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Simulation of Grid-connected Photovoltaic System with Real and Reactive Power Control

D. Anitha, R. Uthra, N. Kalaiarasi

Abstract--- This paper presents a small scale three-phase grid connected system for domestic establishments. The proposed system includes a 4.8 kW PV panel with a DC-DC boost converter with controller for Maximum Power Point Tracking (MPPT), DC-AC inverter with decoupled power controller supplying the load and connected to the grid. The MPPT controller is used to harvest maximum power from the solar panel and decoupled power controller is used for tracking the real and reactive powers and also improves the system stability. The simulation of the proposed model is carried out to show the effectiveness of grid-connected photovoltaic systems.

Keywords--- PV Panel, DC-DC Converter, Voltage Source Inverter, MPPT, PQ Control Strategy.

I. INTRODUCTION

Distributed generation (DG) has become inevitable for utility grids to provide sufficient electrical energy to supply domestic and industrial requirements in a clean world. Microgrids have more capacity and control flexibilities to fulfill system reliability and power quality requirements. Gird-connected Photovoltaic (PV) systems with rating 5-10 kW level have advantages of scalability and energy-saving, suitable for a typical for small-scale solar applications [2], [7]. The generation of electricity from the PV cell and choosing the appropriate panel as per the rating. It is known that the output response from the PV panel depends on the varying irradiance and temperature. Thus, the authors in [9] have discussed the significant effect of irradiance and temperature. The fabrication of a microcontroller based simple maximum power point tracker (MPPT) is mentioned in [5], [6]. Such a controller efficiently enhances the output power. A power controller with MPPT Control is proposed to attain both high-efficiency from the solar panel and grid stability are mentioned in [5] [10]. The MPPT used here employs a P & O algorithm [4]. To boost the output voltage [13] [11] of the PV panel to meet grid voltage, a boost converter is designed. The design considerations of the proposed converter and filter ratings are discussed in [8] [13]. Various power quality issues are discussed by authors in [4] which address the problem related to stability, reliability, frequency.

Problems that arise due to harmonics in inverter output are discussed in [15]. By choosing the proper values of the filter along with PWM based switching can effectively reduce it. Using *d-q* control for inverters becomes easy when classical PI controllers as mentioned in [15], [3]. The inverter output is affected by harmonics and thus appropriate filters are designed as per IEEE standards. Power oscillations deteriorate the power quality in a microgrid and cause stability issues in the system [1], [12]. PQ control for the VSI aims to track the measured powers with the reference powers and also avoids coupling between them [15]. The current controller module in [10] [12] helps to generate reference currents required for tracking the active and reactive power. The tracking of the reference powers indicates that the system responds in the desired manner. The synchronization of the inverter output voltage with the grid is done using a Phase locked loop which employs a VCO circuit. The block diagram of the model is shown in Fig. 1 consisting of a PV source integrated to VSI.

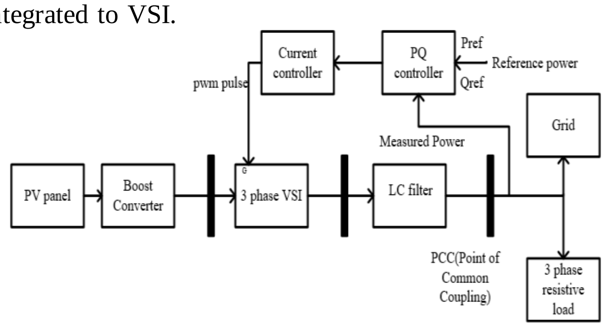

Fig. 1: Block Diagram of the proposed model

A three-phase grid-connected PV system is considered in this paper. The tracking of real and reactive powers has been discussed with the help of a PQ control module. The proposed control technique will improve the reliability and performance of the grid-connected system. A separate control is designed for the *d- q frame* and this arises the concept of a decoupled control scheme for current controller.

II. PV PANEL WITH MPPT AND BOOST CONVERTER

Modeling of PV cells requires input signals irradiance, temperature, and the output signals are current, voltage and power. An ideal PV cell can be modeled as a current source in parallel with a diode. For practical purpose, a solar cell is modeled as an ideal PV cell with shunt and series resistances as shown in Fig.2. The series resistance Rs represents the intrinsic resistance whose value is very small. The equivalent shunt resistance R_{sh} is due to manufacturing defects.

