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# Switched Inductor Based Three-Switch Single-Phase Inverter

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**Abstract**

Electric energy consumption is increasing rapidly due to the increased energy demand in the world. The government is compelled to reduce the utilisation of fossil fuels due to global warming and to invest in renewable source of energy. Non-conventional power-generation methods can be utilised to supplement the energy produced from conventional resources. In photovoltaic (PV), the power that one module can produce is not sufficient to meet the requirements of domestic or industries. Most PV arrays use an inverter to convert the DC power into AC that can power the motors, loads, lights etc. Due to this constrains for PV applications a Switched Inductor Based Three-Switch Single-Phase Inverter is proposed. The proposed inverter eliminates leakage current in PV systems by providing a common ground between the input and output terminals. A comparison of proposed inverter with similar inverters are done. Addition of switched inductor concept boosted the voltage gain to 5.9 for the proposed inverter. The performance study is carried out with MATLAB R2020b software and the result is analysed. For a 26V input DC voltage, an output AC voltage of 110V, 50Hz is obtained. A 9W prototype of proposed inverter is implemented using TMS320F28027F controller and the experimental results prove the performance of the proposed Inverter.

***Keywords:*** Microinverter, Common Grounding, Single Phase Inverter

## 1. Introduction

The growing public attention to global warming and its adverse consequences pushes the government and industrial firm to replace the fossil fuel-based energy sources with clean renewable ones. In the last three-decade renewable energy (RE) has become challenging field and many researchers make RE the main focus in order to create a new sustainable, natural abundance and environmental friendly natural energy resources. In many applications, such as PV, fuel cell and battery-powered systems, there is a rising need for low-cost single-phase DC-AC inverters. An inverter refers to a power electronic device that converts power in DC form to AC form at the required frequency and voltage output. It has two classes; current source inverter and voltage source inverter. A multilevel inverter is a more powerful inverter. It does the same thing as an inverter except, it provides energy in higher power situations. A two-level inverter has two different output voltages and is the simplest one. But the AC output is rectangular with high total harmonic distortion (THD) whereas the load needs sinusoidal voltage. Multilevel inverter (MLI), a step ahead of the two-level inverter tends to reduce this effect. It does so by using many low rated DC voltage sources as input for the desired AC voltage output. So, in a multilevel inverter, the output voltage is stepped more than twice. As the level increases in the multilevel inverter, the waveform is smoother than the two-level inverter. In MLI a short circuit in the circuit can cause a very high fault current which will damage any other types of equipment connected to the circuit. Hence, multilevel voltage source inverters are preferred. There are four types of MLI topologies; neutral point clamped (NPC), diode clamped (DC), flying capacitor (FC) and cascaded H-bridge (CHB) multilevel inverter. Cascaded H-bridge multilevel inverters have preferably low THD [7]. Nowadays PV systems are used extensively for the generation of energy in private and commercial circles. The PV inverters convert the energy given by a PV array and delivered it into the AC mains (on grid). Since a single PV panel's output voltage is insufficient, a high voltage conversion ratio is required to connect the PV system to the grid. Although connecting the PV panels in series might enhance the output voltage, any mismatch in any of the PV panels would significantly reduce the power [3]. Transformer elimination in grid-connected PV systems has many advantages. This not only reduces cost, size and weight, but also increases the whole system efficiency. However, once the transformer is removed, there is no galvanic isolation between grid and PV array. As a consequence, leakage current appears due to parasitic capacitance to the ground, resulting in prohibitive electromagnetic interference and security issues. Microinverters are used to increase energy capture in shaded areas and also make it easy to expand a solar system because they are plug-and-play [2]. Furthermore, leakage current flows in the system as a result of high stray capacitors between PV panels and the ground, reducing system efficiency and posing safety concerns. As a result, this current needs to be reduced or abolished. Common grounding is an advantage of half-bridge and three-level neutral-point clamped inverters with an asymmetrical inductor. They do, however, require an input voltage that is double the grid peak voltage. As a result, multiple PV panels must be connected in series to achieve this voltage, resulting in a reduction in maximum power extraction owing to partial shading [9]. A full-bridge converter is widely used with transformerless symmetrical inductor-based inverters. Although using bipolar sinusoidal pulse width modulation (SPWM) in these full-bridge-based inverters can greatly reduce leakage current, it also results in a lot of electromagnetic interference noise, a lot of THD and a lot of switching losses [1]. When using unipolar SPWM, on the other hand, the THD and inductor size can be lowered. Quasi-ZSIs (Quasi-ZSIs) are a type of quasi-ZSI that PV, electric car, motor drive, and uninterruptible power supply applications benefit from reducing the capacitor's voltage stress and improving the input current profile. Despite having a boost capability, the inverters in [2] suffer from leakage current. Using common-ground topology is another way to prevent leakage current. The ZSIs provided in [1] and [2] are not half/full bridge based and have a common grounding characteristic. The highest voltage gain of these inverters, however, is restricted to one. To increase the dynamic responsiveness and resilience, the common-ground inverter in [8], which is similar to semi-ZSI in [2], uses sliding-mode control instead of traditional pulse width modulation control. However, the control theory that is being used is somewhat sophisticated. In addition, the voltage gain is less than one. Both inverters in [5] and [1], on the other hand, lack the capacity to generate reactive power. Despite the fact that the common-ground inverter in [8] overcomes this problem, its maximum voltage gain is still less than one. Huang et al. [10] introduced a series of three-switch three-state single-phase Z source inverters (TSTS-ZSIs) that provide common grounding and better voltage gain. The buck – boost-based variety, on the other hand, the signal creation of TSTS-ZSIs is highly difficult, and these inverters cannot provide reactive power. A novel single-phase switched-coupled-inductor inverter with common grounding and a voltage gain greater than 1 is described in [2]. Despite the fact that this inverter employs a connected inductor the power switches are subjected to significant voltage and current stress. This single-phase inverter's high voltage gain qualifies it for usage in single-stage microinverter systems. A transformerless single-phase inverter with a larger voltage gain than the buck – boost based TSTS-ZSI in [10] and the inverter in [2] is presented in this study. Furthermore, compared to [2] and the boost-based TSTS-ZSI, the burden on switches is reduced, boosting system reliability. The high voltage gain of this single-phase inverter qualifies it for use in single-stage microinverter systems. A new structure of switched inductor based three switch single phase inverter for high voltage gain is designed. This shows the requirement of low input voltage for high output voltage.

