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Design of Grid Connected Buck-Boost PV Inverters for Residential Application in a Single Stage

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Abstract:- **The Proposed design topology has numerous attractive (useful) features such as higher efficiency since photovoltaic array is utilized efficiently, compact size as only three switches are used in the inverter circuit, low cost, simpler control circuit. A combination of Sinusoidal Pulse Width Modulation (SPWM) and Square wave is used for switching the inverter circuit. To control SPWM duty cycle and to regulate instantaneous ac output current from the inverter and to stabilize the output as fast as possible, a closed loop control circuit is employed. The proposed design is mathema-tically modeled in MAT Lab Simulink and PSIM. Finally, the simulation results are presented to verify the viability of the proposed single stage three-switch buck-boost inverter for grid-connected PV application.**

I. INTRODUCTION

Electricity plays an important role for the survival of the mankind and the growth of a nation. The classical and conventional method of generating electricity is by burning fossil fuels which is no longer being able to fulfill the increasing electricity demand all around the globe. This conventional method is giving rise to environmental problems which is causing dramatic change to the world climate and this is calling upon a serious threat to the noble planet. The emission levels of harmful

Gases such as Carbon dioxide (CO2), Carbon monoxide (CO), Sulphur dioxide (SO2) are increasing in large scales which in turn are blatantly killing our planet and alarm the rise in global warming problems. The cost of fossil fuel is increasing on a daily basis as the natural reserves will get exhausted with a few decades which will create shortage of the world'senergy. In such circumstances, the conventional method can no longer be thought as the optimum solution for the energy crisis. Hence, the renewable energy sources have taken over the electricity generation process. Renewable energy sources are of many types such as solar, wind, biomass, hydro and tidal power. Photovoltaic energy is one of the potential sources of renewable energy, which sets more preference due to its availability, simplicity, and lower maintenance and reliability options. PV system converts solar energy into electrical using an inverter.

Conventionally, the grid-connected inverters are classified as single-stage and two-stage configuration. Two-stage or multiple stage configurations has four-switched buck-boost GTI are commonly used in PV application. Even though two-stage buck-boost inverter can reach a reasonably high capacity, the additional power stage requires more power components, which condenses circuit complexity as well as shoots up the cost.

Typically a single-stage inverter is an inverter is an inverter with only one stage of conversion for both stepping up and stepping down the DC voltage from a PV sources and modulating the sinusoidal output current or voltage.

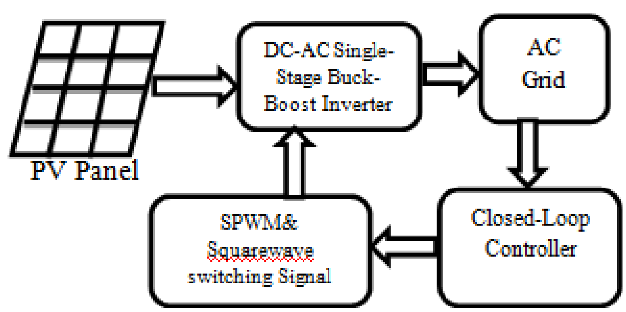

Fig.1. Block diagram of Single stage Buck-Boost PV inverter

The design of a three-switch single stage grid-connected buck-boost inverter, in which buck-boost dc-dc converter and a fly-back operation principles are applied to transfer energy from input PV dc side into output utility grid side. Fig.1. shows the block diagram of Single stage Buck-boost PV inverter. From the Photovoltaic panel DC voltage is sent to the Buck-Boost inverter, depending on the voltage the inverter will step down or step up the DC voltage and convert it in to AC voltage and send it to the AC Grid.

A combination of Sinusoidal Pulse Width Modulation (SPWM) and Square Wave Signal is used for switching the inverter with grid synchronization. Closed loop controller is used to control the duty cycle of SPWM and to regulate instantaneous AC output current as fast as possible. As compared to the conventional single stage buck-boost inverter, other two-stage buck-boost inverters and buck inverters with line frequency transformers, both the component count, size and cost of the proposed buck-boost Grid Tie-Inverter (GTI) is minimized, thus exhibiting a more reliable and cost effective design with overall high efficiency for domestic PV system.