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D. Anitha, Department of EEE, SRMIST. Chennai, T.N, India. (e-mail: anitha.da@ ktr.srmuniv.ac.in)
R. Uthra, Department of EEE, SRMIST. Chennai, T.N, India. (e-mail: uthra.r@ ktr.srmuniv.ac.in)
N. Kalaiarasi, Department of EEE, SRMIST. Chennai, T.N, India. (e-mail: kalaiarasi.n@ ktr.srmuniv.ac.in)

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The equivalent circuit of a PV cell is shown in Fig. 2.

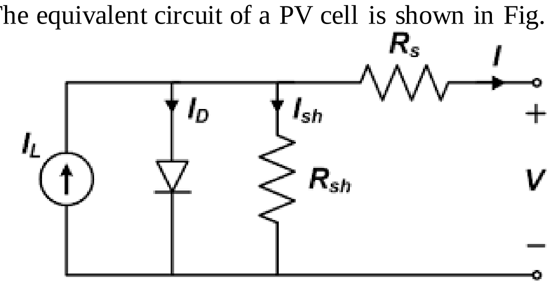

Fig. 2: The equivalent circuit of the PV cell

A number of PV cell are connected in series (to obtain the required voltage) and parallel (to obtain the required current) to form a module. Similarly, a number of modules are connected to run the loads. For the purpose of simulation, a PV Array with following parameters listed in Table I and Table II.

Table I: Parameters of PV module

Parameter	Values
Open Circuit Voltage(Voc)	64.2 V
Short circuit current(Isc)	5.96 A
Voltage at MPP(Vmp)	54.7 V
Current at MPP(Imp)	5.58 A
Number of cells per module	96

Table II: Parameters of PV array

Parameter	Values
Modules in series(Ns)	5
Modules in parallel(Np)	3
Panel rating	4.78 KW

the A DC-DC Boost Converter [8] links the PV Panel and the inverter so that the voltage of the PV panel matches with the inverter. The Maximum Power Point Tracking (MPPT) is implemented by P & O algorithm. The MPPT is embedded in DC-DC Boost Converter to maximize the harvesting of solar energy.

Maximum Power Point Tracking

MPPT is implemented in PV based system to continuously track the maximum power point for a given solar irradiance and temperature [5], [9], [10]. The voltage at which the PV module can produce maximum power is called maximum power point as shown in Fig. 3. MPPT is implemented using P & O algorithm [4] because it has simple implementation and the tracking time is quick. This algorithm perturbs the operating voltage to ensure maximum power point.

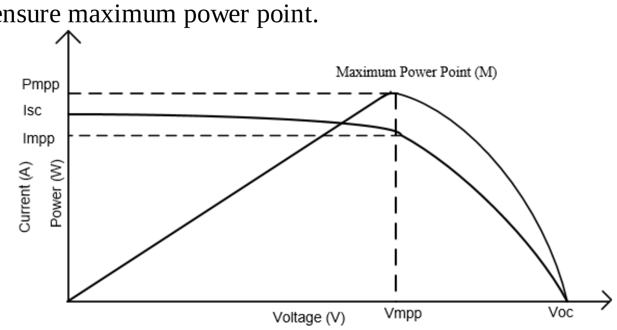

Fig. 3: P-V and I-V characteristics of PV array

The increase/ decrease in voltage depends on the difference between power generated at the current instant and the is previous instant. The algorithm is explained in Fig. 4.