## 2. Methodology

Switched Inductor Based Three Switch Single Phase Inverter has three switches ($S_1, S_2$ and $S_3$), four capacitors ($C_1$, $C_2$, $C_0$ and $C_{pv}$), five inductors ($I_{L11}$, $I_{L12}$, $I_{L21}$, $I_{L22}$ and $I_{L3}$,) and seven diodes ($D_1$, $D_2$, $D_3$, $D_4$, $D_5$, $D_6$and D) which is shown in figure 1. The inductors in proposed inverter values are much less than $L_1$ and $L_2$ in base paper mentioned in [1].

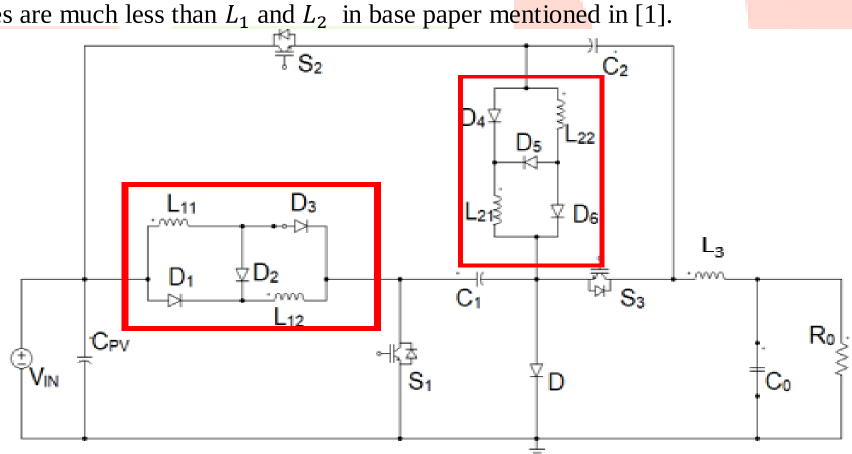



Fig. 1. Switched Inductor Based Three Switch Single Phase Inverter

## 3. Modes of Operation

There are two modes of operation for the inverter, mode 1 and mode 2. In both modes, the inductor L3 and the capacitor $C_0$ form an LC filter at output side of the inverter.

**1.1 Mode 1**: In mode 1, Switches $S_1$and $S_3$ are turned ON while switch $S_2$ is turned off, as shown in Fig. 2. The input voltage $V_{in}$ magnetises the inductors $L_{11}$ and $L_{12}$ through $D_1$ and $D_3$ diodes. The inductor $L_{21}$ and $L_{22}$ charges capacitor $C_2$ through $D_5$. In addition, $C_1$ is released. Where $I_{L11}$, $I_{L12}$, $I_{L21}$, $I_{L22}$, $I_{L3}$, $V_{C1}$ and $V_{C2}$ signify the current through inductors $L_{11}, L_{12}$ , $L_{21}, L_{22}$ and $L_3$ as well as capacitors $C_1$ and $C_2$ respectively. The input voltage is $V_{in}$, while the output voltage is $V_0$.

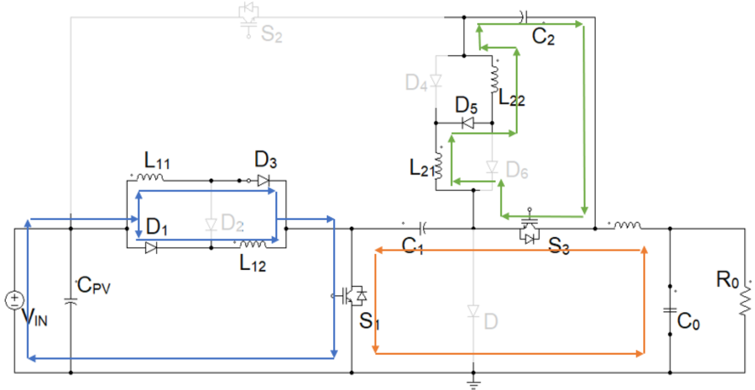



Fig. 2. Mode 1 of the Inverter

**1.2 Mode 2:** In mode 2, Switch $S_2$ is turned ON, in this, while switches $S_1$ and $S_3$ are turned off, as shown in Fig.3 Capacitor $C_1$ is being charged by inductors $L_{11}$ and $L_{12}$ through $D_2$. At the same time inductors $L_{21}$ and $L_{22}$ are magnetised by the input voltage $V_{in}$ through $D_4$ and $D_6$.

