# Design and Analysis of a Transformer-Less Single-Phase Grid-Tie Photovoltaic Inverter Using Boost Converter with Immittance Conversion Topology

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*Abstract*—**The following paper presents a newly developed transformer-less grid-tie pure sine wave inverter (GTI) for photovoltaic (PV) application. The proposed topology employs a PV panel, a dual-stage switch mode boost converter, a voltage divider circuit, an H-bridge inverter and a T-LCL Immittance conversion filter circuit. For gate drive circuit of inverter, a combination of sinusoidal pulse width modulation (SPWM) and square wave signal under grid synchronization form are used. The proposed design has a various desirable features such as better utilization of the photovoltaic array, low cost, compact size, simpler control, and lower harmonics with higher efficiency. It highly reduces total harmonic distortion (THD) which is less than 0.5%, and swells inverter efficiency up to 98%.The proposed design is mathematically modeled which is simulated via PSIM and finally the results are presented to confirm the effectiveness of this grid-tie inverter viability.**

Keywords— **Boost Converter; voltage divider; T-LCL Immittance Converter; Grid-Tie Inverter (GTI)**

## I. INTRODUCTION

Pollution free green-energy demand is increasing exponentially due to the change of world climate. With the increase of population of the world and the rapid growth of the global economic, the demand of the energy resources especially electricity is faced a tremendous increase. Such rapid increase in electricity demand, using conventional and classical electricity generation by burning the fossil fuel to fulfill the electricity demand is no longer able fulfill the demand. Besides that, burning the fossil fuel will result in environmental problems. The emission of carbon dioxide, methane and other greenhouse gasses will result in global warming problem. This has given an opportunity for the renewable energy resources and technology to take over the electricity generation process. Therefore renewable energy sources play a very crucial role now a day in electric power generation due to its environmental friendly and pollution free green energy. Photovoltaic (PV) energy is one of the potential sources of renewable energy, which gets more preference due to its availability, simplicity, less maintenance and reliability options [1].

In photovoltaic (PV) system solar energy is converted into electrical energy through PV arrays [1-6].There are two mandatory tasks in PV system. They are-(1) utilizing maximum energy from PV arrays, (2) using the most reliable, highly efficient and cost effective configuration for the power converter in order to inject only active current into the grid, i.e. pure sinusoidal current in phase with the grid voltage [4]. In a conventional inverter, transformer is used to match the inverter output with the utility grid output [2-4]. But the only limitation here is that transformers are bulky, heavy weighted and costly equipment. Moreover transformer highly influences the enhancement of Total Harmonic Distortion (THD) in inverter [2], [7].

In this paper, a boost power converter is recommended instead of transformer in order to achieve low THD as well as high efficiency. The boost power converter converts a large scale of voltage similar to the grid value but a single-stage boost converter requires a high duty cycle which is inconvenient for MOSFETs switching. Therefore, the DC-DC power conversion is employed through a dual-stage boost converter to obtain suitable duty cycle for MOSFETs switching. Likewise, a voltage divider circuit is also used to synchronize the output frequency with the grid. Instead of using a conventional low-pass LC filter, a T-LCL immittance converter is employed in the proposed inverter, which not only suppresses the harmonics contained in the inverter output but also maintains a constant output current for any type of load, and thus stabilizes the inverter output [8-9].

The proposed inverter configuration consists of five main parts. They are-1) a PV array for converting solar energy to electrical energy, 2) a dual-stage DC-DC boost converter to step up PV array voltage to the grid level, 3) an H-bridge DC-AC converter to acquire AC voltage, 4) a T-LCL immittance converter to deliver a nearly constant as well as filtered output current, and 5) a voltage divider circuit which is used as gate signal by combining SPWM and square wave for switching the gate drive of the inverter. The block diagram of proposed inverter is shown in Fig.1.