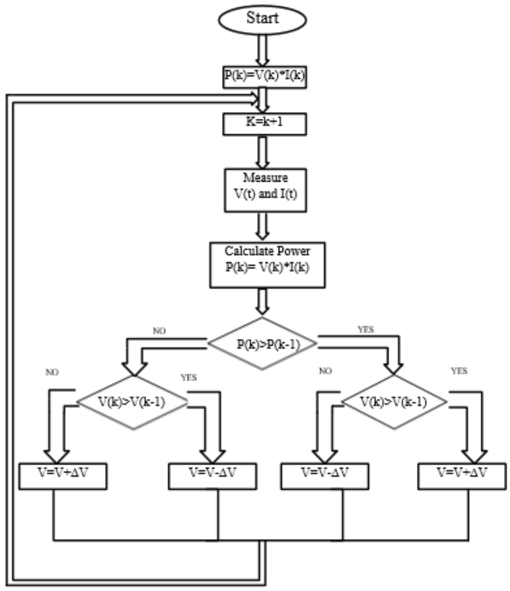

Fig. 4: Flowchart for P & O Algorithm

Boost Converter

The output of the PV Panel is given to the boost converter [11]. The boost converter steps up the voltage up to a level so that inverter generates system voltage. The boost converter consists of switches, inductor and capacitor and power conditioning circuits. The designed parameters are given in Table III [7] [8] [13]

Table III: Parameters of boost converter

Parameter	Values
Input voltage, V_i	273.5 V
Input current, I_i	17.54A
Output voltage, V_o	620V

The output current from converter(I_o)

Since the power at the converter input and output are the same, the output current I_o is given as (1)

$$I_0 = \frac{V_i * I_i}{V_0} \qquad (1)$$

Selection of Duty cycle(D)

The required duty cycle is given. (2)

$$D = 1 - \frac{V_i}{V_o} \qquad (2)$$

Selection of Inductor(L)

The permissible inductor ripple current (ΔI_L) decides the inductor value given by (3)

$$L = \frac{D \cdot V_i}{\Delta I_L \cdot f_s} \qquad (3)$$

Where f_s is the switching frequency

Selection of Capacitor (C)

The permissible capacitor ripple voltage (ΔV_o) decides the capacitor value given by (4)

$$C = \frac{D}{R_o \cdot \frac{\Delta V_o}{V} \cdot f_s} = \frac{D \cdot I_o}{\Delta V_o \cdot f_s} \qquad (4)$$

The block diagram of a PV panel with a boost converter and MPPT is shown in Fig. 5

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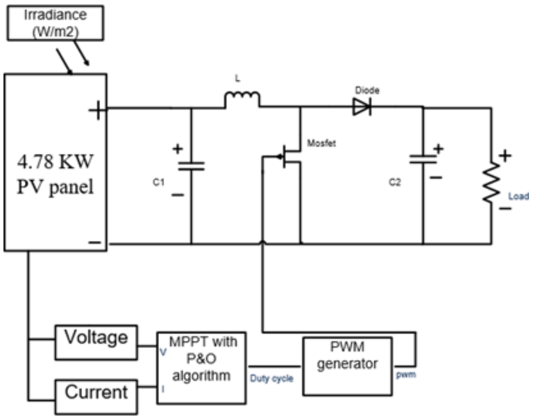

Fig. 5: Block Diagram of PV Panel with MPPT

III. INVERTER CONTROL STRATEGY FOR ACTIVE AND REACTIVE POWER TRACKING

The boost converter output is given as input to the inverter. Since PV is sensitive to climatic conditions, their output power is intermittent and variable. So, a PQ Control strategy is adopted as in Fig 6 which makes the inverter real and reactive output powers track the reference powers.

PQ Control Mechanism

The PQ control module tracks the reference power from the panel and ensures the decoupling of real and reactive powers. The decoupling between real and reactive powers is achieved by converting to d-q frame. [1] [12] [14] It also has

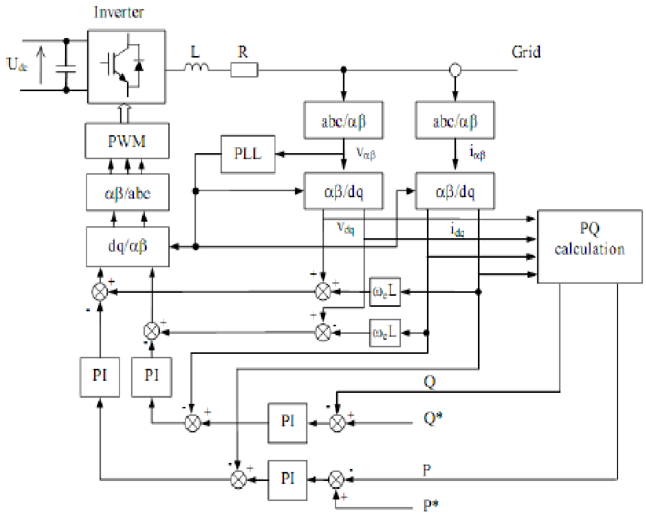

Fig. 6: Block Diagram of the PQ Control Strategy

The PQ calculation block implemented in Fig 6 is based on equations (5) and (6)

