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TRANSFORMERLESS GRID-CONNECTED BOOST INVERTER WITHOUT SHOOT-THROUGH PROBLEM

[1]Meera Mohan, [2]Beena M Varghese, [3]Dr. Bos Mathew Jos, [4]Smitha Paulose, [5]Eldhose K A

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

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

Abstract: The photovoltaic (PV) power systems have become very popular among the renewable energy sources. As output of the PV array is DC voltage and the grid voltage is AC voltage, the grid-connected inverter is used as an interface between them. Compared to the isolated inverters, transformerless PV inverters are most preferred because of lower cost, smaller size, and higher efficiency. As applications of non- conventional source of energy is low in buck inverter, a transformerless grid-connected boost inverter is proposed with the combination of a boost converter and a buck- boost converter. Thus, boost function can utilize optimum amount of input source and used in wide range of applications. As grounds of the PV array and the grid are shorted, the common mode leakage current can be eliminated. The inverter consists of 5 switches and the control strategy is based on sinusoidal pulse width modulation technique (SPWM). The performance study of transformerless grid-connected boost inverter is carried out with MATLAB / SIMULINK R2017b platform for an output power of 350W. Finally, output voltage of the inverter is obtained as 110V with an input voltage of 65V with THD 6.5% and efficiency 97%. The control circuit used is dSPACE ds1104 controller. This inverter can be used in the grid connected PV applications.

Index Terms **- Boost Inverter, Transformerless, Gain, Efficiency, THD**

I. INTRODUCTION

Grid- connected inverters are widely used in the microgrid and distributed power generation system. Transformerless PV grid-connected inverters are more preferred because of lower cost, smaller size, and higher efficiency compared with the isolated grid-connected inverters. Here, the output is a buck function so gain and eficiency is less compared to boost function and applications are also less in buck converters. The transformerless PV grid- connected inverter with boost function[1] has boost capability, so the power generated by the PV panel can be fully utilized under shading condition. But more number of components are used and control strategy is difficult hence voltage stress across switches is very high. The non-isolated PV inverters has issue of common mode leakage current, which may cause problems of personal safety, severe electromagnetic interference, distorted grid current, and extra loss. Here also SPWM control strategy is used [2]. A Doubly Grounded Transformerless PV Grid-Connected Inverter [3] consists of a buck converter and a buck-boost converter, which operates at positive and negative half cycles, respectively. There is no shoot-through problem in this inverter, so dead-time in gate signals is not required. The common mode leakage current can be eliminated by shorting the grounds of PV array and the grid. Here, the output is a buck function so gain and eficiency is less compared to boost function and applications are also less in buck converters. A single stage transformerless PV gridconnected inverter [4] is the combination of two boost and one buck converters. As the ground of the grid is directly connected to the cathode or anode of the PV panel, there is no common mode leakage current and inverter has boost capability, so the power generated by the PV panel can be fully utilized under shading condition. But more number of components are used and control strategy is difficult. Thus circuit has more weight and voltage stress across switches is very high. A Transformerless Grid-Connected PV Inverter [5] consists of a buck-boost converter and a dual-buck half-bridge inverter, so there is no shoot-through problem, as grounds of the input source and the grid are shorted, there is no common mode leakage current. Effect on the reduction of the leakage current is affected by the environmental conditions and parameters of power devices. Here, reliability of system is improved but have high input voltage and high grid current. A Two-Switch Dual-Buck Grid-Connected Inverter [6] having all switches and diodes operate at each half line cycle, and the freewheeling current flows through the independent freewheeling diodes instead of the body diodes of the switches, so the efficiency can be increased potentially. As the shoot-through problem does not exist in the DBFBI, dead time between the switches need not be set. The input voltage utilization rate of the DBFBI is twice that of the DBHBI under the same output-voltage condition, i.e., the voltage stress of the power device in DBFBI is half that in the DBHBI. Here, unipolar modulation is used and there is absence of inrush current. A H6 transformerless Full-Bridge PV Grid-tied Inverters[7] have been introduced to meet the safety requirement of leakage currents, such as specified in the VDE-4105 standard. A family of H6 transformerless inverter topologies with low leakage currents is introduced, and the intrinsic relationship between H5 topology, HERIC topology and proposed H6 topology has been discussed as well in detail. One of the H6 inverter topologies is taken as an example for detail analysis with operation modes and modulation strategy. The power losses and power device costs are compared among the H5, the HERIC and the H6 topologies. A universal prototype is built for these three topologies mentioned for evaluating their performances and strategy in terms of power efficiency and leakage currents characteristics. In order to reduce the common mode leakage current, extra power devices should be added into the grid-connected inverters and the control method should be changed [8]. The midpoint of input divided capacitors in the half-bridge inverter can be connected to the ground of the grid to keep the voltage across parasitic capacitor constant, which can effect on reduction of the common mode leakage current by the environmental condition on the PV array and parameters of power devices [9]. In addition, it is a two-stage system and all switches operate at high frequency, so efficiency of the system is low.