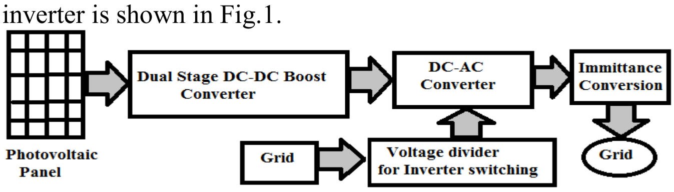


**Fig.1.** Block diagram of proposed GTI

## II. DESIGN OF SOLAR PANEL

At first, under Standard Test Condition (STC) Sanyo HIP-210HKHA6 panel with 2KW maximum output power is being tested. At STC condition of 25-degree temperature and irradiance of 1000 W/m$^2$ the panel is stimulated which output voltage is 24V and is shown in Fig.2. Table-I shows the system parameters of photovoltaic module.

TABLE-I SYSTEM PARAMETERS OF PHOTOVOLTAIC MODULE

| Parameter | Value |
|---|---|
| Manufacturer | Sanyo |
| Solar Panel Model | HIP-210HKHA6 |
| Short circuit Current (Ix) | 5.57 A |
| Open Circuit Voltage (Vx) | 50.9 V |
| Maximum Power (Pmax) | 210 W |
| Characteristic Constant (b) | 0.0773 |

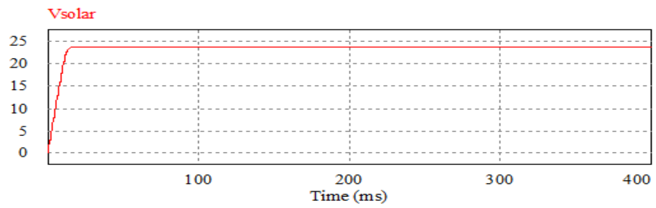


**Fig.2.** PV array voltage

## III. DESIGN OF BOOST CONVERTER

This section describes the design of a dual-stage DC-DC boost converter for converting unregulated voltage of PV array to a fixed high level regulated voltage which is same as the grid value (312V peak or 220V rms in Bangladesh). In this paper, a dual-stage (N=2) boost converter is proposed since the duty cycle of single-stage boost converter would be large (above 90%), which is not convenient for MOSFET switching. Dual-stage converter provides a more symmetrical duty cycle, and reduces the voltage stress on the MOSFETs. Here the conversion of boost converter is done based on the conversion ratio, $x^2 = 312/24$ which is converted voltage from 24V DC to 86V DC in the first-stage and 86V DC to 312V DC in the second-stage. The design parameters of the first-and second-stage boost converters are listed in Table-II and Table-III respectively.

TABLE-II DESIGN OF FIRST-STAGE BOOST CONVERTER

| ***Symbol*** | ***Actual Meaning*** | ***Value*** |
|---|---|---|
| $V_{in}$ | Given input voltage | 24V |
| $V_{out}$ | Desired average output Voltage | 86V |
| $f_s$ | Minimum switching frequency of the converter | 20KHz |
| $I_{LMax}$ | Maximum inductor current | 260A |
| $\Delta I_L$ | Estimated inductor ripple current (1.75% of inductor current) | 4.55A |
| $\Delta V_{out}$ | Desired output voltage ripple (0.05% of output voltage) | 44mV |
| $I_{out}$ | Maximum output current($V_{out}$/R) | 4.3A |

TABLE-III DESIGN OF SECOND-STAGE BOOST CONVERTER

| ***Symbol*** | ***Actual Meaning*** | ***Value*** |
|---|---|---|
| $V_{in}$ | Given input voltage | 86V |
| $V_{out}$ | Desired average output Voltage | 312V |
| $f_s$ | Minimum switching frequency of the converter | 21KHz |
| $I_{LMax}$ | Maximum inductor current | 230A |
| $\Delta I_L$ | Estimated inductor ripple current (26% of inductor current) | 60A |
| $\Delta V_{out}$ | Desired output voltage ripple (0.1% of output voltage) | 0.35V |
| $I_{out}$ | Maximum output current($V_{out}$/R) | 10.4A |

### *3.1 Duty Cycle*

Maximum duty cycle for the first-stage is,

$$D_{1,boost} = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{24}{86} \approx 0.72$$

Maximum duty cycle for the second-stage is,

$$D_{2,boost} = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{86}{312} \approx 0.72$$

