameters	***Buck boost inverter [1]***	***Proposed inverter***
Switches	5	5
Inductors	1	2
Gain	1.85	3.53
Stress across switch S_1	$1.6V_o$	$1.27V_o$
THD	3.27 %	3.42 %

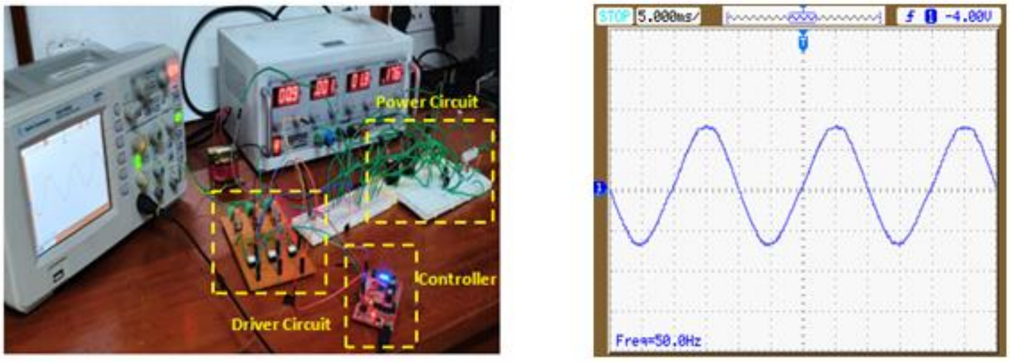
The comparison between transformerless single stage buck boost inverter [1] with the proposed switched inductor based buck boost inverter is done by keeping maximum output voltage as 155V with a switching frequency of 50 kHz. Table.2 shows the corresponding comparison. The stresses across the switches are reduced in case of switched inductor based single stage buck boost inverter with an improved gain. Table.3 shows the comparison between different buck boost inverters on the basis of number of components. It is evident from the table that number of components used in the switched inductor based single stage transformerless buck boost inverter is less.

Table.3 Comparison between Different Buck-Boost Inverters and Proposed Inverter

Parameters	*Switches*	*Inductor*	*Capacitor*
Proposed inverter	5	2	3
Buck boost inverter [1]	5	1	3
Buck boost inverter [2]	8	4	3
Buck boost inverter [3]	4	6	3
Dual buck inverter [10]	4	7	3
Dual Boost inverter [11]	6	2	2

VII. EXPERIMENTAL SETUP WITH RESULTS

For the purpose of hardware implementation, the input voltage is reduced to 5V and the switching pulses are generated using TMS320F28027F processor. Driver circuit is implemented using TLP250H, which is an opto-coupler that isolates and protect the microcontroller from any damage in addition provides required gating to turn on the switches. Fig. 12 shows the experimental setup and the corresponding output waveform.



(a) (b)

Fig. 12 (a) Experimental setup (b) Output Voltage

The output of 16.2V, 50Hz is obtained by drawing an input current of 0.181A.

VIII. CONCLUSION

A switched inductor based single stage transformerless buck boost inverter with low leakage current 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 3.53. The leakage current is reduced by keeping the voltages across the capacitors either constant or varying sinusoidal with line frequency. Buck and boost operation by varying the duty ratio, thereby providing a constant output voltage even in varying input has made application wider. Lower voltage and current stress across the switches when compared with other topologies aids the inverter advantage. For a power of 500W, the system provides an efficiency of 94% with total harmonic distortion (THD) of 3.42%. The control of the proposed inverter is implemented using TMS320F28027F microcontroller. Inverter prototype of 6.5W provides the expected performance with an output voltage of nearly 16V, considering the drop across the components. The overall analysis confirms that the proposed inverter can be used in applications such as photovoltaic, micro grids , electric vehicles.

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