In order to address the aforementioned issues, a transformerless grid-connected boost inverter is proposed with the combination of a boost converter and a buck- boost converter. Thus, boost function can utilize maximum amount of energy with optimum usage of input source and used in wide range of applications. As grounds of input source and the grid are shorted, there is no common mode leakage current. Also no two adjacent switches are connected together, so it can solve the shoot through problem by connecting passive elements between them.

II. METHODOLOGY

A transformerless grid-connected boost inverter is a combination of a boost converter and a buck- boost converter. From [2] they introduced transformerless inverter with boost function but it has more number of components. With that idea this topology is designed by consists of five power switches S_1, S_2, S_3, S_4 & S_5, inductors L_1, L_2 & L_3, diodes D_1 & D_2, capacitance C_1 & C_2 & load resistor R_0. Fig. 1 shows the transformerless grid-connected boost inverter.

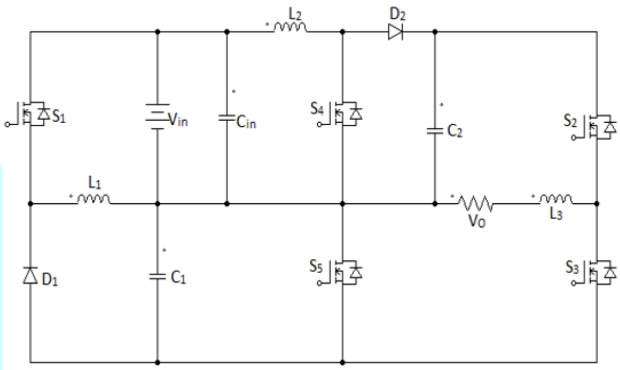

Fig. 1 Transformerless Grid-Connected Boost Inverter

2.1 Modes of Operation

The grid-connected boost inverter is combined with a boost and one buck- boost converter, which operates at unity power factor. The boost converter is composed of L_2, S_4, D_2 & C_2. The buck- boost converter is made up of S_1, D_1, L_1, C_1, S_3, S_5 & L_3. Fig. 2 shows the theoretical waveforms of boost inverter.

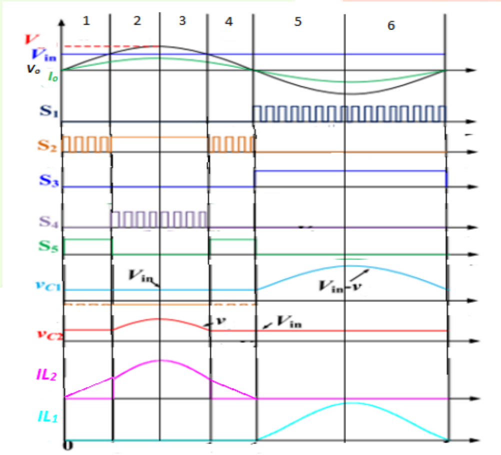

Fig. 2 Theoretical Waveforms of Boost Inverter

At mode I, the switches S_2, S_5 are turned on and switches S_1, S_3, S_4 are turned off. At this moment, the input DC V_{in} charges the inductor L_2 through D_2 and discharges C1. Also, inductor L_3 charges through switch S_2 and discharges C_2. Fig. 3(a) shows the operating circuit of mode 1. At mode II, the switches S_2, S_4 are turned on and switches S_1, S_3, S_4 and diode D_2 are turned off. At this moment, the input DC V_{in} charges the inductor L_2 through S_4. Also, inductor L_3 charges through switch S_2 and discharges C_2. Fig. 3(b) shows the operating circuit of mode 2. At mode III, the switches S_2 is turned on and switches S_1, S_3, S_4, S_5 are turned off. At this moment, the input DC V_{in} discharges the inductor L_2 through D_2. Also, inductor L_3 discharges through switch S_2 and charges C_2. Fig. 3(c) shows the operating circuit of mode 3.