### *3.2 Inductor Selection*

In the boost converter, a smoothing inductor is used in series with the input voltage to limit the current ripple of converter. In conventional processes, inductor value is normally chosen from the recommended data sheets. But here voltage conversion is occurred at a large scale (24V DC to 86V DC) and hence no inductor value is available in the data sheets for this voltage conversion range. Therefore, the following equation is a good estimate for choosing the right output value of inductor for the first-stage boost converter [10]:

$$L_{1,boost} = \frac{V_{in}(V_{out} - V_{in})}{\Delta I_L \times f_s \times V_{out}} = \frac{24\times(86-24)}{4.55\times 20000\times 86} \approx 190\,\mu\text{H}$$

Similarly, the same method can be used in order to choose the inductor value for the second-stage boost converter:

$$L_{2,boost} = \frac{V_{in}(V_{out} - V_{in})}{\Delta I_L \times f_s \times V_{out}} = \frac{86\times(312-86)}{60\times 21000\times 312} \approx 50\,\mu\text{H}$$

### *3.3 Capacitor selection*

The following equation is used to adjust the output capacitor value for a desired output voltage ripple. The estimated capacitor value for the first stage is [10]:

$$C_{1,boost} = \frac{I_{out}\times D}{f_s \times \Delta V_{out}} = \frac{4.3\times 0.72}{20000\ \times .044} \approx 3.5\,mF$$

And the estimated capacitor value for the second-stage is,

$$C_{2,boost} = \frac{I_{out}\times D}{f_s \times \Delta V_{out}} = \frac{10.4\times 0.72}{21000\times .35} \approx 1mF$$

### *3.4 The Designed 24-312V DC-DC Boost Converter*

The power converter which consists of two boost converters and two PWM gate pulses to drive the MOSFETs is shown in Fig.3. The output of the designed boost converter simulates using PSIM is shown in Fig.4 which indicates that the output of the first-stage is 86V and second-stage is 312V DC and which is later converted to 312V AC (or 220V rms) using an H-bridge inverter.

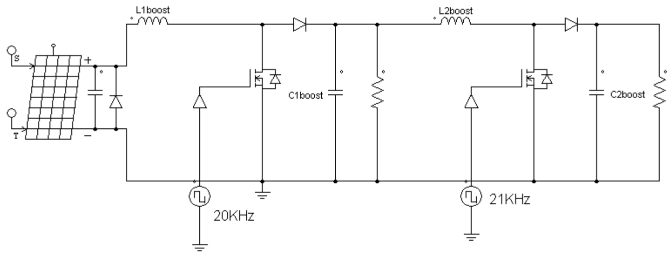


**Fig.3.** PSIM simulation circuit of the dual-stage boost converter using the designed circuit parameters

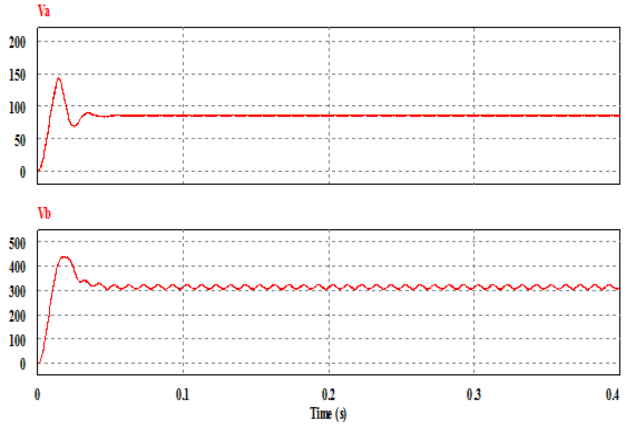


**Fig.4.** Boost converter output: $V_a$ is the first-stage output (86V) and $V_b$ is the second-stage output (312V)

## IV. Design of Voltage Divider Circuit

This section provides the design of an AC-DC step down power converter. Here AC voltage sample is taken from grid which is converted into 312V pulsating DC through full bridge rectifier as shown in Fig.6. Then 312V pulsating DC is converted into 7.07V pulsating DC by implying voltage divider circuit which is shown in Fig.5. Here voltage divider circuit can be considered as dc equivalent to an ac step down transformer.

