SWITCHED INDUCTOR BASED QUASI-SINGLE-STAGE TRANSFORMERLESS INVERTER

Mr. Vishak Ravi, PG Scholar
Dept of Electrical & Electronics Engg,
Mar Athanasius College of Engineering
Kothamangalam, Kerala, India

Prof. Eldhose K A
Dept of Electrical & Electronics Engg,
Mar Athanasius College of Engineering
Kothamangalam, Kerala, India

Prof. Mohitha Thomas
Dept of Electrical & Electronics Engg,
Mar Athanasius College of Engineering
Kothamangalam, Kerala, India

Prof. Ashna Joseph
Dept of Electrical & Electronics Engg,
Mar Athanasius College of Engineering
Kothamangalam, Kerala, India

Prof. Elizabeth Paul
Dept of Electrical & Electronics Engg,
Mar Athanasius College of Engineering
Kothamangalam, Kerala, India

***Abstract*—The rapid growth of photovoltaic (PV) systems has led to an increased demand for efficient and reliable power inverters that can effectively convert DC power generated by PV modules into AC power for grid integration. Power inverters for distributed photovoltaic (PV) power generation systems usually need to fulfill several requirements, such as safety, voltage boost capability, and the reduced volume and the cost. An improved switched inductor based quasi-single stage transformerless inverter with four switches is presented and analysed here. The inverter features double grounded to solve potential safety issues caused by the leakage current. Mitigating leakage current effects is vital to enhance the performance, efficiency, and safety of PV inverter systems. The circuit also features low stress across the components and have improved gain. Its voltage boosting is accomplished by a quasi- single-stage conversion structure so that PV system efficiency can be improved. Meanwhile, it benefits continuous input current so is suitable for PV application. Inverter is further studied and simulated using MATLAB/SIMULINK 2021b, required results are obtained. The voltage and current stresses of the components are analyzed, and parameter design guideline is further given. The simulation results shows that the inverter achieves a peak efficiency of 90%The hardware prototype of inverter is implemented to verify the performance and operation of the circuit using the dSPACE controller .**

***Index Terms*—Transformerless inverter, Leakage current, Switched inductor, Voltage gain, THD**

I. INTRODUCTION

In the traditional photovoltaic (PV) power generation system, the line-frequency or high-frequency transformers are used to boost the voltage and achieve the connection to the grid. However, applying transformers increases the volume, weight, and cost of PV power generation system. On the contrary, the transformerless system improves energy conversion efficiency and benefits low cost, reduced volume, and improved power density. Nevertheless, due to a lack of galvanic isolation, transformerless inverters produce high-frequency switching actions with the modulation strategy, resulting in the variable common-modevoltage (CMV). The CMV high-frequency component causes a common-mode (CM) leakage current on parasitic capacitors of PV modules. The leakage current increases the system loss and causes electromagnetic interference, worse, endangers personal safety.

By applying two symmetric filter inductors with the bipolar modulation strategy, the traditional single-phase full-bridge(FB) inverter can reduce the leakage current, which is the simplest method to suppress the leakage current. However, the bipolar modulation strategy has disadvantages of the higher current ripples, total harmonic distortions (THDs) and switching losses than the unipolar modulation strategy, so may cause a greater filter parameter and a heat dissipation size. When the traditional unipolar modulation strategy is applied by the transformerless FB (TL-FB) inverter, CMV has many levels and changes at high frequency, so it causes a significantleakage current. Therefore, a series of improved FB inverters are proposed, such as H5, H6, and HERIC inverter. By disconnecting the dc side and ac sides via additional switches during the zero state, CM loop is ideally opencircuit and the leakage current may decrease . This leakage current suppression method is called decoupling. However, because of the existence of switches junction capacitors, CM loop is not really open-circuit, so the leakage current suppression effect relies on the junction capacitance and environments.

Different from improved TL-FB inverters, the CM inverters feature common-grounded of the dc side and ac side, where the parasitic capacitor of PV array is short-circuited, so CMV is zero. This kind of topology can eliminate the leakage current.In a two-switches CM inverter, whose output voltage before ac filter has two levels. Its required filter inductor is usually larger than that of inverters with three-level output voltage. Besides, a sliding-mode controller is required to balance the output voltage of the positive and negative half-cycles of the grid. And, it is also noted that the output ac voltage can only be regulated by the front-end boost converter. The output voltages of the inverters have three levels so THDs decrease and output voltage can be regulated by modulation index. However,the flying-capacitor of both inverters needs to be large enough, because it is only charged in the positive half-cycle.