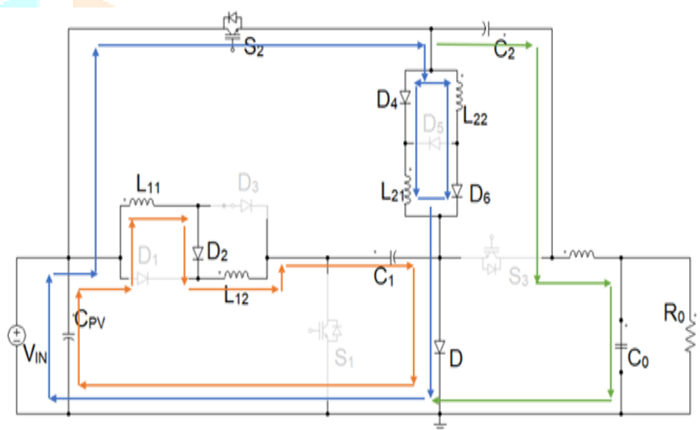



Fig. 3. Mode 2 of the Inverter

**1.3 Gate Pulse Generation Circuit:** The gate signal generating technique used here is SPWM. A carrier signal with 40kHz frequency is compared to a reference signal with 50Hz frequency, as shown in Fig. 4. Reference signal is an equation mentioned in equation 4, that controls the duty cycle. When reference signal is greater than the carrier, $S_1$ and $S_3$ conduct, whereas $S_2$ is switched ON when reference signal is less than the carrier.

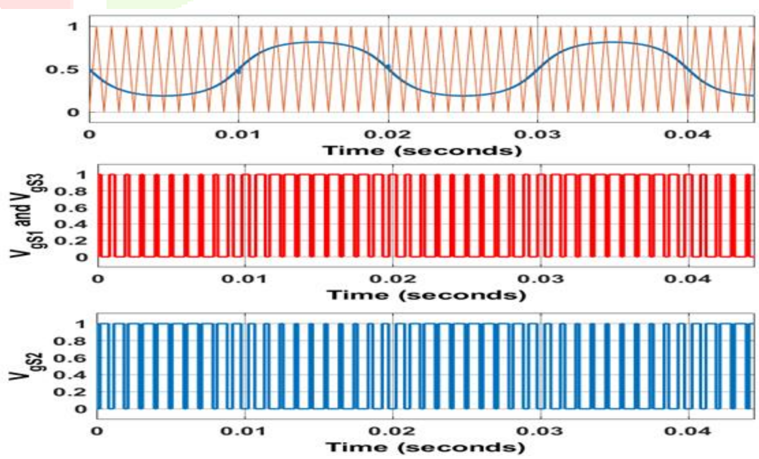



Fig. 4. Modulation Scheme

Design of components the proposed inverter has high conversion ratio (26V - 110V) and high gain. The output power, $P_0$ is taken as 280W with a switching frequency 40kHz. The output voltage can be obtained as a sine wave
ie, (1)

$$V_0 = V_m * \sin(wt)$$

So, modulating index can be calculated by,

$$M = \frac{V_0}{V_{in}} = \frac{110\sqrt{2}}{26} = 5.9 \quad (2)$$

where ω, $V_m$ and M are the angular frequency, the output voltage and the modulation index, respectively. On applying volt-sec-balance rule to $L_3$ inductor, the gain can be written as

$$\frac{V_0}{V_{in}} = \frac{1-2D}{D(1-D)} \quad (3)$$

On substituting equation 1 and 2 in 3, can obtain equation 4

$$D = \frac{2 + M\sin(wt) - \sqrt{M^2\sin^2(wt) + 4}}{2M\sin(wt)} \quad (4)$$

On solving equation 4, when wt $= \frac{3\pi}{2}$, value is approximated to $D_{max}$ = 0.860 and when wt $= \frac{\pi}{2}$, $D_{min}$ = 0.139 can be obtained.

$$I_{L11} = I_{L12} = \frac{D_{max}}{1 - D_{max}} * I_0 \quad (5)$$

$$I_{L21} = I_{L22} = \frac{1 - D_{min}}{D_{min}} * I_0 \quad (6)$$

$$I_{L3} = I_0 = 3.8A \quad (7)$$

With the load current and duty ratio equations inductor current can be obtained, shown in equation 5, 6 and 7, and taking 10-40% of inductor current, the allowed maximum current ripples of the inductors (i.e. $\Delta i_{L11}, \Delta i_{L12}, \Delta i_{L21}, \Delta i_{L22}, \Delta i_{L3},$ ) are determined, the minimum required inductance can be calculated as follows:

$$L_{11}, L_{12} \leq \frac{D_{max}V_{in}}{f_s \Delta i_{L1}} \quad (8)$$

$$L_{21}, L_{22} \leq \frac{(1 - D_{min})V_{in}}{f_s \Delta i_{L2}} \quad (9)$$

So, choose the inductance value as $L_{11} = L_{12} = L_{21} = L_{22}$ = 22μH from equation 8 and 9.

