Design and Simulation of two Stages Single Phase PV Inverter operating in Standalone Mode without Batteries

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Abstract- *This paper presents the complete design and simulation of transformer-less single phase PV inverter for converting the energy extracted by the PV arrays to AC power to be used in stand alone applications without batteries storage. The proposed model consists of two stages. The first stage is a DC-DC boost converter. It is responsible to regulate and boost the DC output voltage of the PV system to 312V. The second stage is a full bridge DC-AC inverter that converts the regulated output voltage of the boost converter to sinusoidal AC voltage. The designed system has been tested using MATLAB simulation at different load and weather conditions and capable for converting the PV system DC voltage level from (90-140 V) to the 50Hz/220V AC output voltage at all states. Thus, the proposed system is suitable for supplying an isolated load without needing to the batteries when PV power is available during a day.*

Keywords- *Photovoltaic system, DC-DC boost converter, Full bridge inverter, Pulse Width Modulation.*

I. INTRODUCTION

The world trends nowadays to use the photovoltaic (PV) systems as distributed generator for being environmentally friendly, renewable, and a significant descent was seen in the price of the PV panels. Also PV panels do not include moving portions, therefore; a long lifetime (25 year with more 80% power output) is guaranteed with a very simple maintenance [1].

Power inverters are required to convert the DC power from the PV panels (or arrays) and feed to the AC load.

In recent years, large numbers of projects are aimed to make utilize of the energy generated by PV systems as a reserve sources to support the existent utility grid or used as standalone system. They scout about producing sinusoidal output current that meet the required standards.

This paper focused on design and analyze of two stage single phase PV inverter operates in stand alone mode without batteries and can be used for domestic application.

II. SINGLE PHASE FULL BRIDGE INVERTER

A full bridge, or H-Bridge, inverter is a circuit that converts DC to AC current. It consists of four power MOSFETs or IGBTs switches as shown in Fig. 1. The four anti-parallel protective diodes connected across MOSFET switches provide a path for inductive load current to flow when the MOSFET switch is turned OFF.

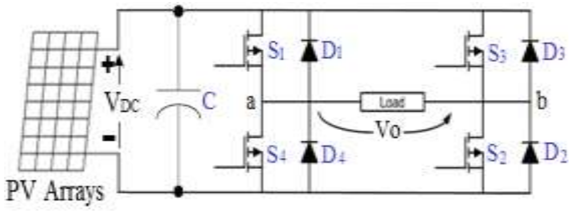


Fig. 1: Full bridge single-phase inverter circuit

There are four possible cases for switches that can produces voltages across the output of the inverter. These possibilities are listed in Table I. The other possibilities are neglected since they would short circuit the DC power supply. Note that neither S1 and S4 nor S2 and S3 must not be closed at the same instant [2].

Table I: Valid H-Bridge Switch States

Mode	Voltage across load (Vab)
S_1 and S_2 ON	$+V_{DC}$
S_3 and S_4 ON	$-V_{DC}$
S_1 and S_3 ON	0
S_2 and S_4 ON	0

The most important aspect of the Inverter technology is the output waveform. There are two main different output AC waveforms produced by the inverter:

A. Modified Sine-wave Inverter

An upgrade to the square wave inverter is the modified sine wave inverter. In this inverter, there are three voltage levels in the output voltage, ($+V_{DC}$),

($-V_{DC}$), and zero as shown in Fig. 2 [2]. There is a dead time between the +ve and -ve levels. This type of inverter is inexpensive as compare with the pure sine wave inverter and can be used by most domestic electrical equipments but it has significant harmonic frequencies which can prevent certain loads work properly.

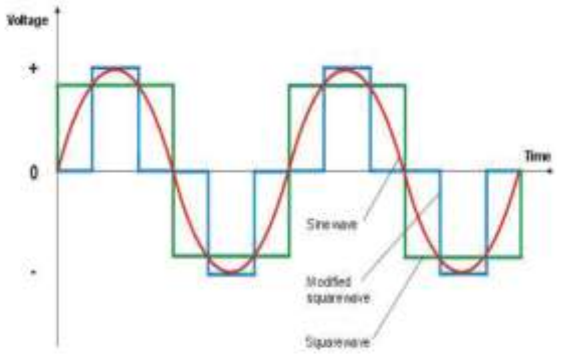


Fig. 2: Square, Modified, and Pure Sine Waves

B. Sine wave Inverter

Some appliances such as light dimmers, medical equipments, and variable speed devices may not work well with modified sine wave Inverter. These appliances must use a pure sine wave inverter which provides sinusoidal ac output voltage identical to AC grid voltage. In pure sine wave inverter, the output voltage magnitude and frequency is controlled by PWM technique and hence such inverter is known PWM inverter [2]. Generally the output voltage signal of this inverter passes through low pass filter to reduce the THD and produce the final pure sine wave output [3].