Here introduced a quasisingle-stage four-switches CM inverter with CM leakage current elimination ability. The continuous input current is friendly toprotect the life span of PV arrays and components. Meanwhile, an improved unipolar carrier-based modulation strategy is proposed and efficiently eliminates output voltage spikes caused by the deadtime of switches. This solution is a candidate to improve the systems safety and overall efficiency

II. METHODOLOGY

The Switched inductor based quasi-single-stage transformerless inverter consists of two parts. The boosting network and the inverting network. And they are common-grounded.The boosting network applies a quasi-Z-source(qZs) with a switched inductor. Figure 1 shows the switched inductor based quasi-single-stage transformerless inverter. The boosting network consist of inductors L_{11}, L_{12}, & L_2, diodes D_1, D_2, D_3 & D_4, and capacitances C_1 & C_2. The inverting network consists of four switches S_1, S_2, S_3 & S_4 and a virtual dc bus cell. It consists of capacitances C_3 , C_4, and diodes D_5 & D_6. The output of the inverting circuit is connected to a load resistor R_0. The negative terminal of PV and neutral of grid is commonly grounded to eliminate the leakage current.

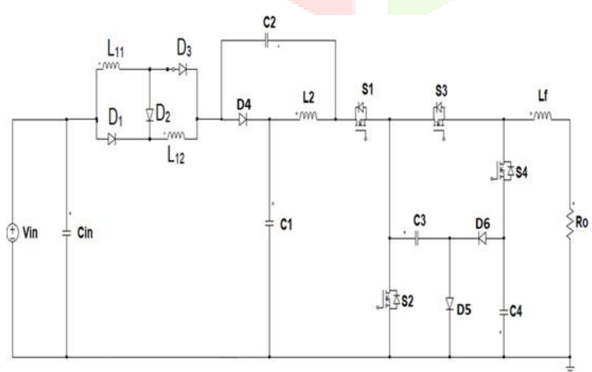

Fig. 1. Switched Inductor based quasi-single-stage transformerless inverter

A. Modes of Operation

In Switched inductor based quasi-single-stage transformer-less inverter, there are four steady state modes of operations. Positive half-cycle of the grid current include mode 1, mode 4, and mode 3, while those of the negative half-cycle of the grid current include mode 1, mode 4, and mode 2.

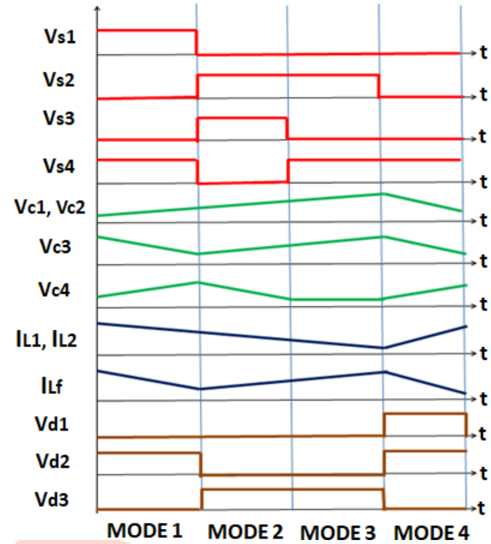

Fig. 2. Theoretical Waveforms of inverter

1) Mode 1: At mode 1, the switches S_2, S_3 are turned on and switches S_1, S_4 and diodes D_1,D_3 & D_5 are turned off. At this moment, the input DC power V_{in} and discharged energy from L_{11} & L_{12} charges the capacitor C_1 through diode D_2. Cpacitor C_2 get charged by the discharging of inductor L_2. Cpacitor C_4 get charged by the discharging of capacitor C_3 through Switch S_2. Output voltage V_o is 0 here. Figure 3 shows the operating circuit of mode 1

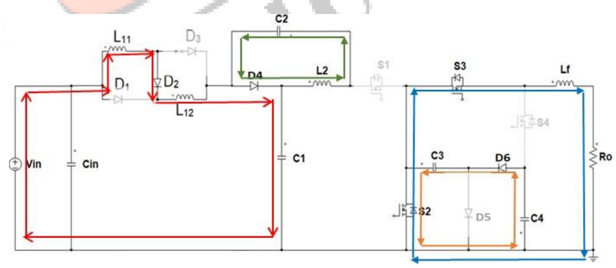

Fig. 3. Operating Circuit of Mode 1

2) Mode 2 : At mode 2, the switches S_1, S_4 are turned on. Switches S_2, S_3, are turned off. The input DC power V_{in} and discharged energy from L_{11} & L_{12} charges the capacitor C_1 through diode D_2. Capacitor C_2 get charged by the discharging of inductor L_2. Since switch S_1 is on, discharging energy from inductors and input V_{in} charges C_3 . C_4 discharged to R_o through switch S_4. output voltage V_o is negative. V_o is equals to -V_{C4}. Figure 4 shows the operating circuit of mode 2.