II. REQUIREMENTS OF GRID-SYNCHRONIZATION.

The Grid-Tie Inverter (GTI) design contrasts a bit from traditional stand-alone inverter. GTI is an electric power conversion device used to convert raw generated power in various form into regulated AC and feed it into the utility grid in a grid in a synchronized and controlled manner. The output voltage from GTI is required to meet certain conditions for the inverter to be connected to the grid.

1. Voltage magnitude and phase of inverter must be same as grid voltage.

2. The GTI output frequency must match with the grid frequency (50Hz).

To fulfill the above conditions, the grid voltage is sampled and then kept as a reference for the design of switching signal. This require for the GTI has to force power produced from the PV panels into the grid. The real and reactive power flow of the GTI into grid is as shown,
Real Power,P=$(|Vinv||Vgrid|)sin\phi/Zt$...(1)

Reactive Power, Q
Q=$(|V^2_{inv}|/Z_t)$-$(|Vinv||Vgrid|)cos\phi/Zt$…(2)

Where, Z_t= Linking line impedance
V_{inv}= Output voltage of inverter
V_{grid}= grid power voltage
ϕ = angle difference between V_{inv} and V_{grid}
Practically for stability reasons the phase angle should be kept less than 90degrees.

III. DESIGN OF PROPOSED BUCK-BOOST GTI.

A. Power Circuit Design.

The Proposed single-stage grid-connected buck-boost inverter power circuit configuration consists of three MOSFET switched Q1, Q2, and Q3, three diodes D1, D2 and D3, two Coupled inductors Land same turns, which is used to transfer energy from the input PV array dc side to the utility grid. Only one MOSFET switch is turned ON in each state and inductor is always connected with charging and discharging circuit. The inverter operation is divided into two states charging and discharging states in-turn these states are sub-divided into two cycles called as positive half cycle and negative half cycle.

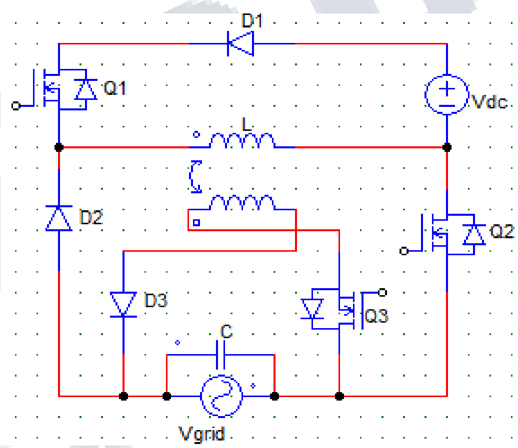

Fig.2. Power Circuit of Buck-Boost GTI

Positive Half Cycle

In the positive half cycle there are two operations such as charging and discharging states. Switch Q3 is always closed in the positive half cycle state of the inverter.

(1). During charging state in the positive half cycle, the switches Q2 and Q3 are turned off, and the switch Q1 is turned ON to charge the inductor L1 through the diode D1. At that time the capacitor provides continuous current to the load.

(2). During discharging state, the switches Q1 and Q3 are turned off, and energy that was stored in inductor, L1 releases through the switch Q1, to the grid utility.

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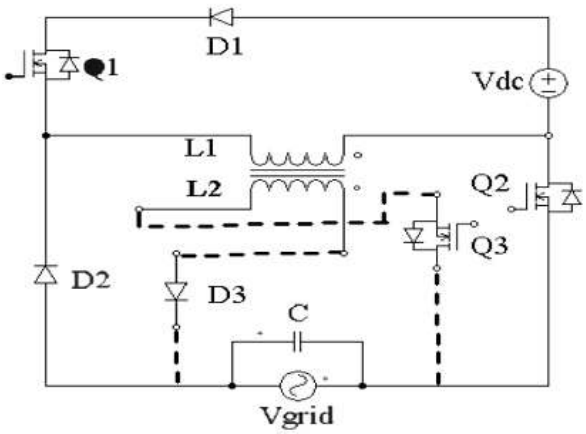

Fig. 3. Equivalent circuit on positive half cycle.