$$L_3 \geq \frac{V_{in}}{f_s \Delta i_{L3}} \quad (10)$$

So, choose the inductance value as $L_3$ = 1500μH from equation 10. The voltages across the capacitors can be calculated using following equations.

$$C_1 \leq \frac{D_{max} * I_0}{f_s \Delta V_{C1}} \quad (11)$$

So, choose capacitance value as $C_1$ = 220μF from equation 11.

$$C_2 \leq \frac{(1 - D_{min}) * I_0}{f_s \Delta V_{C2}} \quad (12)$$

So, choose the capacitance value as $C_2$ = 220μF from equation 12.

## 4. Simulation and Results

The inverter of 280W is simulated using MATLAB/SIMULINK R2020b, by choosing the parameters DC input voltage 26V with switching frequency 40kHz to obtain RMS output voltage of 110V.

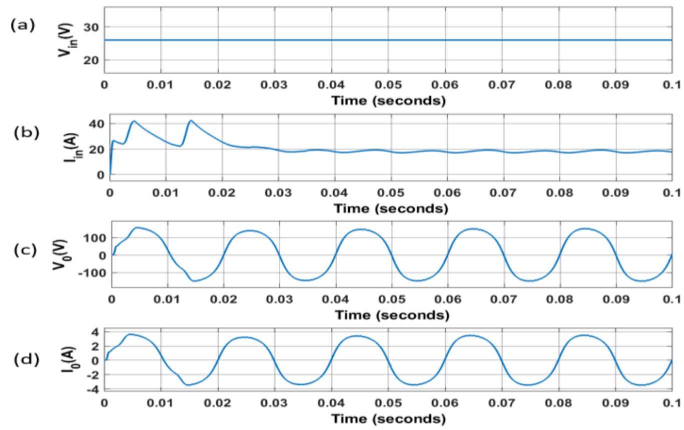



Fig. 5. (a) Input Voltage, (b) Input Current, (c) Output Voltage and (d) Output Current of the Inverter

The inductors $L_{11}, L_{12}, L_{21}, L_{22}$ are designed to 10μH and $L_3$ as 1500μH. The capacitors $C_0$ =3.3μF, $C_1$ = $C_2$ = 220μF, $C_{PV}$ =100μF. The output voltage and current of the inverter is obtained in the Fig. 5, $V_0$ = 110V and $I_0$ = 3.5A.

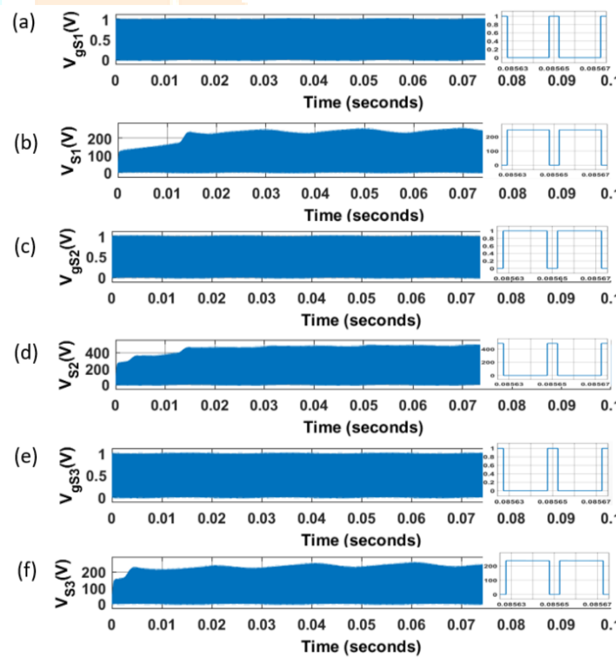



Fig. 6. (a) Gate Voltages of $S_1$, (b) $S_2$, (c) $S_3$, (d) Voltage Across Switch $S_1$, (e) $S_2$ And (f) $S_3$ of the Inverter