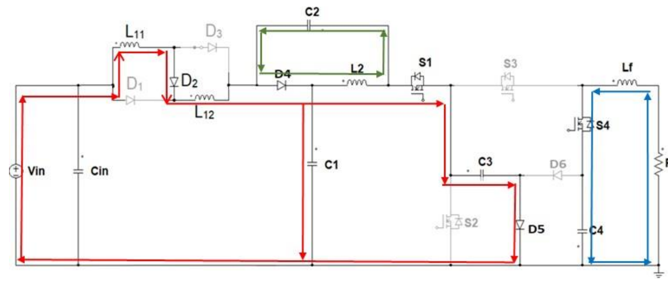

Fig. 4. Operating Circuit of Mode 2

3) Mode 3 : At mode 3, the switches S_1, S_3 are turned on. Switches S_2, S_4, are turned off. C_1, C_2 & C_3 charges similar to previous modes. Since switch S_3 is on, output voltage V_o is positive. V_o is equals to $+V_{C3}$. Figure 5 shows the operating circuit of mode 3.

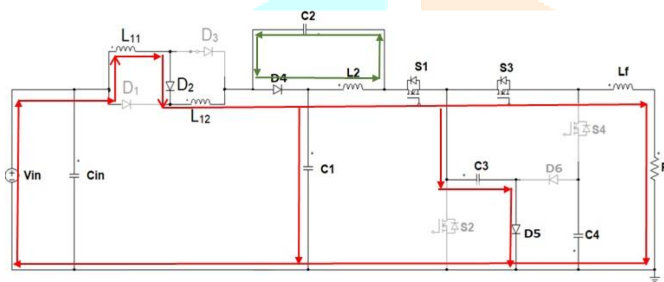

Fig. 5. Operating Circuit of Mode 3

4) Mode 4 : At mode 4, the switches S_1, S_2 & S_3 are turned on and switch S_4, and diodes D_2, D_4 & D_5 are turned off. Inductors L_{11} ,L_{12} & L_2 are charging here. Capacitors C_1,C_2 & C_3 are discharging. Since circuit is short-circuited, Output voltage V_o is 0 here. Figure 6 shows the operating circuit of mode 4.

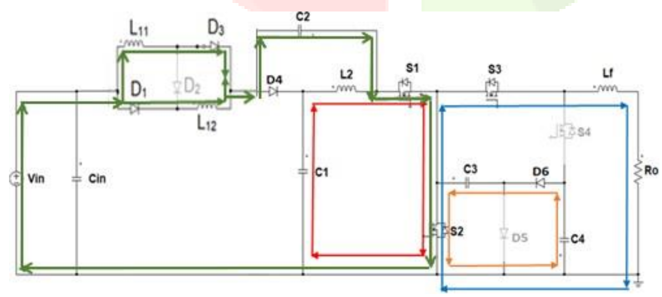

Fig. 6. Operating Circuit of Mode 4

B. Design of Components

The input voltage is taken as Vin = 70V. The output power and output voltage are taken as P_o = 500W and V_o = 220V. Switching frequency, fs = 20kHz, so time period, Ts = 1/fs = 0.00005sec.

Load resistance can be found by the equation,

$$R_o = \frac{V_o^2}{P_o} = \frac{220^2}{500} = 96.8\Omega \quad (1)$$

Duty ratio,

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} = 0.75 \quad (2)$$

The values of capacitors are obtained from the following equations.

Inductor, C_1, C_2

$$V_{C1} = \frac{(1-D_0)V_{in}}{(1-2D_0)} = \frac{(1-0.18)*70}{(1-0.36)} = 90V \quad (3)$$

$$a = \frac{V_{C1ripple}}{V_{C1}} = \frac{0.81}{90} = 0.009 \quad (4)$$

$$I_{in} = I_{L1} = \frac{V_0 * I_0}{V_{in}} = \frac{220\sqrt{2} * 3.21}{70} = 14.2A \quad (5)$$

$$C_1 \geq \frac{I_{L1}}{f_s * a * V_{c1}} = \frac{14.2}{20000 * 0.009 * 90} = 876\mu F. \quad (6)$$