III. SINUSOIDAL PULSE WIDTH MODULATION

Sinusoidal Pulse Width Modulation (SPWM) is widely used in industrial applications, such as motor control and inverter applications [4]. It is characterized by constant amplitude pulses that have various pulse widths. Two common SPWM techniques are described here which have different harmonic content in their output signals. Thus the choice of a SPWM technique depends on the permissible harmonic content in the inverter output.

A. SPWM with Bipolar Switching

This version of SPWM is known as bipolar because the output voltage alternates between $+V_{DC}$ to $-V_{DC}$. Here, there is only one reference signal and the diagonally opposite transistors (S_1, S_2) and (S_3, S_4) are turned ON or OFF simultaneously. The outputs of legs 'a' and 'b' of Fig. 1 are equal but opposite in polarity. The output voltage is specified by comparing V_{ref} with V_{tri}. The generalized switching signals are shown in Fig. 3. The switching pattern is as follows [5]:

- When $V_{ref} > V_{tri}$, S_1 and S_2 are ON ➡ $Vo = +V_{DC}$
- When $V_{ref} < V_{tri}$, S_3 and S_4 are ON ➡ $Vo = -V_{DC}$

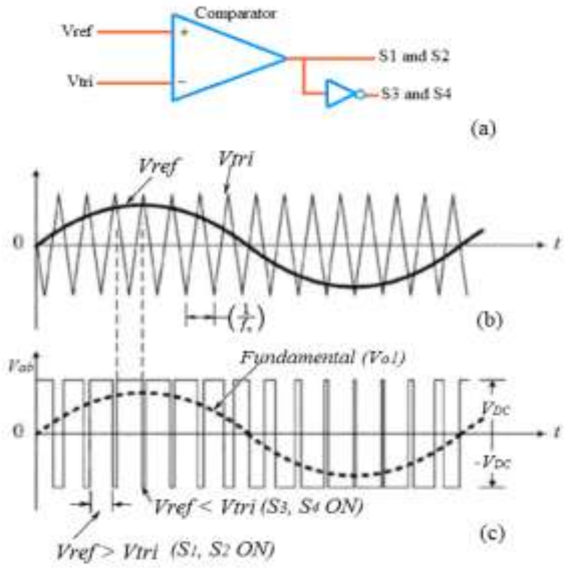


Fig. 3: Bipolar SPWM switching scheme
a) Bipolar SPWM generation circuit
b) Comparison V_{ref} with V_{tri} waveforms
c) Output of the switching patterns

B. SPWM with Unipolar Switching

This version of SPWM is known as unipolar switching, because the output voltage takes $+V_{DC}$ and **0** in the positive part and $-V_{DC}$ and **0** in the negative part. The difference between the unipolar and bipolar SPWM is that the unipolar employs a second comparator that compares between the inverse of reference waveform ($-V_{ref}$) with the same triangle waveform as shown in Fig. 4[5].

The diagonally switches in the two legs of the H-bridge inverter are not switched simultaneously in the unipolar SPWM scheme. The state of switches in the first leg depends on the comparison of V_{ref} with V_{tri}, while the state switches in the other leg depends on the comparison of $-V_{ref}$ with the same triangular wave. The state switches and the corresponding voltage levels are summarized as follows [5].

- When $V_{ref} > V_{tri}$, S_1 ON , $V_a = V_{DC}$,
- When $V_{ref} < V_{tri}$, S_4 ON, $V_a = 0$,
- When $-V_{ref} < V_{tri}$, S_2 ON , $V_b = 0$,
- When $-V_{ref} > V_{tri}$, S_3 ON, $V_b = -V_{DC}$

It can be observed from the Fig. 4 that when the upper switches (S_1&S_3) or the lower switches (S_2 & S_4) are turned "*ON*" the output voltage is *zero*.

In unipolar SPWM, the effective switching frequency is doubled. Due to this, the harmonic content of the output voltage waveform is reduced as compared with bipolar switching. Thus the size of the filter is being significantly smaller. These advantages of unipolar SPWM encourage its use in this work.