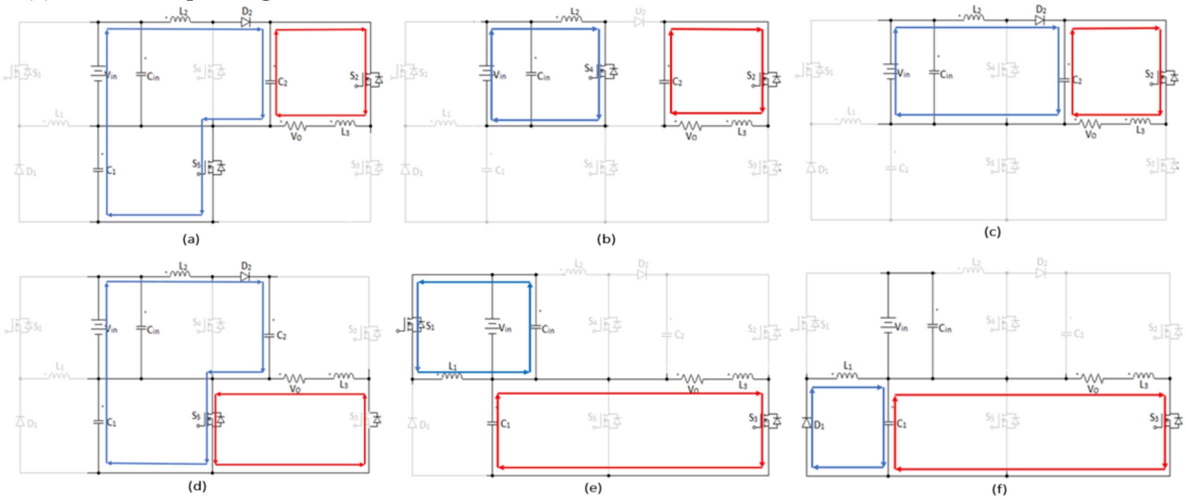

Fig. 3 Operating Modes. (a) Mode I; (b) Mode II; (c) Mode III; (d) Mode IV; (e) Mode V; (f) Mode VI

At mode IV, the switch S_5 & diode D_{s3} are turned on and switches S_1, S_2, S_3, S_4 are turned off. At this moment, the input DC V_{in} discharges the inductor L_2 through diode D_2 and charges C_1 & C_2. Also, inductor L_3 discharges through switch S_5. Fig. 3(d) shows the operating circuit of mode 4. At mode V, the switches S_1, S_3 are turned on and switches S_2, S_4 and S_5 are turned off. At this moment, the input DC V_{in} charges the inductor L_1 through S_1. Also, both L_3 and C_1 discharges through S_3. Fig. 3(e) shows the operating circuit of mode 5. At mode VI, the switches S_3 is turned on and all other switches are turned off. At this moment, the input DC V_{in} discharges the inductor L_1 through diode D_1. Also, inductor L_3 discharges through switch S_3 and charges C_1. Fig. 3(f) shows the operating circuit of mode 6.

2.2 Design of Components

In order to operate an inverter properly, its components should be designed appropriately. Some assumptions are taken for the design of transformerless grid- connected boost inverter. It consists of design of load resistance, inductors L_1, L_2 & L_3 and the capacitors C_1 & C_2. The input voltage is taken as 65V. The output power and output voltage are taken as 350W and 110V. Switching frequency is 90kHz. On solving (1) output current is obtained as 3.2A. So, the ripple of indutor current is taken as ΔI_L = (0.1- 0.4) of I_o .

$$I_o = \frac{P_o}{V_o} \tag{1}$$

Duty Ratio can be found by (2) which is taken as 0.4. The value of load resistor is set as 35Ω in (3).