$$P = 1.5\,(v_{inv,d}\,i_d + v_{inv,q}\,i_q) \qquad (5)$$

$$Q = 1.5\,(v_{inv,q}\,i_d + v_{inv,q}\,i_q) \qquad (6)$$

Where $v_{inv,d}$, $v_{inv,q}$ are two phase voltages from inverter terminals.

Proportional reference currents are generated by comparing reference powers P^*, Q^* from the panel and calculated powers in (5) and (6). The errors are given to respective PI controllers. The controller output is the reference current. The respective dq- axis currents i_d, i_q are compared with the reference and the error is fed to the next set of PI controllers. The output of this PI controller and feed-forward voltages used as reference wave for sinusoidal PWM for generating pulses for switches in the inverter. The feed-forward voltages V_{fd}, V_{fq} are given as (7) and (8) [14]

$$V_{fd} = v_{inv,d} + \omega L i_q \qquad (7)$$

$$V_{fq} = v_{inv,q} + \omega L i_d \qquad (8)$$

Where ω is the grid angular frequency and L is the filter inductance. A PLL is also used to make the inverter operate in synchronism with the grid.

Parameters used in Simulation

The design considerations of the filtering inductor and capacitor are given in Table IV and voltage and current parameters are listed in Table V. The gain values required for the PI controllers are listed in Table VI.

Table IV: Specifications of filtering inductor and capacitor

Parameter	Values
Filtering inductance	50 mH
Filtering capacitance	50 µF

Table V: Parameters of grid connected inverter the circuit

Parameter	Values
DC link voltage (V_{dc})	620 V
Nominal grid voltage	415 V, 60 Hz(L-L)
Load	8 KW

TABLE VI PI Controller gain parameters

Controller	Kp	Ki
Power controller loop	3.5	60
	0.04	100
Inner current loop	3.2	60
	0.05	100

IV. SIMULATION RESULTS AND DISCUSSION

A. Effect of Irradiance and Temperature of PV panel at the load

The Simulink model of PV source with boost circuit is shown in Fig 7 and the current, voltage and power waveforms for the irradiance of 1000 W/m^2 is shown in Fig.8.

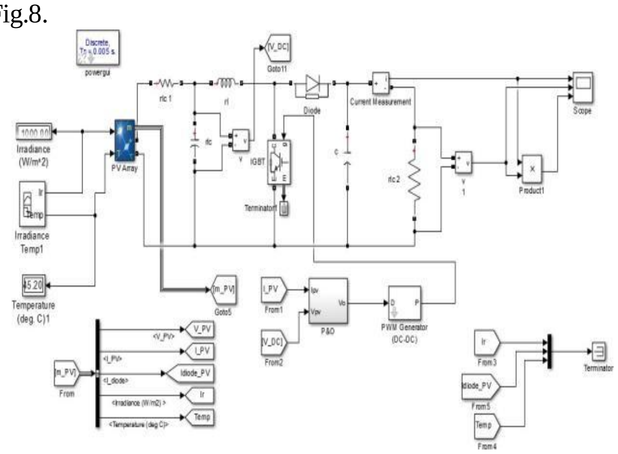

Fig. 7: PV panel simulation with MPPT and boost converter

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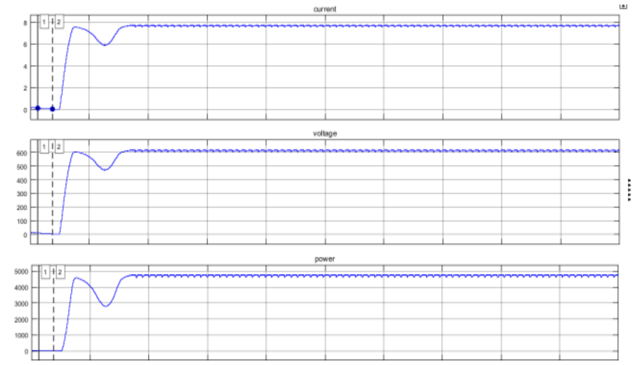