Pulsating input current of base inverter is improved to almost continuous constant input current which helps to eliminate imbalance of cells and batteries connected in series. In Fig.6, gate pulse and corresponding switch stresses are shown ($V_{S1}$ = 200V, $V_{S2}$= 450V and $V_{S3}$ = 250V). In the Fig.7 and Fig.8 inductor currents and capacitor voltages are given respectively. ($I_{L11}$= 22A, $I_{L12}$ = 22A, $I_{L21}$ = 21A, $I_{L22}$ = 21A, $I_{L3}$ = 3.5A, $V_{C1}$ = 25VA, $V_{C2}$ = 240V and $V_{C0}$ = 155.5V)

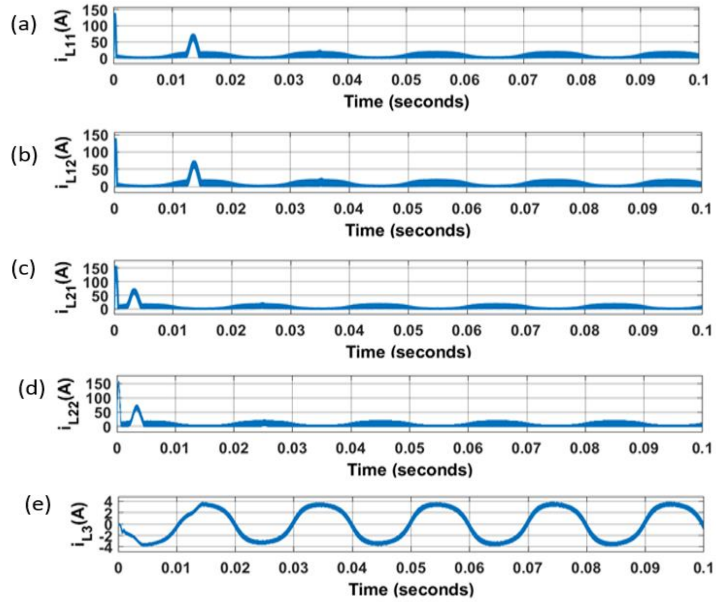



Fig. 7. (a) Current Through Inductors $L_{11}$, (b) Inductors $L_{12}$, (c) Inductors $L_{21}$, (d) Inductors $L_{22}$ and (e) Inductors $L_3$

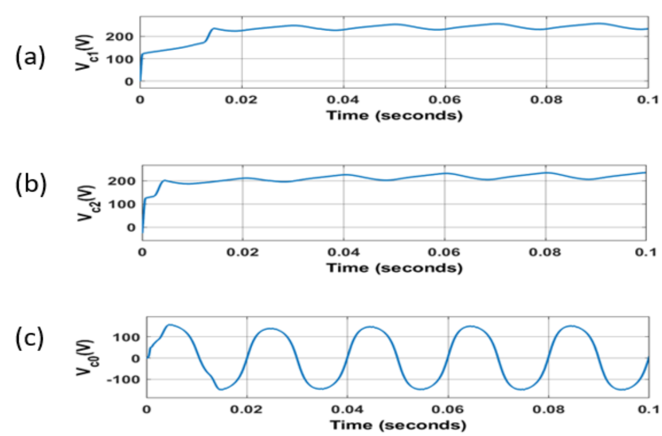



Fig. 8. (a) Voltage Across Capacitor $C_1$, (b) $C_2$ and (c) $C_0$

## 5. Analysis

The analysis of the proposed inverter is carried out by considering parameters like efficiency, THD, switching frequency etc.

### 5.1. Efficiency Vs Output Power

Efficiency tells the fraction of the input power delivered to the load. Here efficiency Vs output power with R load and RL load are obtained in the Fig.9 and Fig.10 respectively. The proposed inverters work efficiently about power 280W, around 93% efficiently in R load. It is observed in graph which is shown in Fig.10, that the efficiency is not much varied with power in RL load, therefore it can be used in motor drive applications.