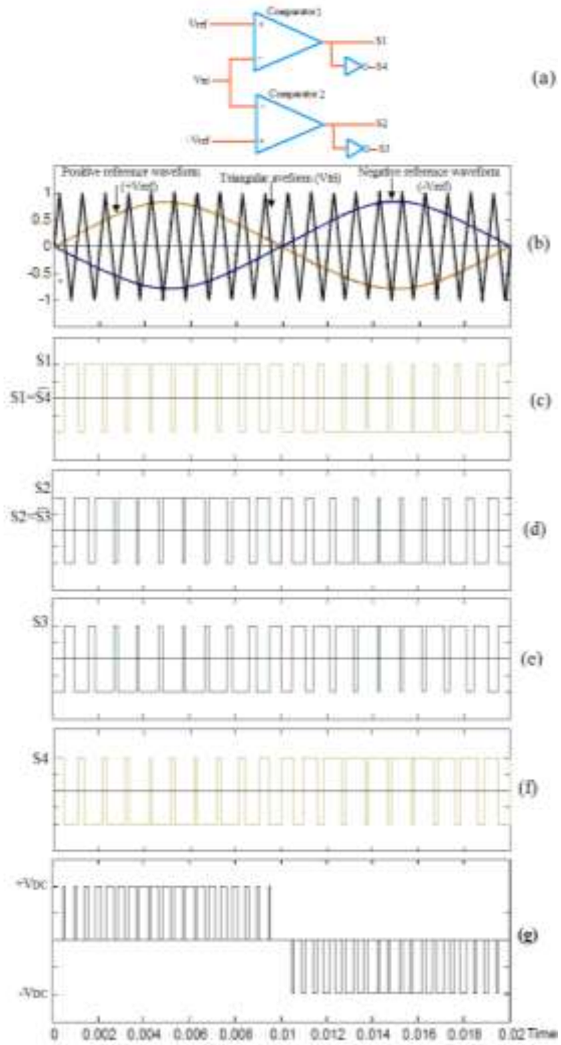


Fig. 4: Unipolar SPWM switching scheme
(a) Bipolar SPWM generation circuit,
(b) V_{ref} , $-V_{ref}$ and V_{tri} ,
(c) Switching pulses for S_1,
(d) Switching pulses for S_2,
(e) Switching pulses for S_3,
(f) Switching pulses for S_4,
(g) Output voltage

IV. Schematic Diagram of the Proposed Standalone PV Inverter

The complete schematic diagram of the proposed model is depicted in Fig. 5. It consists of the following main stages:

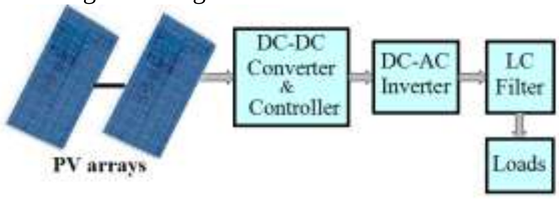


Fig. 5: Complete block diagram of a standalone PV inverter

A. PV arrays system

This system is consisting of (12) Mitsubishi UE125MF5N solar panel which are connected in series and parallel (2 parallel strings and 6 series panels for each string). The whole PV system specifications are listed in Table II at Standard Test Conditions (STC).

Table II: Whole solar system specifications at STC

Characteristics of Parameters	Specifications
maximum power point (P_{mpp})	125 x 12 = 1500 W
Voltage at MPP (V_{mpp})	17.3 x 6 = 103.8 V
Current at MPP (I_{mpp})	7.23 x 2 = 14.46 A
Open circuit voltage (V_{oc})	21.8 x 6 = 130.8 V
Short circuit current (I_{sc})	7.9 x 2 = 15.8 A

B. DC-DC boost converter

The DC-DC boost converter is an important stage in the PV inverter system because it increases the overall efficiency of the system. In fact, the operating with higher input voltage leads to lower input current required for a given power and hence reduces the losses. It is responsible to regulate and boost the DC output voltage of the PV system.

In this work, a boost converter operating in continuous conduction mode (CCM) has been designed to step up the voltage of the PV system to a higher constant voltage of 312V. All selected components of the boost converter should meet the design specifications and the parameters tabulated in Table III.

Table III: Specifications of the boost converter

Power rating (P_{max})	1.5 kW
Input voltage range (V_{in})	(90 – 140) V
Output voltage	312 V
Max. load current $=P_{max}/V_{out}$	≈ 5 A
Switching frequency (f_{sw})	10 kHz
V_{out} ripple (ΔV_{out})	$\leq 0.5\%$
I_{in} ripple (ΔI_{in})	$\leq 20\%$

Table IV summarized the calculated parameters and selected components of the proposed boost converter based on the considerations mentioned in Table III above.

Table IV: Boost converter calculated parameters

Component	Value /or Component specifications
MOSFET switch	40A, 500V
Diode	60A, 500V, Fast recovery diode
Critical Inductance ($L_{critical}$)> $\frac{V_{in}D}{f_{sw}\Delta I_L}$	3 mH , 30A, R≤ 0.1 Ω
Output capacitor (C_{out})> $\frac{I_{out}D}{f_{sw}\Delta V_{out}}$	330 µF, 450V, Electrolytic Capacitor
Minimum Duty (D_{min})= (1-V_{in-max}/Vout)	0.551
Maximum Duty (D_{max})= (1-V_{in-min}/Vout)	0.711

C. H-bridge Inverter

The H-bridge inverter has been designed according to the specifications given in table V. The selection of its components must meet these specifications.