Negative Half Cycle

Negative half cycle has two modes of operation charging and discharging states. In negative half cycle Q2 is always turned off.

(1). During charging state the switches Q2 and Q3 are turned off, and the switch Q1 is ON to charge the inductor L1, through the diode D1. At that state capacitor provides continuous current to load.

(2). During discharging state the switch Q1 and Q2 are turned off, and the switch Q3 is turned on. The stored energy in L1 will be transferred to the coupled inductor L2 which discharge to the load through switch Q3 and diode D3.

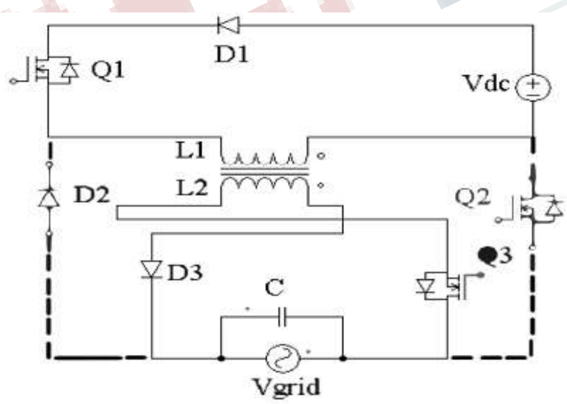

Fig.4. Equivalent circuit of negative half cycle

B. Mathematical Design of Buck-Boost Inverter Circuit.

In this section, we present the mathematical calculations involve in the three-switch grid-connected Buck-Boost inverter design. Table-I illustrates the design specifications of our Proposed 600W PV three-Switch Buck-Boost GTI.

TABLE-I
DESIGN SPECIFICATIOLN OF THREE SWITCH BUCK-BOOST GTI

Symbol	*Actual Meaning*	*Value*
V_{dc}	Input PV array Voltage	24V
V_{ref}	Maximum output voltage	312V
F_{sw}	Switching frequency	10KHz
T_s	Switching period	100µs
M_a	Modulation index	93%
ΔI	Inductor ripple current	0.02
k	Co-efficient factor	3.2
P_{out}	Maximum output power	600W
Vrms	Rms voltage	220V

Modulation Index:

The Modulation Index or Modulation Depth of a modulation scheme describes by how much the modulated variable of the carrier signal varies around its un-modulated level.

$$M_a = \sqrt{2}Vrms\,/(Vdc + \sqrt{2}\,Vrms)$$
$$= \sqrt{2} *220 / (24+220*\sqrt{2}) = 93\%$$

Coupled Inductor Selection:

For a grid-connected inverter a simple critical method, based on input-output power balance, is applied to unearth the mathematical control-to-output solution and to determine the inductance value. The value of coupled inductance, L for DCM operation is calculated by using following equation:

$$L = (M_a{}^{2}\,V_{dc})^{2}/4Pf_{sw}$$
$$= (0.93^2 *24^2) / (4 *600 *10{,}000) = 20\mu H$$

Duty Cycle:

Duty cycle is defined as percentage of one period in which a signal or system is active. A period is a time it takes for a signal to complete an on and off. The duty cycle *D* is determined by the following formula:

$$D = V_{out}/(V_{out}+V_{dc})$$
$$= (220 * \sqrt{2})/(220 * \sqrt{2} + 2 = 93\%$$

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Filter Inductor selection:

In order to limit the current ripple a filter inductor is being used in the inverter circuit. And the critical inductor value of the inductor L_{filter} can be expressed as:

$$L_{filter}=1/\{\Delta I*fD*[(1/V_{dc})+(1/V_{out})]\}$$
$$=1/\{0.02*10{,}000*[0.04+0.00321]\}$$
$$=115\mu H.$$

Output Capacitance Selection:

The average differential equation for output filter capacitor is specified below:

$$C(dVc/dt)=(1-D)i_L-(V_{out}/R)$$

The duty cycle of the circuit is 0.93 and by solving the equation the capacitor of the filter can be selected C=10mF where cutoff frequency is 50 Hz. Thus, the output filter capacitor is responsible for desire ripple voltage, ripple current and loop stability.