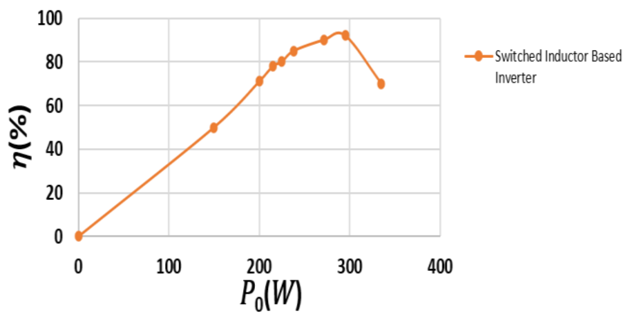



Fig. 9. Efficiency Vs Output Power for R Load

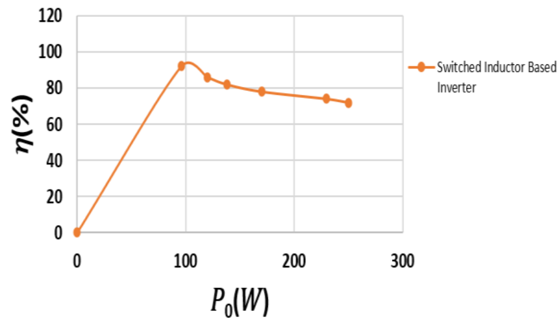



Fig. 10. Efficiency Vs Output Power for RL Load

5.2. THD Vs Switching Frequency

Fig.11 shows the graph of THD Vs switching frequency. At 40kHz frequency low value of THD is obtained. So, 40kHz frequency is selected as switching frequency. From Fig.11, it is observed that the THD of the proposed inverter is 4.3% which is within the IEEE std. limit.

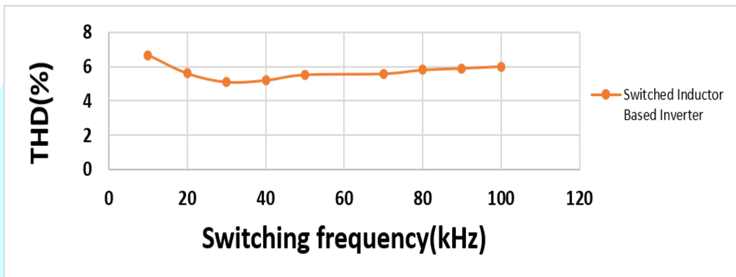



Fig. 11. THD Vs Switching frequency

## 6. Comparison

The comparison between transformerless common ground three switch single phase inverter and switched inductor-based inverter is given in table I. On comparison, it is observed that the number of components is more in proposed inverters. But the gain is more in proposed inverter. Even-though slight increase in stresses across switches is noticed, the input voltage required for proposed inverter is less for same power output. A component wise comparison is done in table II, shows that, although the number of components are increased in proposed inverter, the size of inductance are reduced much as compare to base paper [1], the overall weight of the inverter is reduced, hence in inverter has compact size with boosted gain.

TABLE 1

Comparison Between TCGS AND SI-TSI [Output Voltage =110VRMS]

| *Parameters* | *TCGS [1]* | *Proposed inverter* |
|---|---|---|
| No. of switchs | 3 | 3 |
| No. of capacitors | 4 | 4 |
| No. of inductors | 3 | 5 |
| No. of diode | 1 | 7 |
| Output power | 280W | 280W |
| Input voltage | 38V | 26V |
| Switching freqency | 40kHz | 40kHz |
| Gain | 4.1 | 5.9 |
| THD | 2.33 | 4.31 |
| Efficiency | 94% | 93% |