Fig. 8: PV panel response at the load with irradiance 1000W/m^2 and temperature 25^oC (Current output of panel vs time, Voltage output of panel vs time, Power output of panel vs time)

In Fig 9, the irradiance is varied as 600 W/m^2(0 to 3 sec), 1000 W/m^2 (3 to 6 sec), decreasing ramp from 500W/m^2 to 200 W/m^2 (6 to 8 sec) and 200W/m^2 (8 to 10 sec) at constant temperature of 25^oC. The corresponding output current, voltage and power at the load are shown in Fig. 10.

It can be clearly seen from Fig. 10 that power is varying significantly with the irradiance. However, the maximum power obtained at irradiation of 1000 W/m^2 is 4.78 KW.

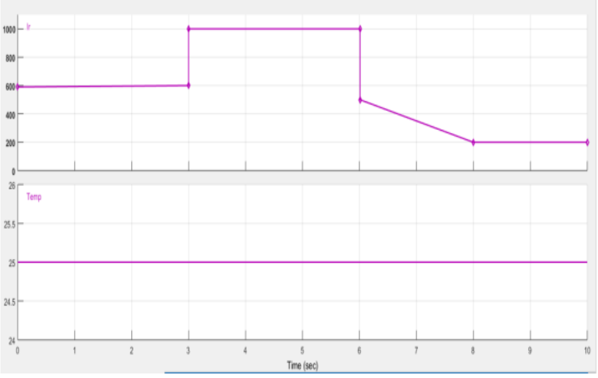

Fig. 9: Change in irradiance from a signal builder block

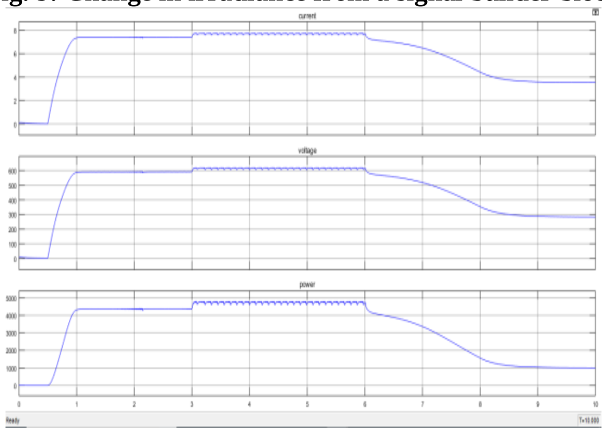

Fig. 10: Effect of change in irradiance at the load at constant temperature

In Fig. 11, the temperature is varied as 20^{o}C (0 to 3 sec), ramp increase from 20^{o}C to 30^oC (3 to 7 sec) and 45^oC (7 to 10 sec) at constant irradiance of 1000W/m^2. The corresponding output current, voltage and power at the load is shown in Fig 12.