Table V: Specifications of the H-bridge inverter

Power rating	1.5 kW
Input voltage (V_{out} of the boost converter)	312V
peak inverter current= $\frac{\sqrt{2}\times 1500}{220}$	≈ 10 A
Output AC voltage (r.m.s.)	(220 V ±5%)
Frequency of AC output	(50 Hz ± 1%)
Total harmonics content (THD)	less than 5%
PWM Switching frequency	10 kHz

C. Output Filter

The output of the full bridge inverter is connected to a low pass filter to supply a pure sinusoidal output voltage. The factors such as efficiency, voltage and current harmonics constraints, weight, volume and cost must be taken in to account when selecting the optimal filter design [5]. Also, the saturation of the inductor core should be avoided [6].

There are various filters topologies of sine wave inverter. These topologies include L filter, LC filter and LCL filter as illustrated in Fig. 6.

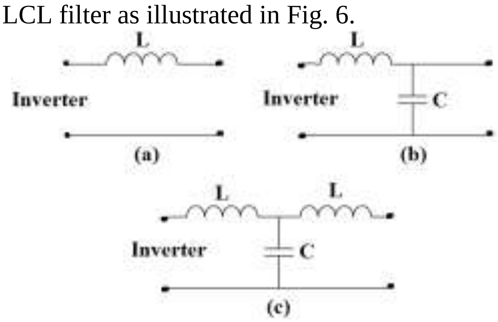


Fig. 6: Filter Topologies
a) L-Filter b) L-C Filter c) L-C- L Filter

As mention in [1] and [5], the L-filter filter has super performance in terms of voltage to current conversion but the damping of the high frequency (HF) noise is weak. The LC filter has good performance in terms of current to voltage conversion and noise damping but the filter capacitor may be insecure to line voltage harmonics, which result in large currents. The LCL filter has the same good properties with the L and the LC filters. Moreover, the damping of HF noise is better due to the extra inductance, and the capacitor is no more exposed to line voltage distortion. On the other hand, LCL can sometimes cost more than other topologies and is inherently unstable due to resonance [1].

For reducing oscillations and unstable conditions of the LCL filter, a damping resistor (R_d) is placed in series with the filter capacitor as shown in Fig. 7 [5]. Damping resistor is reliable, but it increases the losses and decreases the efficiency of the system. The benefits of LCL filter over other types of filter are the reasons that made this filter are used in the proposed inverter circuit.

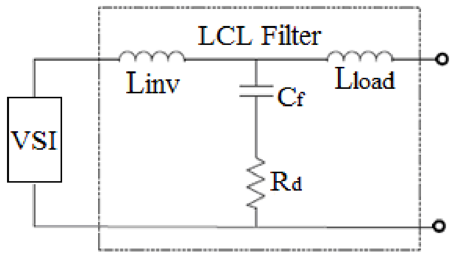


Fig. 7: L-C-L filter and components

A simplified formula for the LCL filter parameters with damping resistance has been discussed and analysis with their equations in references [5] and [7]. The same approximation will be applied here to calculate the inverter side inductance (L_{inv}), load side inductance (L_{load}), filter capacitance (C_f) and the damping resistance (R_d). Equations 1 to 7 have been used to evaluate the filter elements.

There are some important factors that should be considered when design LCL filter which comprise [5]:

i- Inverter output ripple current,

ii- Inverter to load inductor ratios

iii- Filter capacitance maximum power variations.

The first step in calculating filter parameters is founding L_{inv}, which is given as;

$$L_{inv} = \frac{V_{inv-peak}}{16 \times f_s \times \Delta I_L} \quad (1)$$

where $V_{inv\text{-}peak}$ is the peak output voltage of the inverter which is equal to V_{DC} input to the inverter. The output ripple current (ΔI_L) in the design of L_{inv} was assumed up to 10% of the rated output current of the inverter (I_{inv}).

$$\Delta I_L = 10\% \times I_{inv} = 0.1 \times \frac{\sqrt{2} \times 1500}{220} \approx 1A \quad (2)$$

Substitute the values of $V_{inv\text{-}peak}$, f_s and ΔI_L in equation (1), yields ($L_{inv} = 2\ mH$)

The load side inductance (L_{load}) is given by:

$$L_{load} = r * L_{inv} \quad (3)$$

The constant (r) is called relation factor which represents the ratio between L_{inv} and L_{load} and assuming is equal to 0.8. Then,

$L_{load} = 0.8 * 2 = 1.6$ mH

The voltage drop across the inductor filter ($L_{inv}+L_{load}$) must be less than 3% of the inverter output voltage (V_{inv}) [8]:

$$I_{inv(max)} \times 2\pi \times f \times L < 0.03 V_{inv} \quad (4)$$

Where, $I_{inv(max)}$ is the max inverter current (rms), f is the output frequency(50 Hz) and ($L \approx L_{inv}+L_{load}$).