TABLE II
Component Wise Comparison Between Inverters

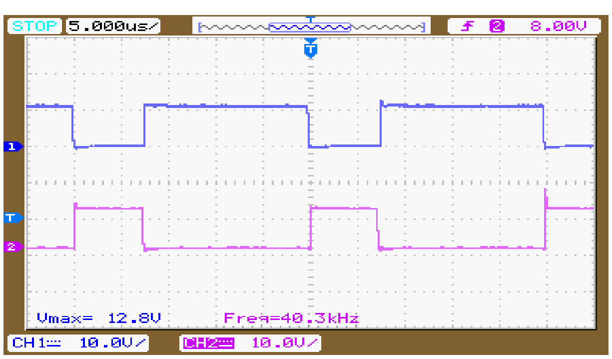
| *Table* | *Proposed inverter* | *TCGS [1]* | *SCII[2]* | *SUTI[2]* |
|---|---|---|---|---|
| No. of switchs | 3 | 3 | 3 | 6 |
| No. of capacitors | 4 | 4 | 4 | 4 |
| No. of inductors | 5 | 3 | 4 | 3 |
| No. of diode | 7 | 1 | 0 | 2 |
| Total | 19 | 11 | 11 | 15 |

TABLE III
Designed Parameters for Hardware Implementation

| *Parameters* | *Values* |
|---|---|
| Switch | TGAN60N60FD, IGBT |
| Capacitors $C_0 C_1, C_2, C_{pv}$ | 22μF, 47μF, 100μF, 4.7mF |
| Inductors $L_{11}, L_{12}, L_{21}, L_{22}$ | 10μH |
| Inductors $L_3$ | 1500μH |
| Output power | 9W |
| Input voltage | 5V |
| Switching freqency | 40kHz |
| Output voltage | 26V |
| Diode | MBR30100 |

Experimental setup for hardware implementation is given in Fig.12 and parameter are listed in table III. The switching pulses are obtained from TMS320F28027F controller given to interfacing circuit. Interfacing circuit includes optocoupler TLP250h for isolation between driver and power circuits. The output from driver circuit is given to IGBT switches as gate pulse of the proposed inverter in the control circuit. Input 5V with 0.486A DC supply is given from DC source. Switching pulse for S1 and S3 are same and it is NOT pulse is given to $S_2$ shown in Fig.13. An output voltage of about 20V with 50Hz frequency is obtained which is given in Fig.14 respectively.


Fig. 12. Hardware Implementation



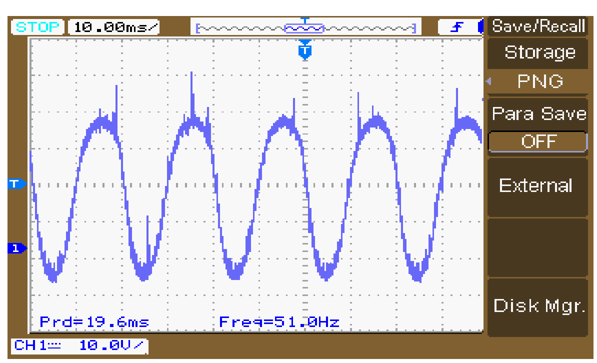




Fig. 13. Switching Pulses for Hardware

Fig. 14. Hardware Output Voltage

## 7. Conclusion

In this project a switched inductor based three switch single phase inverter is proposed. It is a combination of switched inductor-based boost converter and semi-quasi-Z-source converter. The proposed inverter has a common ground between the input and output terminals which results in the elimination of leakage current in PV systems, high voltage gain than that most of similar common-ground inverters, compact size and also has the capability of injecting power to the grid. All these advantages make it a candidate to use in single stage microinverter systems. The circuit is simulated in Matlab R2020b software. From the simulation 93% of efficiency corresponding to load resistance of 43$\Omega$ is obtained. Operational principle is described and theoretical analysis is done. The comparative study shows the superiority of the proposed inverter and a 9W prototype is built using TMS3280F28027F controller and the experimental results proves the performance of the proposed inverter.

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