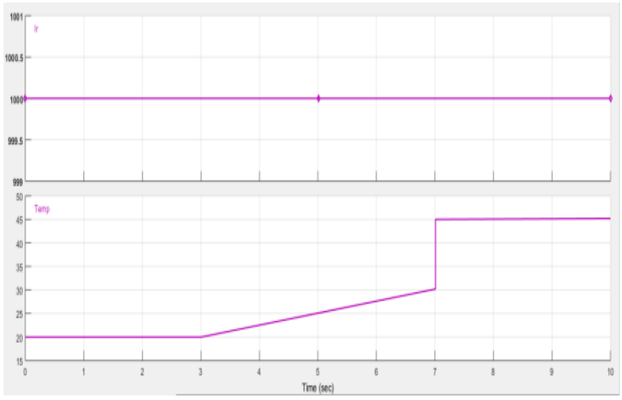

Fig. 11: Change in temperature from a signal builder block

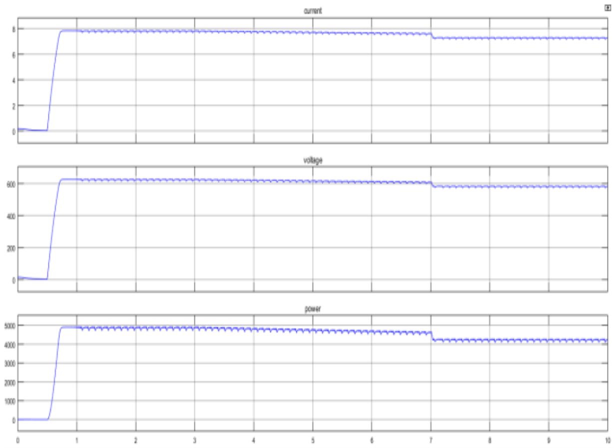

Fig. 12: Effect of change in temperature at the load at constant irradiance

It can be clearly seen from Figure 12 that power is varying with the temperature supplied. However, the maximum power obtained at a temp of 20^oC is 4.78 KW.

B. Simulink Model of Grid Connected PV system

The simulation model of the inverter connected with a PV panel is given in Fig. 13. The Simulink power control scheme is shown as a subsystem and the enlarged figure is shown in Fig. 14.

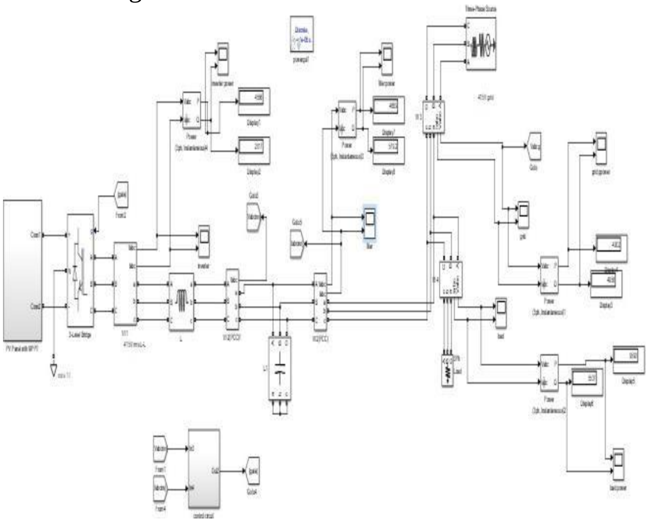

Fig. 13: Complete Simulink model of Inverter with Grid and PV panel

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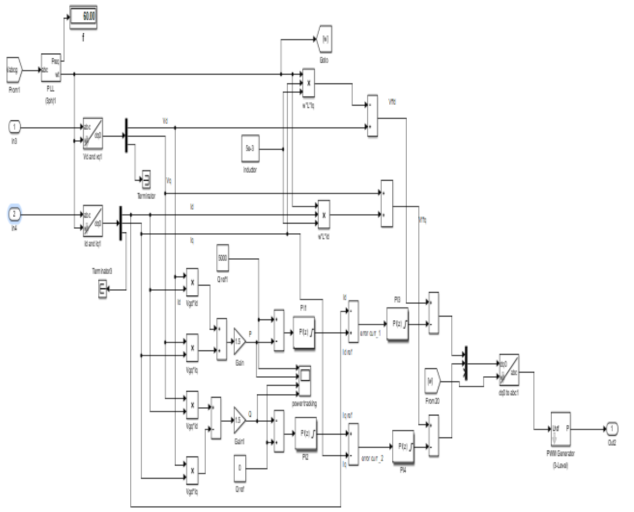

Fig. 14: Simulation Circuit Showing the PQ and Current Controller Scheme

To observe the power control, the reference values of active and reactive power are set as P* is kept as 6 kW and Q* is kept at 3.5 kVar. The outcome of power control is shown in Fig. 15.