The capacitance of the filter (C_f) is limited to less than 5% of the base capacitance (C_b) that is given by:

$$C_f = 0.05 \times C_b = 0.05 \times \frac{P_{inv}}{2 \times \pi \times f \times V_{inv}^2} \approx 5\mu F \quad (5)$$

Where, P_{inv} is the rated output power of inverter.

The design of the filter capacitance adopts the fact that the max power factor variation acceptable by the grid in case of grid tied inverter should not exceed 5 % [5].

The value of the R_d ought to be one third of the impedance of the filter capacitor at the resonant frequency (f_0). The values of f_0 and R_d are given in the equations 6 and 7 respectively.

$$f_o = \frac{1}{2\pi} \times \sqrt{\frac{L_i + L_g}{L_i \times L_g \times C_f}} \approx 2400Hz \quad (6)$$

$$R_d = \frac{1}{3} \times \frac{1}{2 \times \pi \times f_0 \times C_f} \approx 5\Omega \quad (7)$$

Table VI summarizes all LCL filter components

Table VI: LCL filter components

Component	Value
Inverter Side Inductor (L_{inv})	2 mH
Grid Side Inductor (L_{load})	1.6 mH
Filter Capacitor (C_f)	5 µF
Damping Resistance (R_d)	5 Ω

V. HARMONIC CALCULATIONS

Total harmonic distortion of voltage (THD_v) and total harmonic distortion of current (THD_i) can be calculated by the following equations [9]:

$$\%THD_v = \frac{\sqrt{\sum_{h=2}^{\infty} V_{h(rms)}^2}}{V_{1(rms)}} \times 100\% \quad (8)$$

$$\%THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} I_{h(rms)}^2}}{I_{1(rms)}} \times 100\% \quad (9)$$

Where; $V_{h(rms)}$ and $I_{h(rms)}$ are the r.m.s. values of h^{th} harmonic of the voltage and current respectively, $V_{1(rms)}$ and $I_{1(rms)}$ are the r.m.s. values of fundamental voltage and current respectively.

Harmonic content for the V_{inv} and I_{inv} are analyzed using Fast Fourier Transform (FFT) block which introduced in the (powergui block) of MATLAB simulink library.

VI. SIMULATION AND VALIDATION OF THE STANDALONE PV INVERTER

The whole simulink block diagram of the proposed standalone single phase PV inverter system is depicted in Fig. 8. The detail simulink block of the PV arrays system is given in Fig.9.