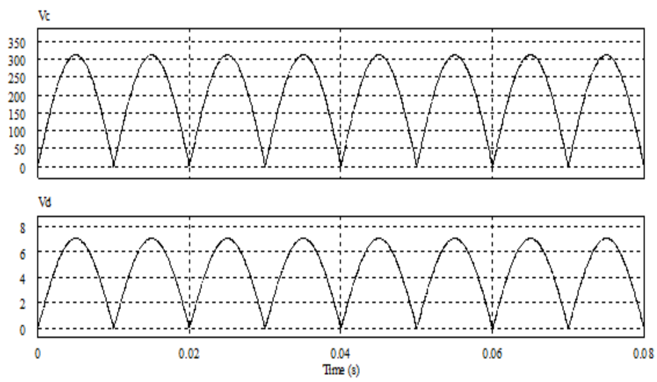


**Fig.5.**Voltage divider output: $V_C$ is output of precision rectifier (312V) and $V_d$ is the output of voltage divider (7.07V)

### *4.1 The Designed 220V-5V AC-DC Voltage Divider*

The voltage divider which consists of a rectifier circuit with two resistors is shown in Fig.6. The output is 7.07V (5V rms) as shown in Fig.5. In such a circuit, output is given to non-inverting input portion of a comparator; which compare with the triangular wave in inverting portion of comparator. This part is assisted to match the inverter output voltage frequency with the grid frequency.

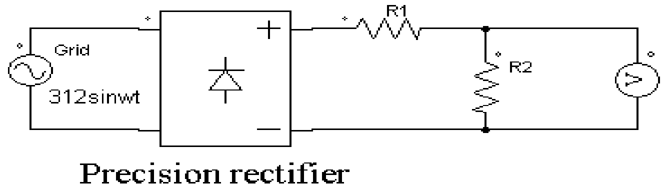


**Fig.6.** Voltage divider circuit in PSIM simulation

## V. Proposed Grid-Tie Inverter

### *5.1Grid Synchronization*

The output voltage of a grid-tie inverter should maintain some fixed requirements so that it may provide power to grid utility [3]. The requirements are given below:

i. The output voltage amplitude should equal as grid amplitude.
ii. The frequency of inverter should be equal as grid frequency (50Hz in Bangladesh).
iii. The phase of inverter should match with grid.

In a GTI function are divided into two major parts: grid synchronization, power transmitting. For synchronizing frequency of inverter with the grid a sampled of sine wave is taken from grid. Afterward the sampled sine wave is rectified and passed through a voltage divider circuit and its output is compared with high frequency triangular wave to build SPWM which ensures same frequency [11]. To match same phase SPWM sets with phase-shift to zero. Then two sets of AND gate operation is performed with combination of SPWM and square wave to construct four individual signal for switching of inverter. The zero crossing detects when inverter output and grid voltage both are in phase [6]. Once zero crossing is detected inverter and grid connection is tied via connector.

After inverter and grid are connected mutually it starts to transmit power from PV array to grid. Now for protection purpose to avoid transmission of power when grid is down due to unavoidable circumstances a relay circuit is employed to trip inverter circuit from grid at this particular situation. A current transformer takes measurement if any fault is occurred at grid relay circuit will be trip and circuit breaker will isolated inverter from grid. Thus measurement and protection purpose of inverter will be served.

### *5.2Power Circuit*

The proposed inverter circuit has employed four numbers of MOSFETs for switching purpose. The circuit is employed a DC-DC boost power converter, AC-DC voltage divider and H-bridge inverter as shown in Fig.7.