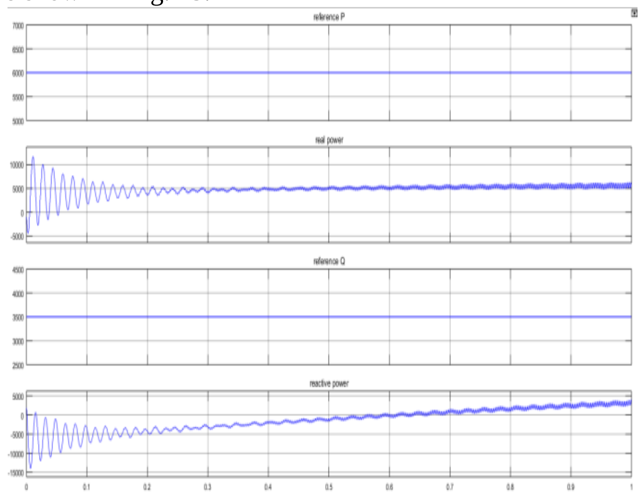

Fig. 15: Tracking of reference powers with P*=6 kW and Q*=3.5 kVar

The voltage and current across the inverter after passing through the filter is shown in Figure 16. The voltage and current across the load can be seen in Fig 17.

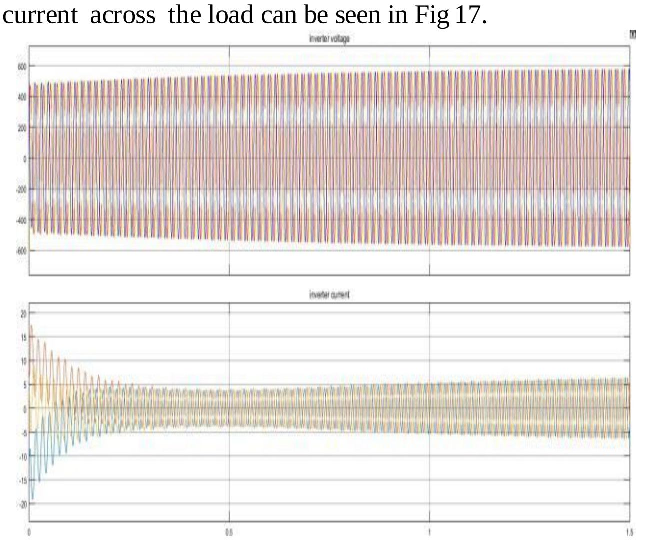

Fig. 16: Voltage and current response of inverter after passing from filter

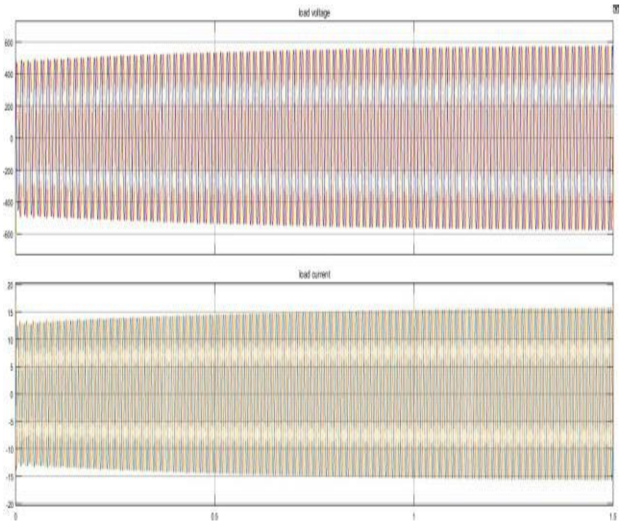

Fig. 17: Voltage and current response across the load

The FFT analysis of the voltage and currents across the inverter in the percentage of the fundamental component is shown in Fig. 18 and 20. The FFT analysis of the voltage and currents after the filter in the percentage of the fundamental component is shown in Fig. 19 and 21. It is seen that the filter has effectively reduced THD in the system.