***Output Current*:**

Considering that the resistance of coupled inductor, switches and diodes are negligible and the inverter is worked at DCM the output current $I_{out}$of the inverter can be expresses by using following equation:

$$I_{out}=\frac{V_{dc}^2\times T_s\times k^2}{2\sqrt{2}\times L}\sin\omega t$$

$$=10.5\sin wt$$

C. Control Circuit Design

In conventional inverter design, only one type switching method is used. But, in this proposed design instead of using one type of switching signal to switch the inverter, a combination of square wave and SPWM is employed. With this kind of combination switching, the switching loss across the switches of the inverter will be greatly reduced. Block diagram ofthe proposed switching control circuit is shown in Fig. 5. In order to simplify the synchronizing process, the sine wave of proposed design will be sampled from power grid by using the voltage transformer to step down 220V grid voltage into 5V. With the sampled sine wave from the grid and used to generate SPWM signal. Thus the frequency of the output from the GTI will be having the same frequency as the grid voltage and current where this is one of the most significant requirement for the GTI.

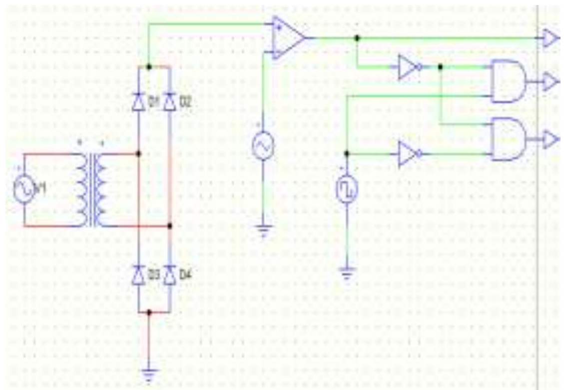

Fig.5. Control Circuit of Grid- connected inverter

After sampling, the sine wave is rectified with a precision rectifier. In addition, a high frequency triangle wave of 10 KHz frequency is used. Then the two signals are passed through a comparator to generate the unipolar SPWM signal. This unipolar signal only has positive values, which changes from +5V to OV and again back to +5V. A square wave signal is used as the line frequency (50Hz for Bangladesh) and is in phase with the SPWM signal.

Then the square wave signals is transmitted through a NOT gate to produce a signal that is 180 degree out of phase of the original signal. The inverter requires three switching signals since it has used three MOSFET switches. In order to generate three switching signals, an AND operation is performed between square wave and the SPWM signals. The three sets of switching signals can be categorized in three groups. The first group contains MOSFETs QI, while the second group contains MOSFETs Q2 and the third group contains MOSFETs Q3. The resulting switching gate pulses of the inverter power circuits from control circuit are illustrated in Fig. 6, Fig. 7 and Fig. 8 respectively.