So, choose the values of capacitors as C_1 =C_2 = 900 μF, 110V.

similarly, the values of capacitors, C_3 & C_4

$$I_Z = \frac{I_{L11}}{2} * (1-2D_0) = \frac{7.13}{2} * (1-0.36) = 4.544A \quad (7)$$

$$M = \frac{(1-2D_0) * V_0}{V_{in}} = \frac{(1-0.36) * 220\sqrt{2}}{70} = 2.84 \quad (8)$$

$$I_m = \frac{2I_z}{M} = \frac{2 * 4.544}{2.84} = 3.24A \quad (9)$$

$$I_{C4max} = \frac{2I_m}{\pi} = \frac{2 * 3.24}{\pi} = 2.1A \quad (10)$$

$$C_4 \geq \frac{I_{C4max}}{V_n * V_r * f} = \frac{2.1}{220 * 0.16 * 50} = 843\mu F \quad (11)$$

So, choose the values of capacitors as C_4 = C_3 = 850 μF, 375V.

similarly, the values of inductors, L_1 , L_2

$$L \geq (V_{c1} - V_{in})\frac{D_0 * T_S}{\Delta i_{L11}} = (90-70)\frac{0.18 * 5e-5}{1.775} = 0.1mH \quad (12)$$

So, choose the values of inductors as L_{11} = L_{12} = L_2 =0.5 mH,20A.

Filter inductor, L_f

$$V_{C2} = \frac{D_0 * V_{in}}{(1-2D_0)} = \frac{0.18 * 70}{(1-0.36)} = 20V \tag{13}$$

$$L_f \geq (V_0 - V_{in} - V_{C2})\frac{D_0 * T_S}{\Delta i_{Lf}} \tag{14}$$

$$L = (220\sqrt{2} - 70 - 20) * \frac{0.18 * 5e{-5}}{0.642} = 3mH$$

So, choose the value of filter inductor as L_f = 5 mH,5A

III. Simulations and Results

Simulation parameters for the switched inductor based quasi-single-stage transformerless inverter is given in Table 1. The switch is MOSFET with constant switching frequency of 20 kHz. The simulation results of the switched inductor based quasi-single-stage transformerless inverter are shown in the following figures. Figure 7 shows the input voltage and input current. A dc input voltage, Vin of 70V gives an ac output voltage, Vo of 220V ac for an output power, Po of 500W. Thus, the voltage gain has doubled. Fig. 8 shows the output voltage and current .

TABLE I
Simulation Parameters

Parameters	Value
DC input voltage, V_{in}	70V
AC output voltage, V_o	220V
Switching frequency, f_s	20kHz
Capacitor, C_1, C_2	900µF, 110 V
Capacitor, C_3, C_4	850µF, 375 V
Duty Cycle, D_0	0.18
Inductor, L_{11}, L_{12}, L_2	0.5mH, 20A
Filter inductance, L_f	5mH, 5A
Load Resistance, R	100 Ω
Rated Power, P_0	500 W

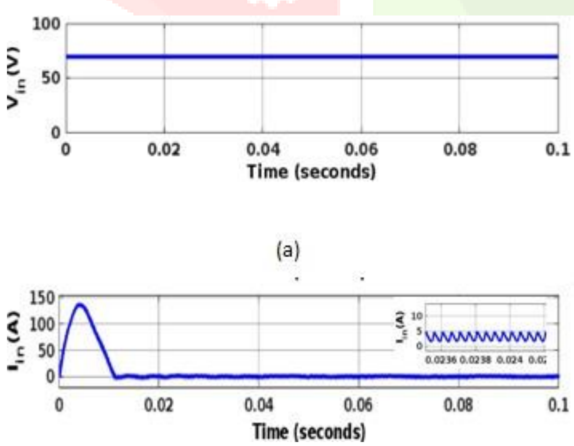

Fig. 7. (a) Input Voltage (V_{in}) and (b) Input Current (I_{in})

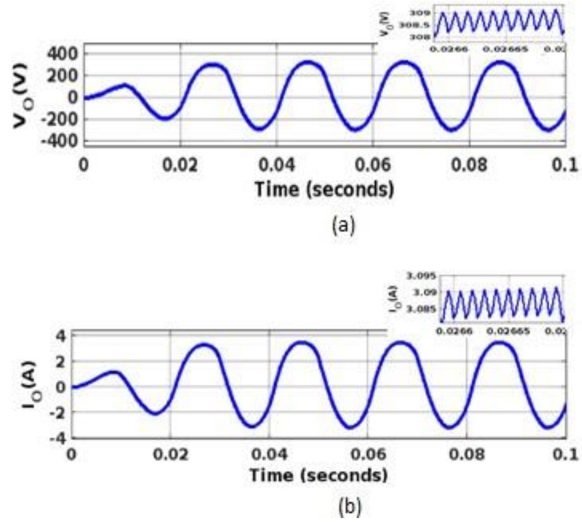

Fig. 8. (a) Output Voltage (V_0) and (b) Output Current (I_0)