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

$$R = \frac{{V_o}^2}{P_o} \tag{3}$$

The inductors L_1 & L_3 are obtained by taking current ripple as 10% of I_o. By substituting values to (4) & (6) it is approximated to 2.2mH each. For inductor L_2 the current ripple is 20% of I_o. It is given in (5) and value chosen to be 550µH.

$$L_1 >= \frac{1}{\Delta I_{L1} * f_s * (\frac{1}{V_o} + \frac{1}{V_{in}})} \tag{4}$$

$$L_2 >= \frac{V_{in} * (V_o - V_{in})}{f_s * \Delta I_{L2} * V_o} \tag{5}$$

$$L_3 >= \frac{V_o * D}{f_s * \Delta I_{L3}} \tag{6}$$

The design of the capacitor mainly considers the voltage stress and maximum acceptable voltage ripple across it. The capacitors C_1 & C_2 are obtained by taking voltage ripple as 10% of V_o. By substituting values to (7) & (8) capacitor values are approximated to 1µF for C_1 & 2.2µF for C_2.

$$C_1 <= \frac{V_o * D}{f_s * \Delta V_o * R} \tag{7}$$

$$C_2 >= \frac{I_o * L_2 * \Delta I_{L2}}{V_{in} * \Delta V_o} \tag{8}$$

III. Simulations And Results

The transformerless grid- connected boost inverter is simulated in MATLAB/SIMULINK by choosing the parameters listed in Table 1. The switches are MOSFET with constant switching frequency of 90 kHz.

TABLE I

Simulation Parameters of Transformerless Grid- Connected Boost Inverter

Parameters	Value
DC input voltage, V_{in}	65V
AC output voltage, V_o	110V
Switching frequency, f_s	90kHz
Rated power, P_o	350W
Inductor, L_1 & L_3	2.2mH each
Inductor, L_2	550μH
DC bus capacitor, C_1	1μF
Capacitor, C_2	2.2μF

The power switches of the boost inverter are based on Sinusoidal Pulse Width Modulation (SPWM). The SPWM signal is used by the comparison of the absolute value of the sine wave as modulation wave with the triangle wave as the carrier wave. Here 2 repeating sequences are taken with different magnitudes for better output voltage. A dc input voltage of 65 V and input current of 5A gives an ac output voltage of 110 V and output current of 3A for an output power, P_o of 350 W. Fig. 4(a), (b) shows the input voltage and current, Fig. 4(c), (d) shows the output voltage and current. Thus, the voltage gain is obtained as 1.7.

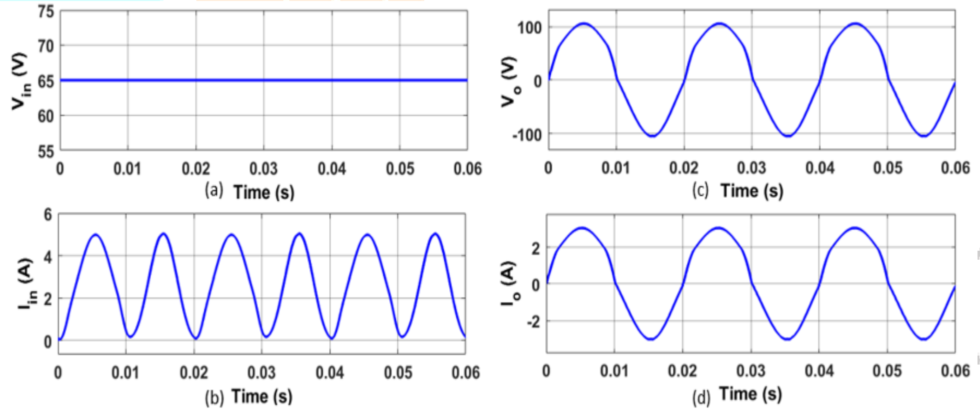

Fig. 4 (a) Input Voltage, (b) Input Current, (c) Output Voltage, (d) Output Current

Fig. 5 & 6 shows the gate pulse and voltage stress across switches S_1, S_2, S_3, S_4 and S_5. The voltage stress of both V_{s1}, V_{s2} is 170V and V_{s3}, V_{s4} and V_{s5} are 110V each.