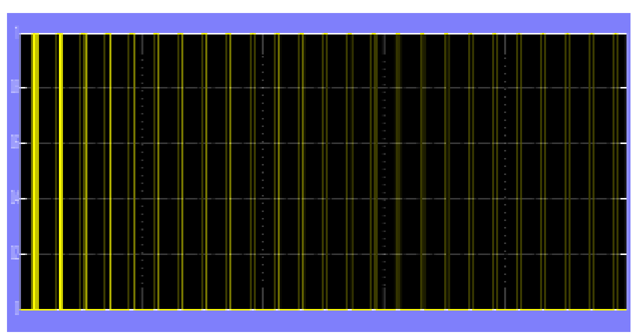

Fig.6. Switching Gate Pulse of Q1

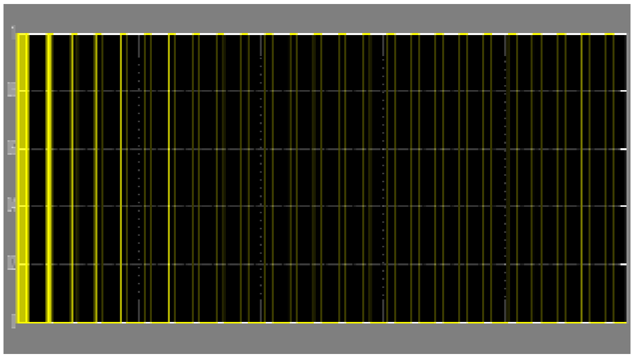

Fig.7. Switching Gate Pulse of Q2

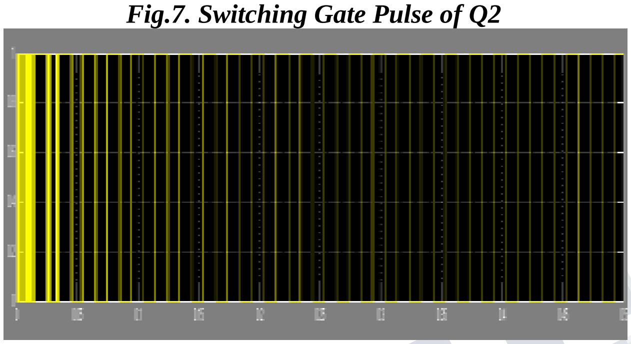

Fig.8. Switching Gate Pulse of Q3

D. Closed-Loop Control

In this Proposed In this proposed GTI design, we use a closed-loop controller scheme where the output current is measured and compared with an AC reference current. Fig. 9 shows the block diagram of real-time waveform feedback closed-loop SPWM control method.

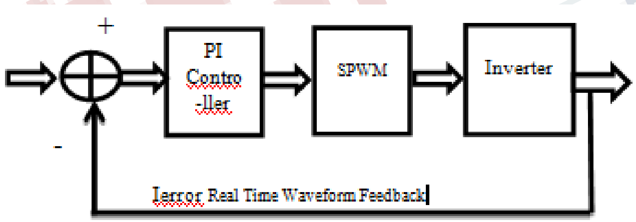

Fig.9. Closed-Loop Block Diagram

The error in between the measured output current and the reference current is compensate by a Proportional Integral (PI) controller and is used to generate the desired SPWM switching gate signals for MOSFET Q1, Q2 and Q3. In this closed-loop operation initially we calculate the peak modulation index Ma for 50 Hz grid voltage cycle by using of equation and then this peak value is used to produce the sinusoidal modulation index. A normalized sine table is used to get the modulation index in each switching cycle, from the peak modulation index. However, this modulation index is corrected via calculating new modulation index from the error between the measured ac current and reference current.

E. Grid Synchronization

This proposed grid-connected inverter design operation involves a grid synchro-nization part. During synchronization, the inverter produces output in phase with grid. The sine wave from grid is sampled and phase shift is set to zero. The un-shifted sine wave is rectified and compared with high frequency triangular wave to generate SPWM signal. SPWM signal is then undergoes an AND operation with square wave and generates three sets of switching signals. With this kind of switching and zero phase shifts, the output voltage and current of GTI controlled with the same phase with the grid. Whenever, the inverter and grid in phase once zero crossing of both voltages are detected the contactor is activated and the inverter is fed into grid. Fig. 10 is shown zero-crossing result of GTI.

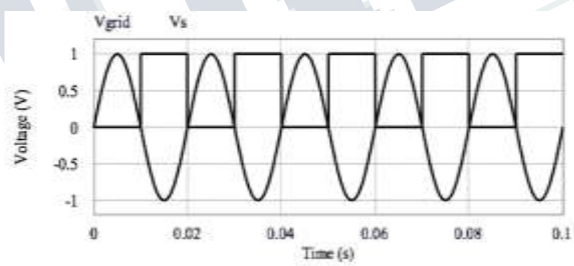

Fig.10. Zero-crossing output result of GTI.