Fig.9, Fig.10, Fig.11 and Fig.12 shows the gate pulse and voltage stress across the switchess. Voltage stress across the switches S_1 & S_2 is 150V. Voltage stress across the switches S_3 & S_4 is 300V.

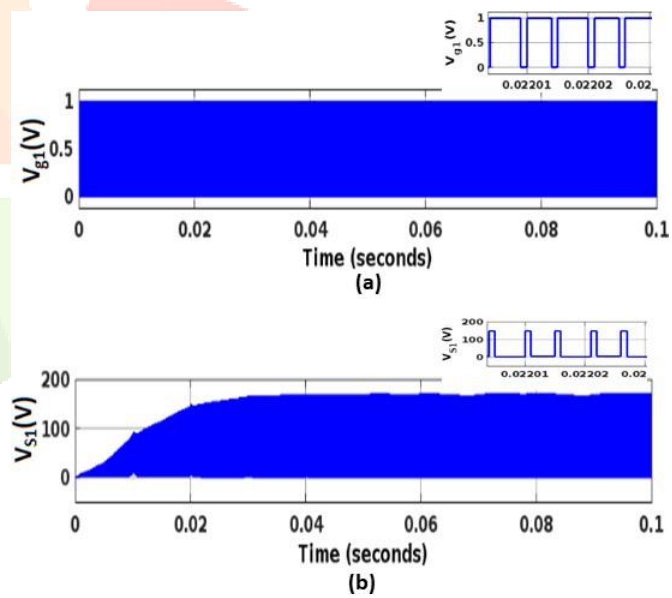

Fig. 9. (a) Gate pulse to S1 (V_{g1}) and (b)Voltage Stress to S1(V_{S1})

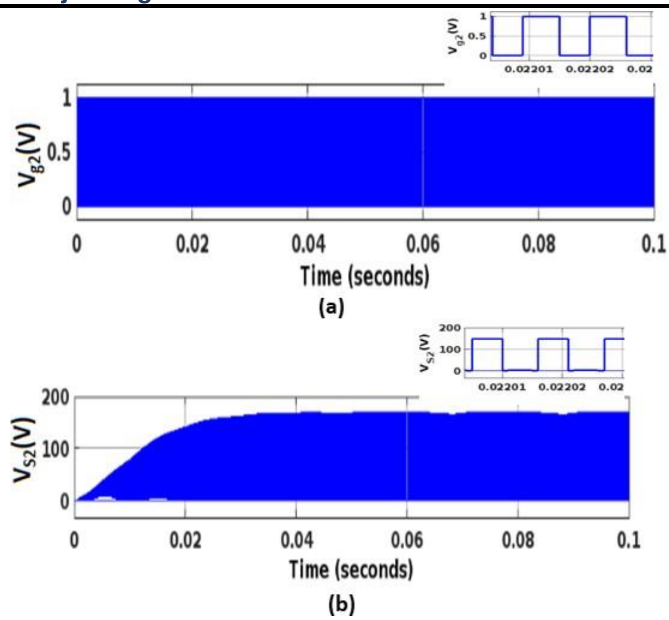

Fig. 10. (a) Gate pulse to S2 (V_{g2}) and (b)Voltage Stress to S2(V_{S2})

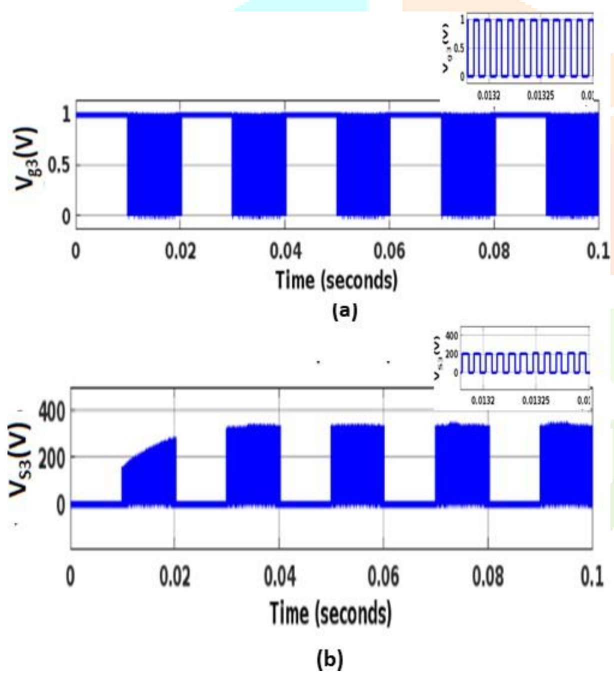

Fig. 11. (a) Gate pulse to S3 (V_{g3}) and (b)Voltage Stress to S3(V_{S3})