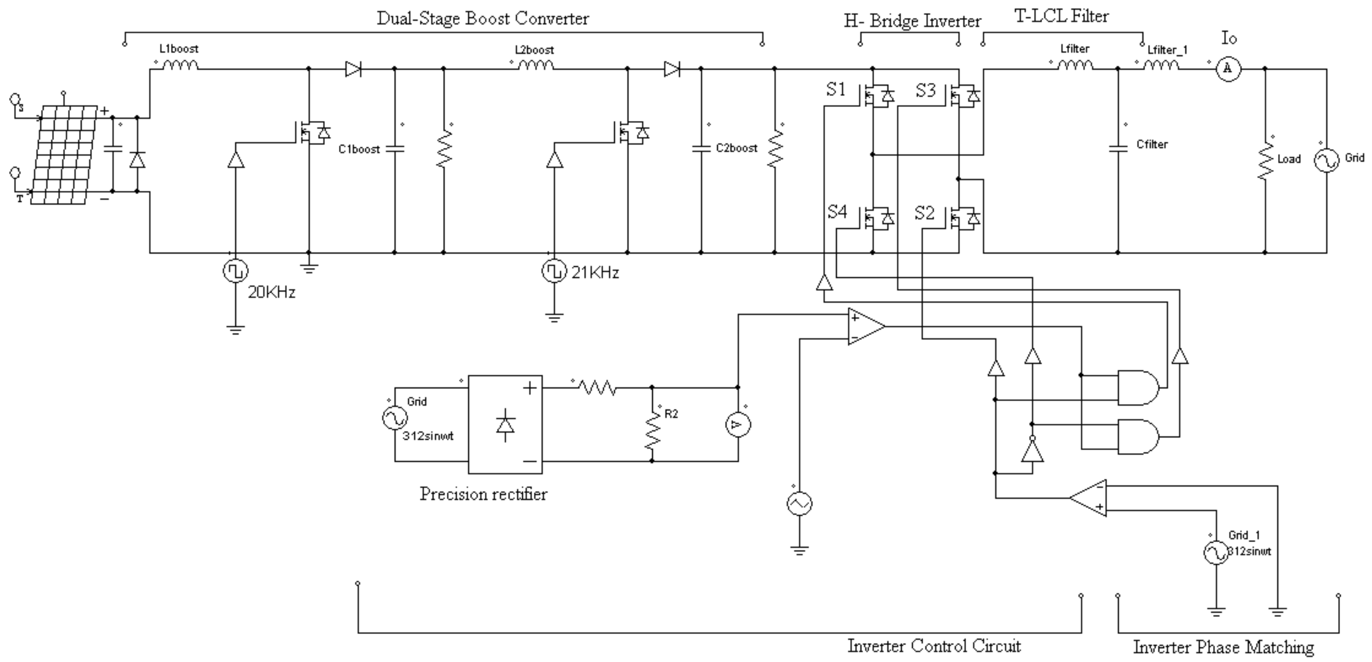


**Fig.7.** Complete schematic diagram of transformer-less grid-tie inverter in PSIM

A DC-DC boost converter, the design of which is shown in section III, is used to step up the unregulated input voltage from 24V to regulated 312V, which is finally converted to 312V pure AC (220V rms) applicable to grid by using inverter.

*5.3Switching Circuit*

The switching control circuit of the proposed inverter contains analogue and digital circuits. Here, the analogue circuit generates pulse for the power circuit while the digital circuit controls the sequence of gate drive. In conventional inverter design, Sinusoidal Pulse Width Modulation (SPWM) is generally used to get AC output [1-3].

However, in this article, the combination of SPWM and a square wave is used for inverter switching as this new technique reduces the losses by reducing switching frequency [6]. The output of the buck converter is compared with high frequency triangular wave (20KHz) using comparator to build SPWM signals. A square wave with 50% duty cycle and frequency similar to the grid frequency (50 Hz in Bangladesh) and in phase with the grid voltage is used. The square wave is also passed through a NOT gate which produces a signal of $180^0$ out of phase with the original signal.

The inverter requires four sets of gate signal as it uses four MOSFETs in the circuit. Under this situation two sets of SPWM signal and two sets of AND gate operations are performed. The four sets of gate signal can be labeled into two groups. The first group consists of MOSFETs S1 and S2 while the second group consists of MOSFETs S3 and S4. When S2 is switched on by the square wave signal, SPWM appears at S1, and at that time S3and S4 switches are off. Again when S4 is turned on by the square wave signal, SPWM appears at S3, at that time S1 and S2 switches remain off. For S1 and S2 pair, positive voltage emerges across the load while for S3 and S4 pair, negative voltage emerges across the load. The gate switching signals for S1, S2, S3 and S4 are shown in Fig.8. Thus the inverter produces a full square wave output which contains lots of harmonics at the output side of the inverter as shown in Fig.9 in section 6.