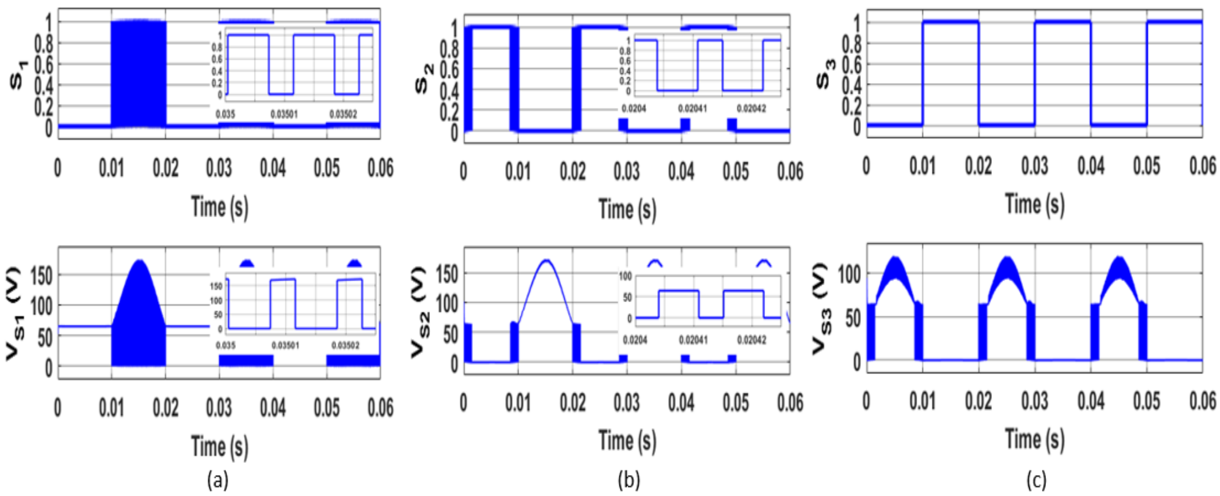

Fig. 5. Gate Pulse and Voltage Stress of (a) S_1 (V_{S1}), (b) S_2 (V_{S2}), (c) S_3 (V_{S3})

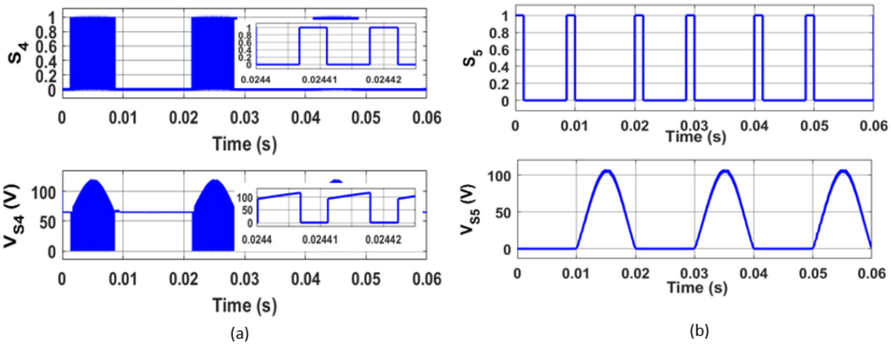

Fig. 6. Gate Pulse and Voltage Stress of (a) S_4 (V_{S4}), (b) S_5 (V_{S5})

The voltage across capacitors V_{C1} & V_{C2} is obtained as 110V each which is shown in Fig 7. Fig. 8 shows the current across inductances L_1 and L_2. It can be seen that the current across filter inductances i_{L1} is 7.5A, i_{L2} is 4.7A

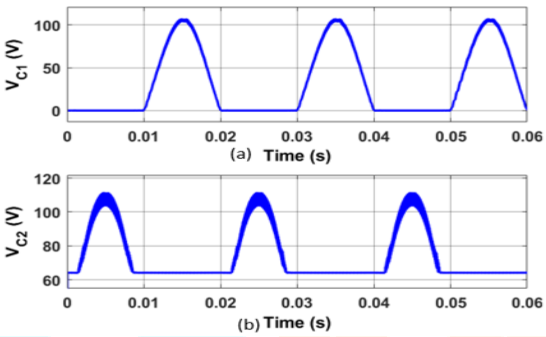

Fig. 7. Voltage across Capacitor (a)V_{C1}, (b)V_{C2}

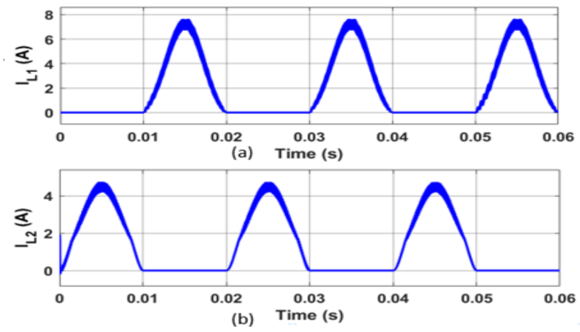

Fig. 8. Current across Inductance (a)i_{L1}, (b)i_{L2}

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 transformerless boost inverter is done and shown in Fig. 9. The maximum inverter 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. Thus, the transformerless boost inverter can be used in medium power applications.