The voltage across capacitors is obtained as V_{C1} = 200 V, V_{C2} = 75 V, V_{C3} = 300 V & V_{C4} = 300 V. which is shown in Fig 13 and 14. Fig.15 shows the current across inductances L_{11} a L_{12} and L_2 . It can be seen that the current across inductances i_{L11} & i_{L12} is 11A and i_{L2} is 10A.

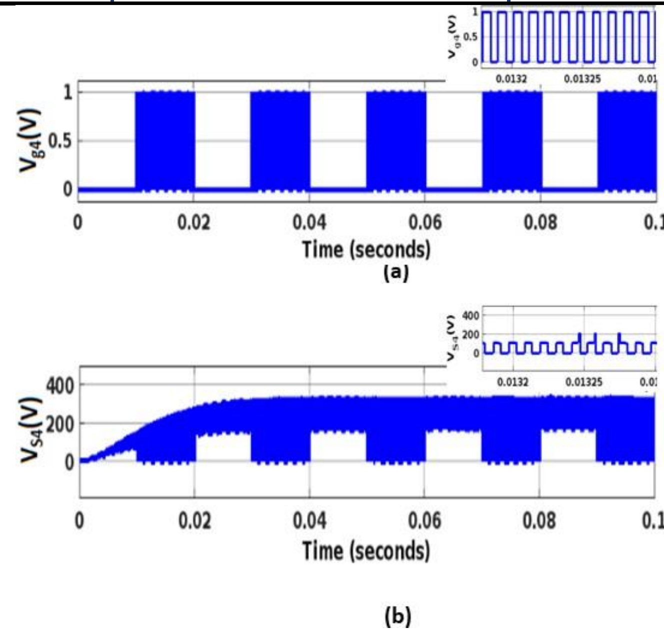

Fig. 12. (a) Gate pulse to S3 (V_{g4}) and (b)Voltage Stress to S3(V_{S4})