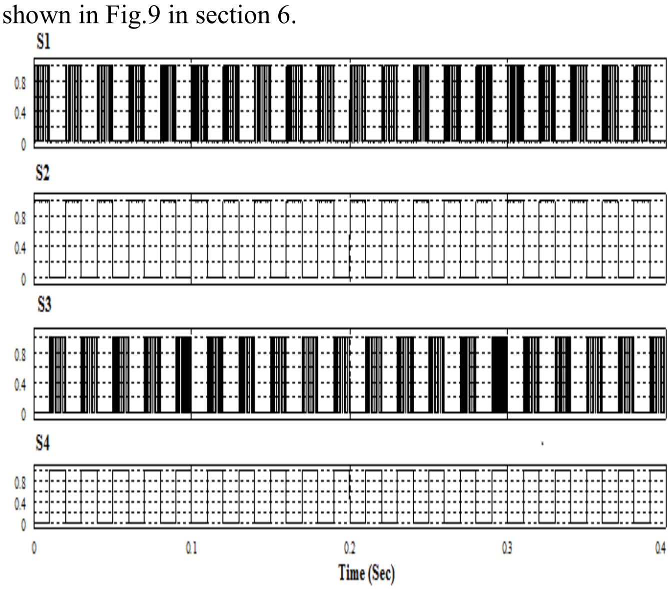


**Fig. 8.** Switching signal from control circuit to MOSFETs S1, S2, S3 and S4

*5.4Filter circuit*

To eliminate harmonics from the inverter output, a filter circuit is employed. In conventional inverters, an LC filter is used. In this article, a T-LCL immitance converter is employed as shown in Fig.7 which consists of two inductors $L_1$ and $L_2$ as well as a capacitor, C in T shape. The equations of the output current of the filter are found as [8-9]:

$$I_2 \cong \frac{V_1}{Z_0}\left[1 - \frac{1}{Q}\frac{Z_2}{Z_o}\right] \quad (1)$$

Where $V_1$ is the input voltage, $Z_2$ is the load impedance, $Q$ is the quality factor

$$Q = \frac{\omega L}{r} \quad (2)$$

Here $\omega = 2\pi f$ is the angular frequency, $r$ is the internal resistance of the inductor and $Z_0$ is the characteristic impedance determined by the filter components, $L$ and $C$:

$$Z_0 = \sqrt{\frac{L}{C}} \quad (3)$$

When the internal resistance of the inductor is negligible or zero, the quality factor becomes infinity. Under this condition, the second term becomes zero, giving the ideal condition:

$$I_2 \cong \frac{V_1}{Z_0} \quad (4)$$

From Eq.(4) it is observed that the output of T-LCL filter is independent of load. Therefore, in the proposed inverter, a T-LCL immittance converter is applied as a filter circuit because it is not only capable in reduction of harmonic but also helpful to maintain constant current at the load.

The value of $C$ and $L$ of T-LCL filter (considering Butterworth type) is calculated using the condition of cut-off frequency of low pass filter i.e.

$$Z_0 = X_C = \frac{1}{2\pi f_C C} \quad (5)$$

In the proposed design, the cutoff frequency, $f_C$ =50Hz and characteristic impedance is assumed as 20Ω. Therefore, the value of $C$ and $L$ is calculated using Eqs.(5) and (3) as,

$$C = \frac{1}{2\times\pi\times f_C \times Z_0} = \frac{1}{2\times\pi\times 50\times 20} \approx 0.159mF$$

$$L = CZ_0^2 = 0.159\times10^{-3}\times(20)^2 \approx 63.60mH$$

## VI. Simulation Results & Discussion

Fig.9 shows the simulated output voltage waveform, which is non-sinusoidal and distorted, and contains excessive harmonics. A low-pass T-LCL filter is employed at the output terminal of the inverter to reduce the harmonics thereby producing a pure sinusoidal output voltage.