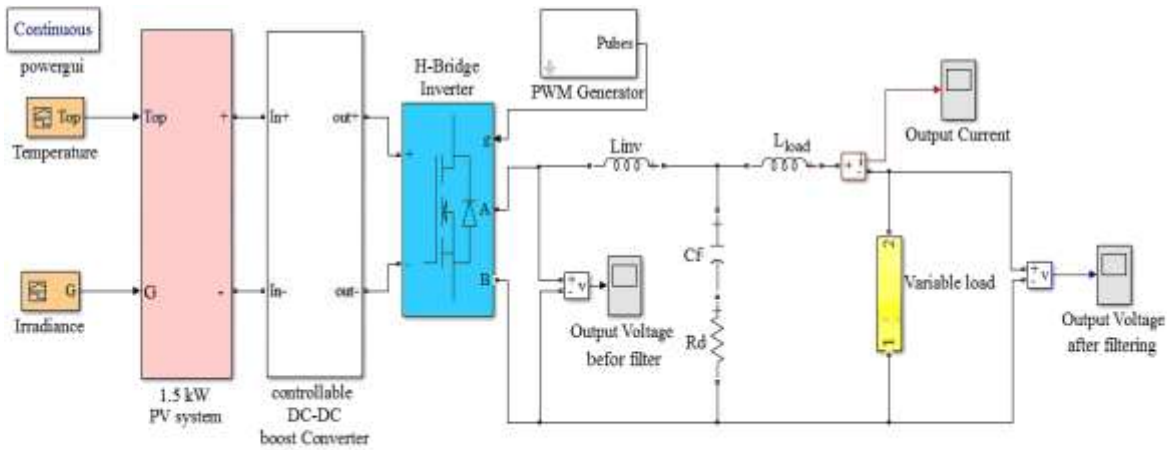


Fig. 8: MATLAB simulink model of standalone PV inverter system

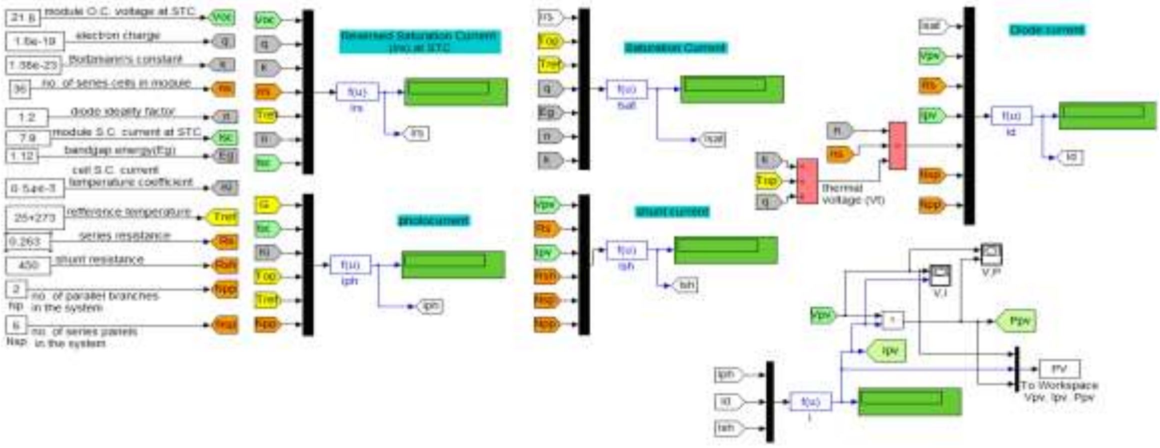


Fig. 9: PV system MATLAB/Simulink model

details simulink block of the closed-loop DC-DC boost converter is shown in Fig. 10, where a PI controller is used to adjust its output at desired value (312V).

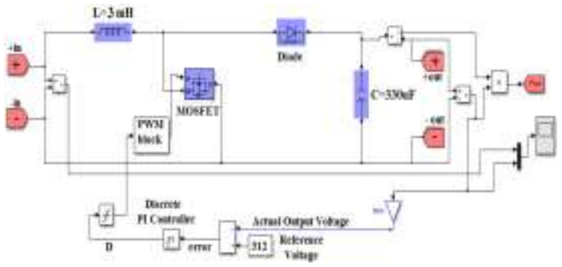


Fig. 10: Simulink model DC-DC boost converter with closed loop system

The performance of the standalone single phase PV inverter system is evaluated takes into account various operating conditions such as load step changes and weather variation (insolation and temperature) to confirm the validity of the system.

A. Constant PV Arrays Power with Variable Load

The system was tested at standard test weather conditions (1000W/m^2 insolation and 25C^0 temperature) and a step changing in the load (increased from 400W to 900W then to 1400W, after that decrease with same step changes) with the help of control switches as given in Fig. 11.

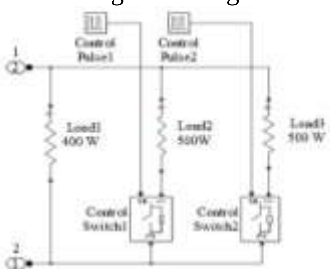


Fig. 11: MATLAB modeling of resistive load

The output voltage of the boost converter and the input voltage responses (PV system voltage) have been pictured in Fig. 12. The figure shows that the output voltage is to some extent constant and equals 312V. After each disturbance in the load (increase or decrease), the controller senses these changes and respond to them quickly (reaches to the steady state value after 0.1s from the instant of disturbance creation in the load). Also, it is obvious that the PI controller response depends on the amount of changes in the load.

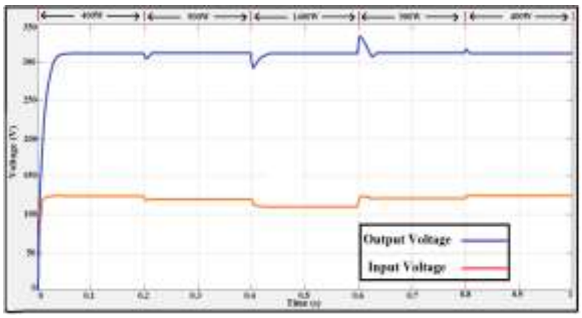


Fig. 12: Output voltage response of the DC-DC boost converter at different loads

Figure 13 shows the waveform of the inverter output voltage (V_{inv}) before filtered.

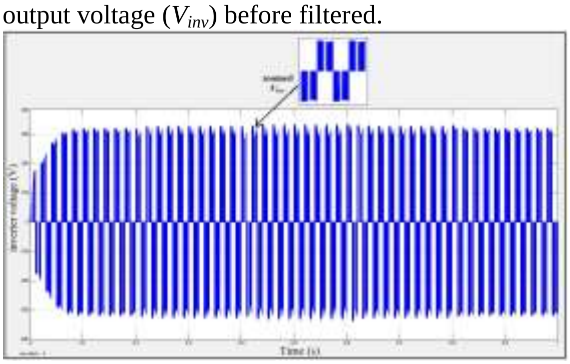


Fig. 13: Inverter output voltage at STC and step load changes before filtered

Figure 14 shows the waveform of the inverter output voltage after filtering. As shown from Figs.