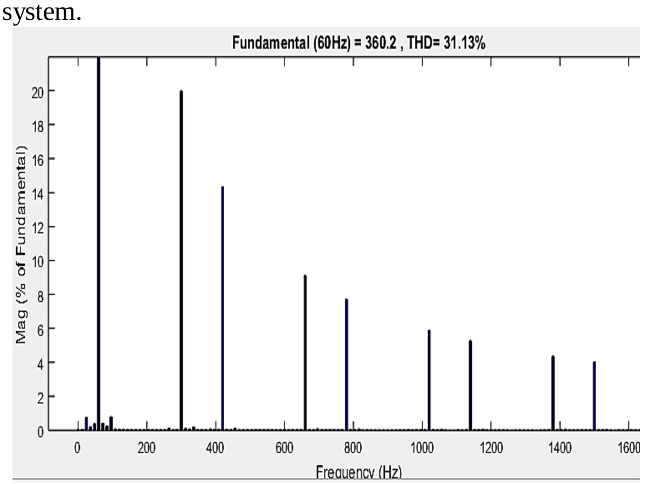

Fig. 18: FFT analysis of VSI terminal line to line voltage

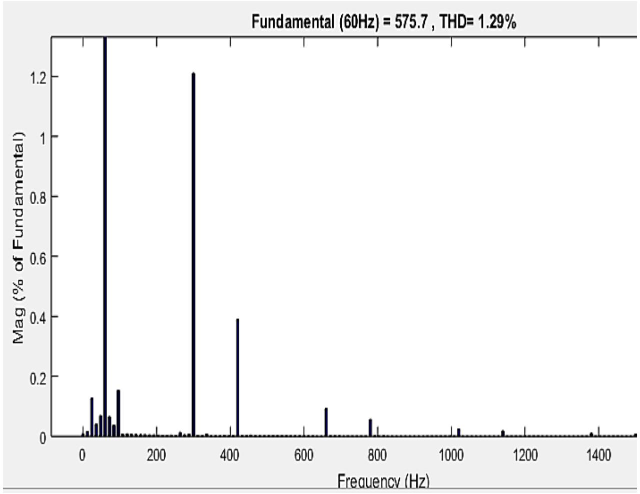

Fig. 19: FFT analysis of the terminal line to line voltage after passing through the filter

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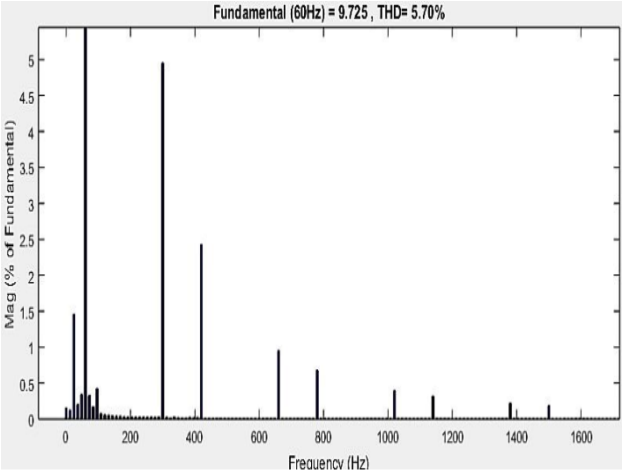

Fig. 20: FFT analysis of current at the output of inverter

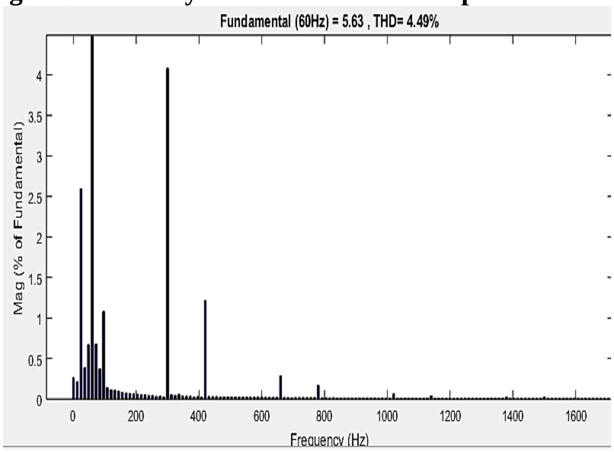

Fig. 21: FFT analysis of current at the load after passing through the filter

V. CONCLUSION

A PV based grid-connected system has been designed and simulated in MATLAB-Simulink. The effectiveness of the MPPT controller and the effect of changing irradiation and temperature has been discussed. The decoupled control of inverter for real and reactive power has been proved. The improvement in THD is shown with FFT analysis.

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