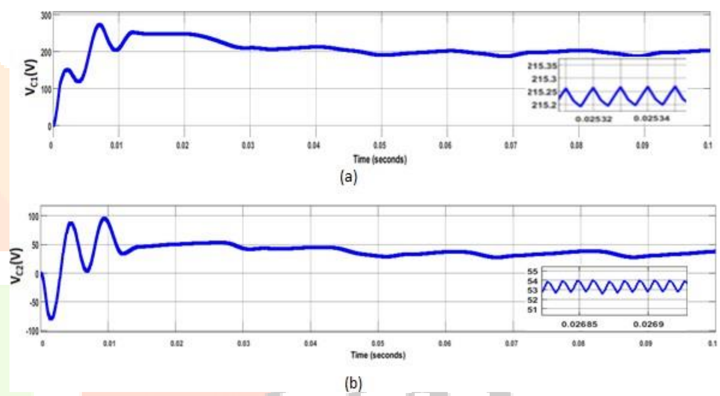

Fig. 13. Voltage across Capacitor (a)V_{C1}, (b)V_{C2}

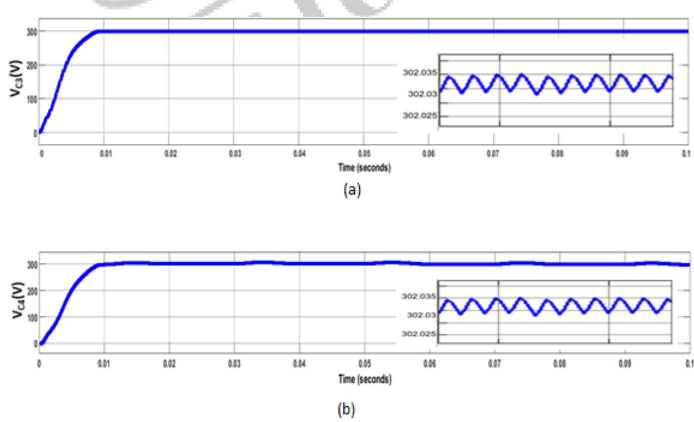

Fig. 14. Voltage across Capacitor (a)V_{C3}, (b)V_{C4}

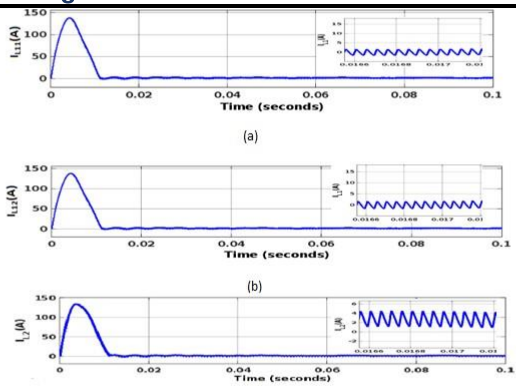

Fig. 15. Current across Inductance (a)i_{L11}, (b)i_{L12}, (c)i_{L2}

The FFT analysis is shown in Figure 16. Figure 16 is the THD of output voltage with filters . The obtained THD for with filter is 5.7%

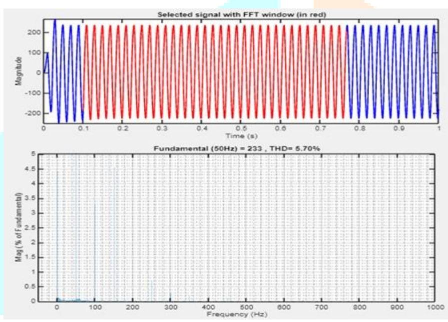

Fig. 16. THD of Output Voltage

IV. Performance Analysis

The analysis of the switched inductor based quasi-single-stage transformerless inverter is carried out by considering parameters like efficiency, THD and switching frequency.

A. *Efficiency vs Output power*

Efficiency of a 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. Figure 17 and figure 18 shows efficiency Vs output power curve for R load and RL load. The efficiency is around 90% for switched inductor based transformerless inverter for R load. And 95% for RL load.

B. *THD VS Switching Frequency*

The plot of THD of the inverter as a function of Switching Frequency is shown in fig 19. Minimum THD was obtained at 20KHz switching frequency.

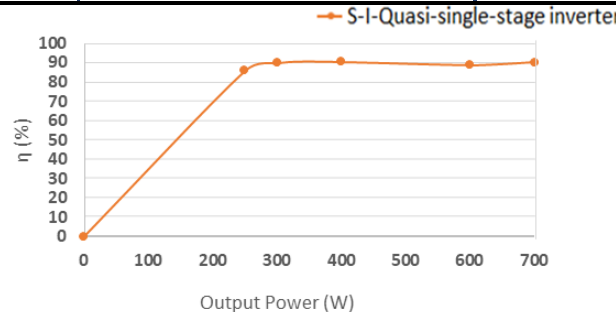

Fig. 17. Efficiency Vs Output Power for R load

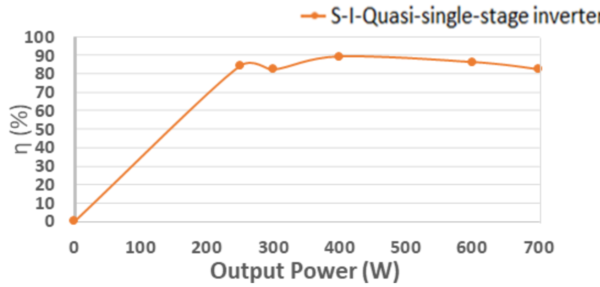

Fig. 18. Efficiency Vs Output Power for RL load

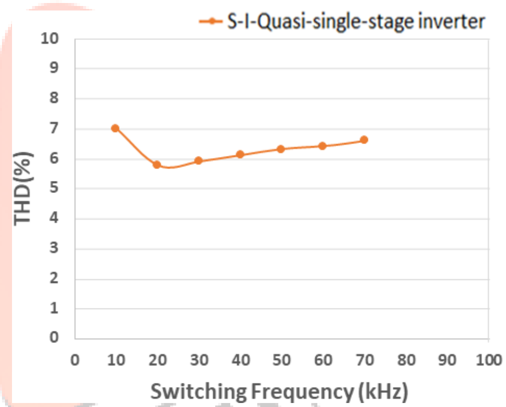

Fig. 19. THD VS Switching Frequency

V. Comparative Study

The comparison between a quasi-single-stage transformer-less inverter with same input voltage and swtching frequency & the proposed Switched inductor based quasi-single-stage transformerless inverter is given in table II. On the comparison it can be observed that,with same values for output voltage as 220V & switching frequency as 20kHz, voltage stress across the switches reduced in the proposed inverter. voltage gain in also doubled.