13 & 14, the amplitude of V_{inv} is alternated between 312V and -312V after reaching to the steady state.

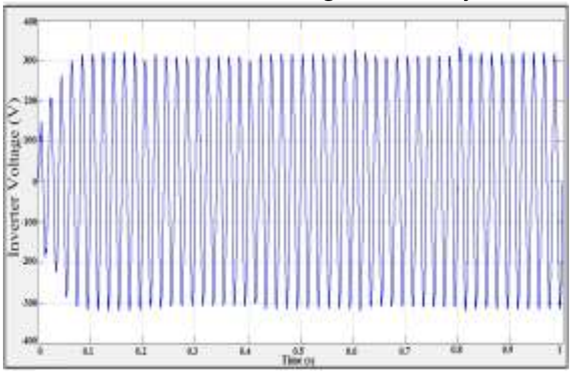


Fig. 14: Inverter output voltage at STC and step load changes after filtering

Figure 15 shows inverter output current (I_{inv}). The results show a good performance during step changes in the load for all cases.

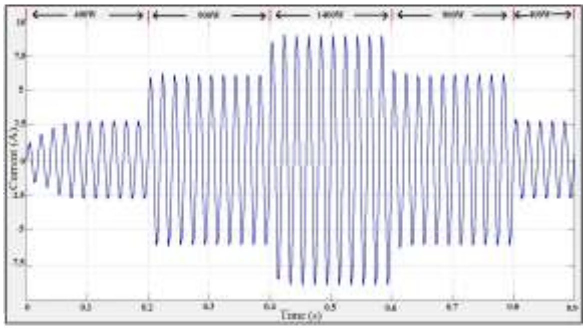


Fig.15: inverter output current (I_{inv}) at STC and step load changes

Figures 16 and 17 illustrate the THD for the V_{inv} and I_{inv} respectively. As can be seen, both having acceptable values of THD (THDv= 4.4% and THDi = 4.61%).

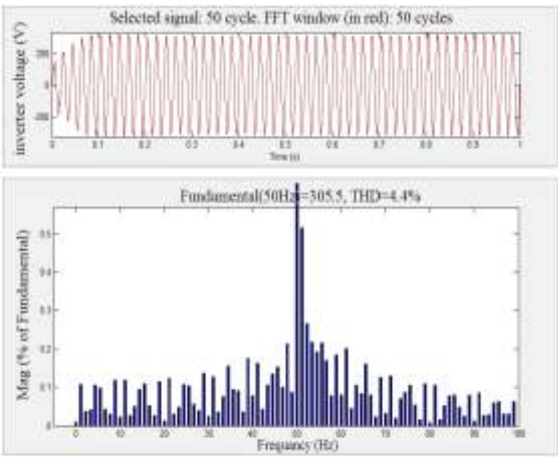


Fig. 16: THD of V_{inv} (THDv) and harmonics spectrum at different loads

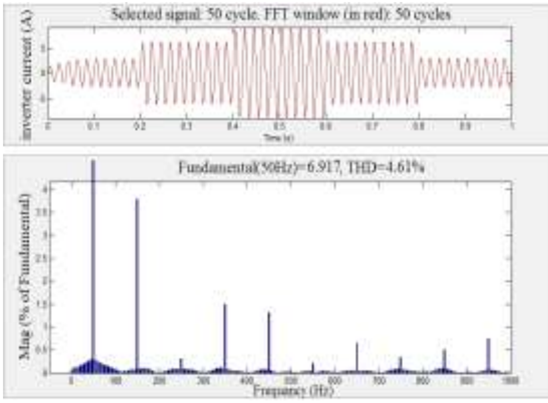
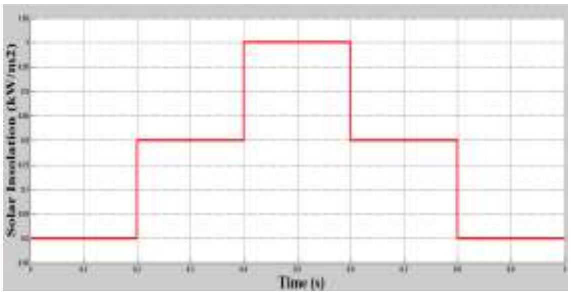


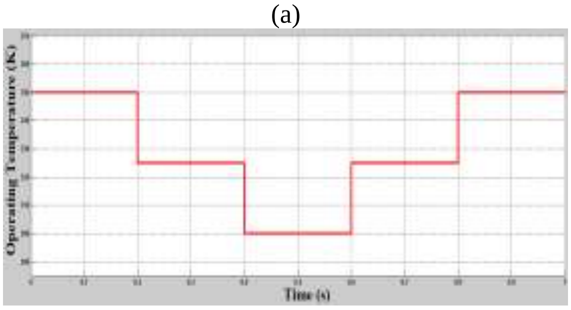
Fig. 17: THD of I_{inv} (THDi) and harmonics spectrum at different loads

B. Variable PV Arrays Power with Constant Load

The inverter system has been tested in presence of the input power variations which caused by solar insolation variations and temperature according to Fig. 18. The system was examined with the resistive load of 650 W.