Where the grid signal and square wave shows the zero point at falling and rising edge. After both voltages are tied, the inverter begins to inject power into the grid. To avoid the grid to having power from the inverter when the grid is down and create undesirable accident, the freewheeling diode is employed between the grid and the inverter MOSFET power circuit that will block the reverse power flow from grid. This isolation process is to avoid the grid to become live part on the time when it should not be.

IV. SIMULATION RESULT AND DISCUSSION

The proposed GTI design will undergo a computer simulation using Powersim (PSIM) software. To confirm the mathematical modeling analysis inthe previous section, 600W of the proposed three-switch single-stage GTI is simulated. The complete simulated schematic diagram of the proposed buck-boost GTI is shown in Fig. 11. The operation of the inverter is simulated for different level

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of input source voltages from 12V dc to 100V dc, as if it were from a PV panel. Fig. 12 shows the sinusoidal ac output voltage waveform that is 220Vrms and 50Hz after tied the inverter to the grid. Fig. 13 represents the simulation result of grid-connected power converter, where we observed that both the output current and voltage are in same phase. Fig. 14 shows the simulation result of the GTI output current is 10.5 A at 600W when the input voltage is 24V dc.

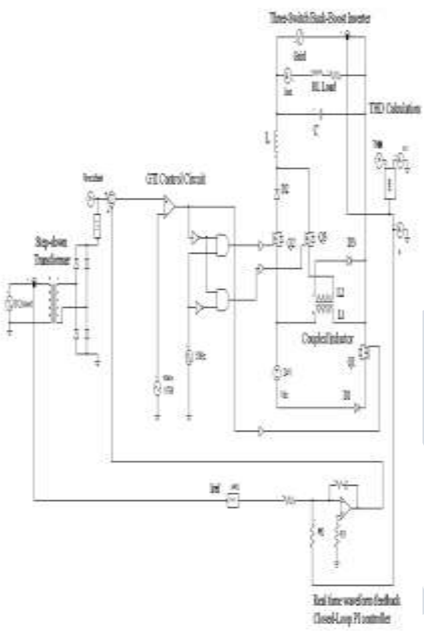

Fig.11. Complete Buck-Boost GTI.