After filtering, we obtained 220V (RMS), 50Hz pure sine wave output voltage as shown in Fig.10. It is observed that the output voltage of proposed inverter becomes stable after couple of cycles since it is connected to grid.

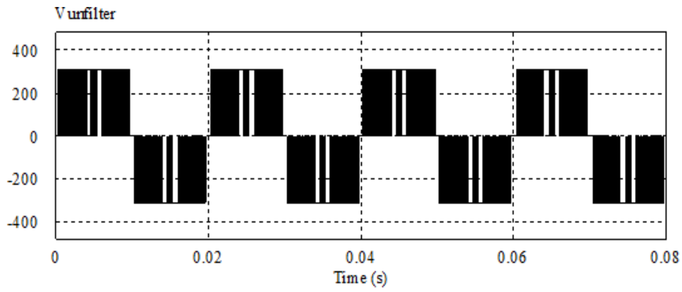


**Fig.9.** Output voltage waveform without filtering in PSIM

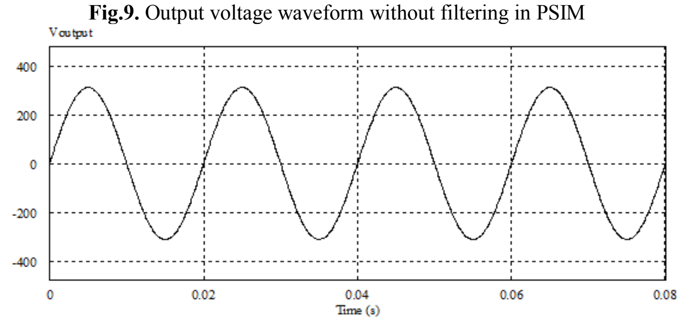


**Fig.10.** Output voltages after filtering in PSIM

The peak value of the inverters output current is an important factor in designing the inverter stack size. The inverter current rating is normally determined by the filter impedance and the rated load impedance in a steady state. The output current should be maintained constantly. Fig.11 shows the inverter output current which becomes stable within a couple of cycles. And in Fig.12 shows inverter voltage and current is in same phase.

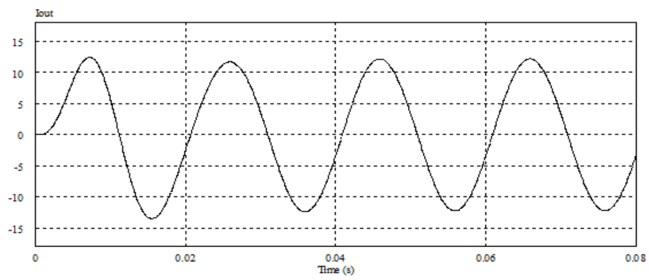


**Fig.11.** Output current waveform in PSIM

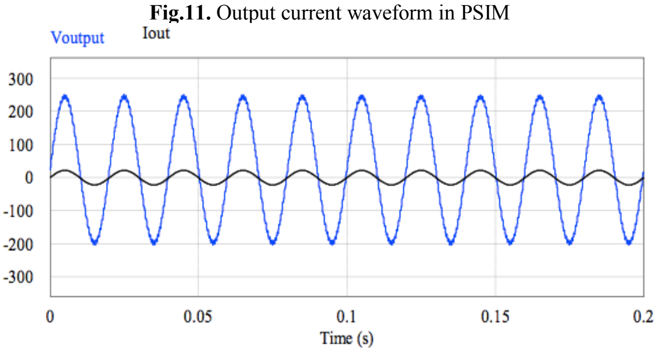


**Fig.12.** Output voltages and current are in phase of GTI in PSIM

In order to test the performance of the inverter, the load current was measured for $R$ Load with and without applying filter circuit. The inverter was tested by employing both $LC$

and *LCL* filter. The load impedance was varied from 5Ω to 100Ω by considering the characteristic impedance as; $Z_0$=20Ω. It was observed that the load current without filter varies in a larger range than that of the load current with filter circuit is employed as shown in Fig.13. It is also observed that the output current is independent of load when employing a *T-LCL* filter.