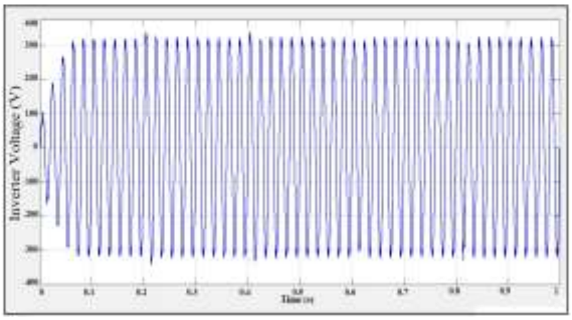
(a)



(b)

Fig. 18: Weather Conditions variations
(a) Solar insolation variations,
(b)Operating temperature variations

The simulation results of the inverter output voltage and current are given in Fig. 19. Figure 20 gives the THD content of the inverter voltage and current which satisfy the THD requirements (THDv=4.41% and THDi = 4.41%). The results show that the PV inverter gives acceptable performance during all conditions when it runs in standalone mode and the goal of the proposed PV system is performed.



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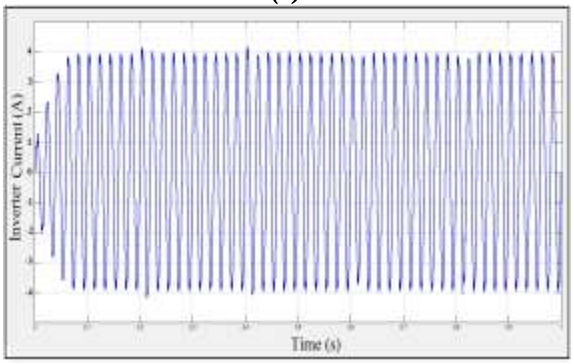
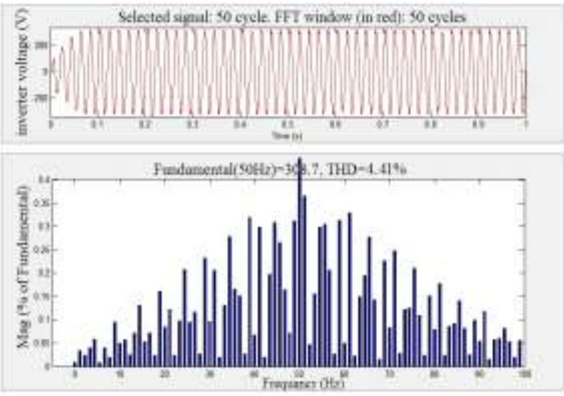
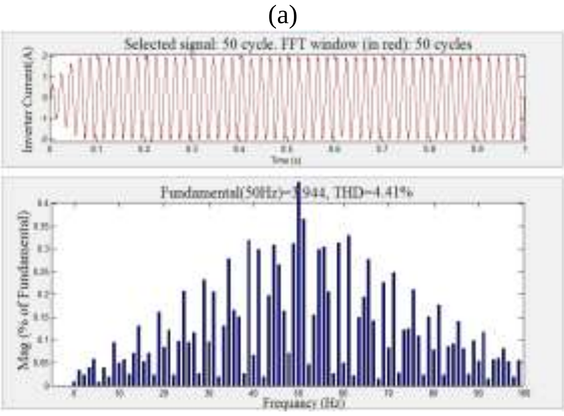


(b)

Fig.19: Inverter outputs at different insolation and temperature levels and constant load;
(a) Inverter voltage, (b) Inverter current



(a)



(b)

Fig. 20: THD and harmonics spectrum at different levels of insolation and temperature
(a) THD of V_{inv} (THDv) , (b) THD of I_{inv} (THDi)

VII. Conclusions

In this paper, a two stages 1.5 kW single phase PV inverter has been simulated using MATLAB software. The system has been tested under different load and weather conditions to examine its validity. The simulation results showed that the proposed design exhibited a good performance for the all studied cases and a nice 220V/50Hz sinusoidal output voltage was obtained. The system was suitable for supplying stand alone load without needing to the batteries and thus the system cost and maintenance have been reduced if the system has been designed practically.

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