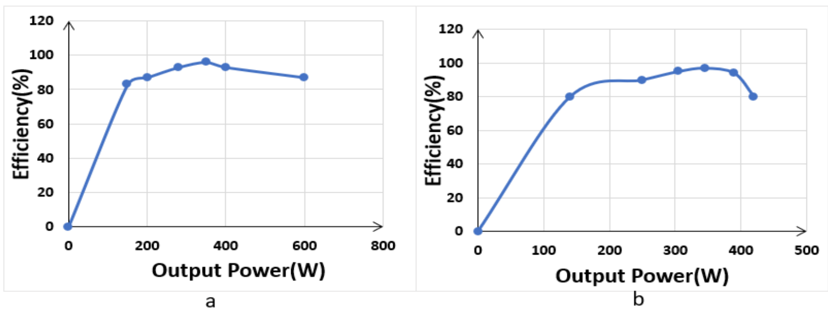

Fig. 9. Efficiency Vs Output Power for (a) R load, (b) RL load

The FFT analysis is done the THD obtained is 6.59% for proposed inverter. The plot of THD Vs Switching frequency is shown in Fig. 10. It is observed that the switching frequency for f_s = 90 kHz, the obtained THD is 6.59% and for other frequencies it has more THD than the proposed one.

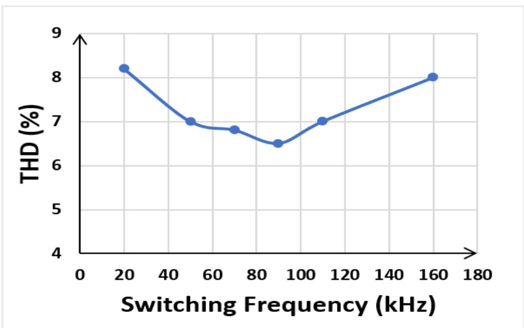

Fig. 10. THD Vs Switching frequency

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 4.967*104 rad/s and gain cross over frequency (W_{gc}) is 3.45*104 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 24.2 dB and 2.36deg. So both are positive values and the $W_{pc} > W_{gc}$. Hence, the system is stable.

$$G(s) = \frac{(1.666 * 10^{11})\, S^2 + (1.039 * 10^{17})\, S + (1.983 * 10^{20})}{S^5 - (5.457 * 10^{-12})\, S^4 + (2.413 * 10^{9})\, S^3 + (1.468 * 10^{-62})\, S^2 - (2.38 * 10^{17})\, S - (1.448 * 10^{-54})} \quad (9)$$

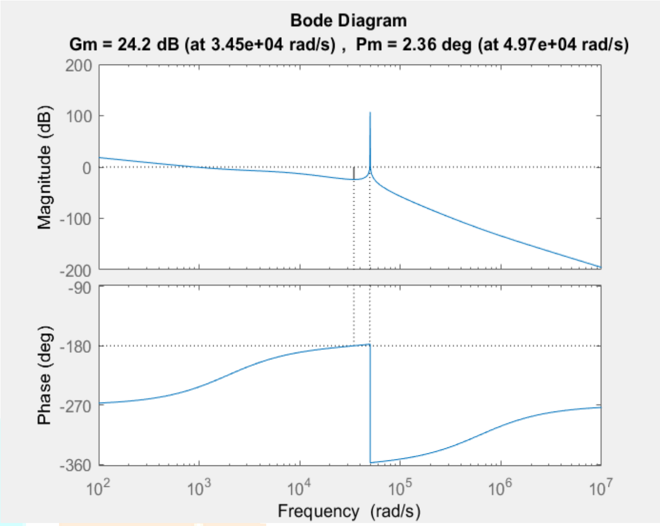

Fig. 11. Bode Plot of Transfer Function

V. Comparitive Study

The comparison between transformerless inverter & transformerless grid-connected boost inverter is given in table 2. On the comparison it can be observed that, keeping same values for input voltage 65V & switching frequency as 90kHz, the required output voltage is 110V for both inverters. But, voltage stresses across switches and diode are more in other inverters compared to the proposed inverter. Also, proposed inverter have low THD and high efficiency than other inverters.