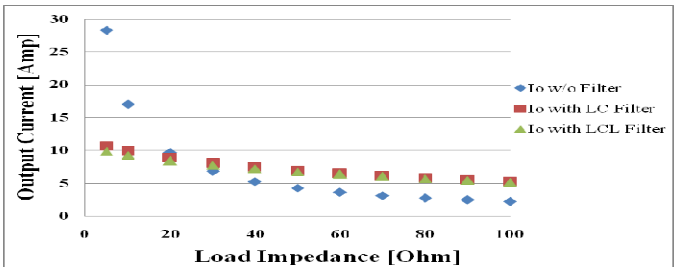


**Fig.13.** Output current vs. Load impedance

By varying resistive load, the efficiency of the inverter was monitored with LC and T-LCL filter as illustrated in Fig.14. It is observed that the efficiency of T-LCL filter is slightly higher than that of the conventional LC filter due to its constant current characteristic.

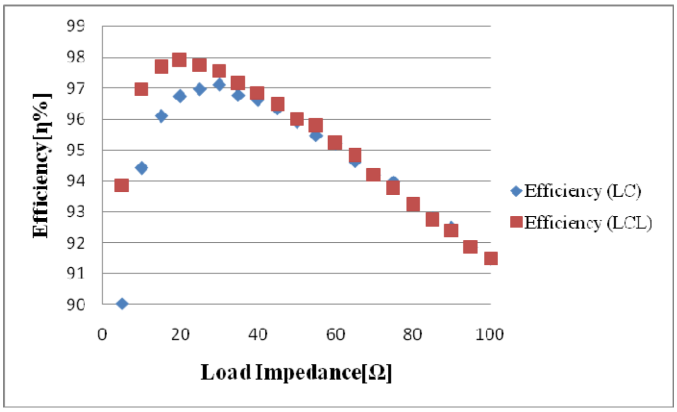


**Fig.14.** Efficiency vs. Load impedance

Table-IV reviews the output current and voltage performances. Thus it is observed from table analysis that inverter output is optimum when modulation index is 0.8. At that time output power of GTI is 2.4KW.

TABLE -IV
SUMMARY OF TRANSFORMER-LESS INVERTER SIMULATION RESULT IN PSIM

| Modulation Index | Voltage THD *(before filtering)* | Voltage THD *(after filtering)* | RMS Output Voltage *Vo(V)* | RMS Output Current *Io(A)* | Power Factor | Power $P_o$ *(Watt)* |
|---|---|---|---|---|---|---|
| 0.3 | 1.53 | 0.01 | 142.25 | 4.82 | 0.99 | 685 |
| 0.6 | 0.89 | 0.007 | 186.63 | 9.10 | 0.99 | 1699 |
| 0.8 | 0.54 | 0.008 | 220.47 | 10.86 | 0.99 | 2393 |
| 1.0 | 0.47 | 0.009 | 231.16 | 11.27 | 0.99 | 2606 |
| 1.5 | 0.46 | 0.013 | 238.94 | 11.65 | 0.99 | 2785 |
| 2.0 | 0.47 | 0.014 | 241.56 | 11.78 | 0.99 | 2846 |
| 2.5 | 0.48 | 0.016 | 242.90 | 11.85 | 0.99 | 2878 |
| 3.0 | 0.49 | 0.016 | 243.85 | 11.89 | 0.99 | 2900 |

## VII. CONCLUSION

This paper presents a transformer-less photovoltaic grid-tie inverter for residential application, the output of which is 220V rms at grid to meet the future power crisis. The simulation result using PSIM ensures that the frequency of the inverter output voltage is exactly 50Hz with a magnitude of 220V rms and is in phase with the grid voltage. The total harmonic distortion (THD) of the inverter output is less than 0.1% which is much lower than the IEEE519 standard, and the efficiency of the inverter also increases up to 98%. Therefore, the proposed inverter is highly efficient, cost effective as well as compact in size for being transformer-less, and it is appropriate for supplying constant current and dynamic load with T-LCL immittance converter.

In future, the hardware of the proposed grid-tie inverter will be constructed with the help of a microcontroller.

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