Table III shows component wise comparison of different transformerless inverters. Eventhough switched inductor based transformerless PV inverter has more number of components, it has high gain.

TABLE II
COMPARISON BETWEEN QUASI-SINGLE-STAGE TRANSFORMERLESS INVERTER & THE SWITCHED INDUCTOR BASED QUASI-SINGLE-STAGE TRANSFORMERLESS INVERTER

Parameter	Quasi-Single-stage Transformer less inverter(QTI)	Switched Inductor Based Quasi-Single-stage Transformer less inverter(SI-QTI)
No. of switches	4	4
No. of inductors	3	4
Input Voltage	140V	70V
Voltage stress across switch	V_{s1}=200V, V_{s2}=200V V_{s3}=500V, V_{s4}=500V	V_{s1}=150V, V_{s2}=150V V_{s3}=300V, V_{s4}=300V
Gain	1.57	3.14
Efficiency(r load) Efficiency(r l load)	95% 94%	90% 89%
THD	6.58%	5.7%

TABLE III
COMPARISON BETWEEN SWITCHED INDUCTOR BASED QUASI-SINGLE-STAGE TRANSFORMERLESS INVERTER & OTHER INVERTERS

Inverters	S-I quasi-single -stage transformerless inverter	BBT Inverter	High gain buck-boost inverter	Flying-inductor inverter
Switches	4	5	5	6
Capacitor	5	1	2	1
Inductor	4	1	2	2
Diode	6	1	0	2

VI. EXPERIMENTAL SETUP WITH RESULT

For the purpose of implementing hardware, the input voltage is reduced to 2V and the switching pulses are generated using Dspace controller. The switches used are MOSFET IRF3205. 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 the switched inductor based quasi-single-stage Transformerless inverter is shown in Figure 20. Input 2V with 0.25A DC supply is given from DC source. Switching pulses are taken from Dspace controller to driver circuit. Thus an output voltage of 7.5V, 50kHz is obtained from power circuit that is shown in Figure 21. Output voltage of converter is taken from the DSO oscilloscope.

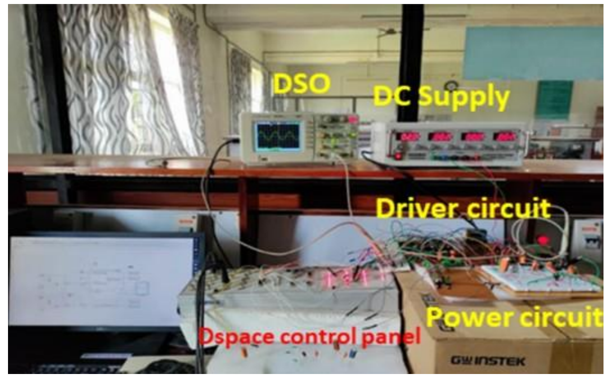

Fig. 20. Experimental Setup

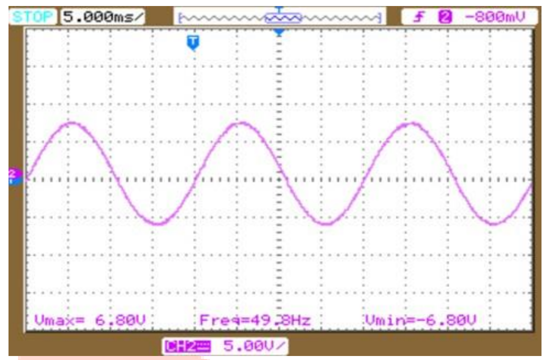

Fig. 21. Output Voltage

VII. CONCLUSION

Switched inductor based quasi-single-stage transformerless inverter is analyzed and validated through simulation results. A switched inductor circuit is introduced in order to achieve a high voltage gain. Circuit provides an improved unipolar modulation strategy .The inverter is double-grounded to solve potential safety issues caused by the leakage current and it features low stress across components and improved gain. The performance study and analysis of switched inductor based quasi-single-stage transformerless inverter is carried out. The inverter was tested at the switching frequency of 20kHz and it has been observed that switched inductor concept improved its gain and efficiency. The control of the proposed inverter is implemented using dSPACE DS1104. Inverter prototype of 10W provides the expected performance with an output voltage of nearly 7.5V for an input of 2V.The efficiency obtained is nearly 90 %.

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