TABLE II
Comparison Between Transformerless Inverters & Proposed Inverter

Parameters	Transformerless Boost Inverter [1]	Proposed Inverter
Number of Switches	5	5
Number of Inductors	3	3
Number of Capacitors	3	3
Number of Diodes	3	2
Input Voltage (f_s = 90kHz)	65V	65V
Output Voltage	110V	110V
Voltage stress of Switches	S_1, S_2 - 175V S_3, S_4, S_5 - 120V	S_1, S_2 - 170V S_3, S_4, S_5 - 110V
THD	7.2%	6.5%
Efficiency	95%	96%

Table 3 shows the component wise comparison between transformerless grid-connected boost inverter & other Inverters. Comparison is based on the components used in the different inverters. From table it can be observed that, the number of total components used in transformerless grid-connected boost inverter is less than other inverters. Hence, size of inverter and cost is less.

TABLE III
Comparison Between Transformerless PV Grid-Connected Inverter & Other Inverters

Inverters	Transformerless Boost Inverter [1]	Dual Switched-Boost Inverter [11]	Coupled Inductor High Boost Inverter [12]	Transformerless Grid-Connected Boost Inverter
Switches	5	6	5	5
Inductors	3	2	4	3
Capacitors	2	2	2	2
Diodes	3	5	3	2

VI. Experimental Setup With Results

For the purpose of implementing hardware, the input voltage is reduced to 5V and the switching pulses are generated using dSPACE ds1104 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 switches. Experimental setup of transformerless grid- connected boost inverter is shown in Fig. 12(a). Input 5V with 0.504A DC supply is given from DC source. Switching pulses are taken from dSPACE connector panel to driver circuit. Thus, an output voltage of 7V with 50Hz frequency is obtained from power circuit that is shown in Fig. 12 (b). Output voltage of inverter is taken from the DSO oscilloscope.

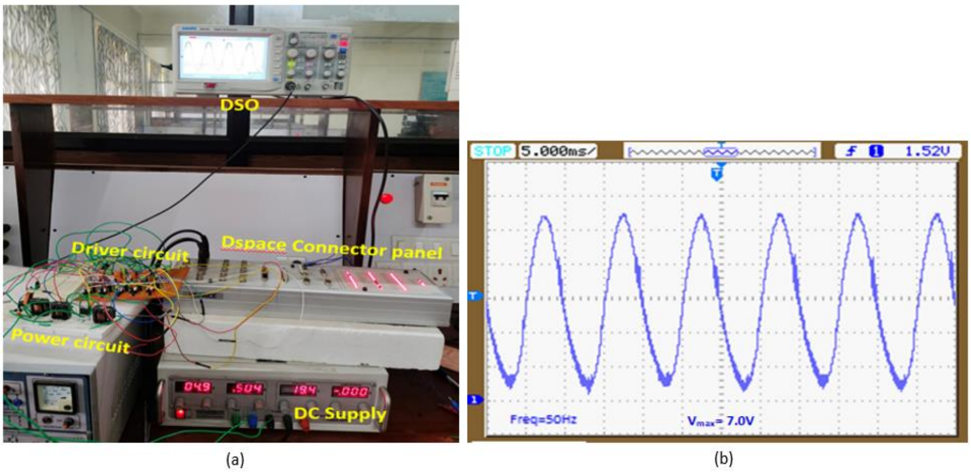

Fig. 12. (a) Experimental Setup, (b) Output Voltage of Proposed Inverter

VII. Conclusion

A transformerless grid connected boost inverter without shoot- through problem is proposed in this paper, which can work in a string- oriented PV applications. The grid connected boost inverter can be derived from a boost converter and a buck- boost converter. As there is no shoot-through problem in the proposed inverter, dead-time in gate signals is not required, and then the grid current quality can be improved. The proposed inverter has boost capability, so the power generated by the PV panel can be fully utilized under shading condition. The performance study and analysis of transformerless PV grid connected inverter is carried out using MATLAB R2017b. From the simulation results and various comparisons, there is no shoot through problem and by using the SPWM strategy the modulation of switches is very simple and thus switching losses is reduced. For a 1.6W prototype of proposed inverter is implemented using dSPACE controller. Thus, these features make the presented topology an excellent interface for the grid connected photovoltaic generation systems.

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