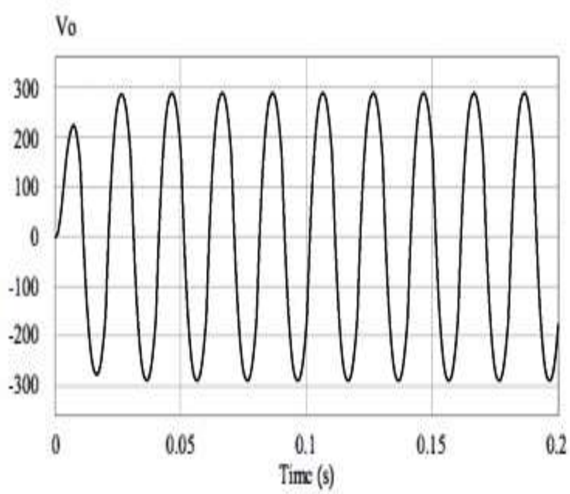

Fig .12. Output Voltage of GTI and Utility Grid Line

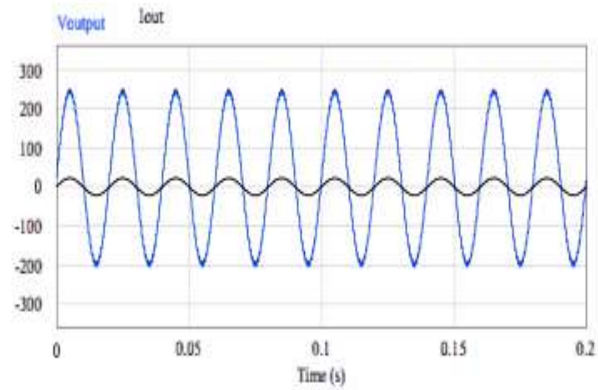

Fig.13. Output voltage and current in phase of GTI

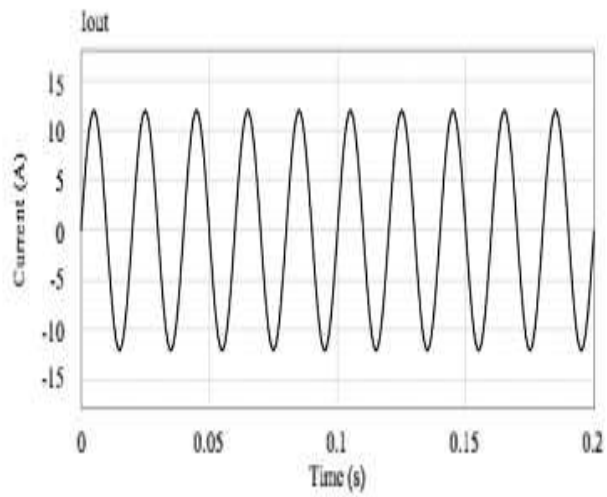

Fig.14. Simulation Waveform of Output current of GTI

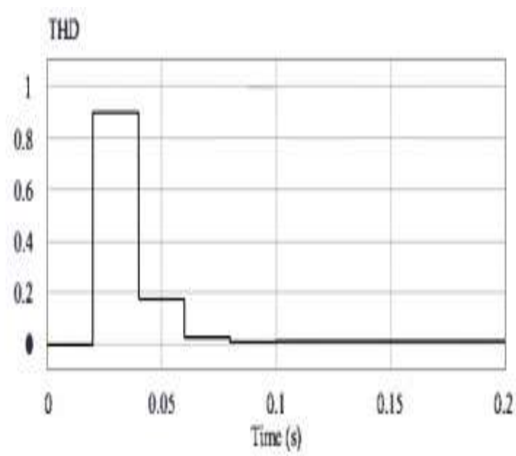

Fig.15. Output current THD of GTI.

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Fig. 15 shows the simulation results, where the Total Harmonic Distortion (THO) of output current is about 0.9% and the value of output capacitor is used only 10mF. However, Table II summarizes the calculated simulation parameters and output current performances of GTI at wide range of input PV dc voltage level. In addition we can affirm that mathematical value of output current is identical with the output current of simulation waveform for 24V dc.

TABLE II
Summary of PSIM Simulation Result at Different Input Photovoltaic Voltage Level

V_{dc}	Coupled inductor L(mH)	Output inductor L_{out}(mH)	Output capacitor C_{out} (mF)	Iout (max) (A)	Iout (rms) (A)	Iout THD(%)
12	5	120	15	14.31	10.12	1.43
24	20	115	10	14.85	10.50	1.41
48	80	85	8	20.18	14.27	1.37
60	130	74	5	21.92	15.50	1.3
100	360	65	3	26.52	26.52	1.26

Total power losses (switching loss& conduction loss) caused by the MOSFET in positive half cycle in conventional four switches H-bridge inverter can be inscribed as following:

$P_{total} = Pcond\text{-}QI + Pcond\text{-}Q2 + Psw\text{-}QI + Psw\text{-}Q2$

From the above equation we can infer that this three-switch single stage buck-boost GTI power losses caused by MOSFET are less than four-switch buck-boost inverter, which needs twoswitches to be turned on in any operation state. Since from gate signal patterns, we acknowledge that the proposed three switch single stage buck-boost GTI needs only one switch to be turned on in any operation state.

V. CONCLUSION

Mathematical modeling analysis of working principle and computer simulation of this proposed single-phase single stage buck-boost GTI is presented in this paper. Further, adoption of a simple control scheme and grid synchronization strategy that would make the inverter more reliable. Since it uses only three switches, the cost and size of the inverter would also be execute this configuration as compared to the conventional single stage four switch grid connected buck-boost inverted.

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