CONTROL STRATEGIES ON GRID-TIED PV INVERTERS

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Abstract - *The grid voltage fluctuates easily due to load changes, affecting the grid's power quality. Grid-tied solar inverters are capable of producing active power only. The reactive power demand of load is solely fulfilled by the grid only. Reactive power drawn from the grid has increased significantly in comparison to active power as a result of the significant rise in the implementation of renewable-based Distributed Energy Resources. If the grid-connected solar inverter is smart enough to supply reactive power in addition to active power, the grid's reactive power requirements will be reduced because the grid will have to supply less reactive power. In this paper for different environmental conditions such as irradiance and temperature and for different loads, the flow of active and reactive power from the solar inverter is studied. MATLAB/SIMULINK software is used to validate the results.*

Keywords: ***Photovoltaic (PV) system, Distributed Energy Resources (DER), Distributed Generation (DG), Maximum power point tracking (MPPT), Perturb & Observe algorithm (P&O), Phase-locked loop (PLL)***

1. INTRODUCTION

The demand for renewable energy has grown as a result of global warming and the finite supply of fossil fuels. The integration of Distributed Energy Resources (DER) systems based on renewable energy resources into the distribution grid has fascinated interest in recent years. Solar radiation is the most abundant renewable energy source. In India, the average annual solar energy incident on land is around 5000 trillion kilowatt-hours, representing a massive solar energy production potential [1]. The solar energy received in a year exceeds the combined energy output of all India's fossil fuel reserves. Solar energy has risen to prominence in recent years as a result of its widespread availability and environmentally friendly operation. Due to various subsidies and promotion proposals provided by governments around the world renewable energy sources getting more popular. Without any moving parts, photovoltaic (PV) power generators convert the energy of solar radiation directly to electrical energy. This happens in materials that have the ability to absorb photons and emit electrons. Silicon is the most common material used in photovoltaics. Because of distinct advantages such as simplicity of allocation, high dependability, absence of fuel cost, low maintenance, and lack of noise and wear due to the absence of moving parts, photovoltaic generation is gaining increased importance among renewable energy source applications [8]. The utility uses a bidirectional meter to transfer excess energy to the grid during average or low peak demands, and the concept of net metering is used by the utility. Grid-connected solar inverters can only produce active power where maximum power can be extracted with the use of MPPT [6, 7]. Electrical loads tend to consume more inductive reactive power because they are predominantly inductive loads. Currently, the grid is the only source of reactive power. The site power factor becomes poor from a utility standpoint as a large number of Distributed Generation (DGs) that inject only active power into the grid become more prevalent, affecting grid performance. Previously, for power quality issues, reactive power injection/absorption was done through FACTS devices. However, these devices have the disadvantages of large size, high cost, large installation area, and so on. It is necessary to regulate the reactive power flow in the network, as this may have an impact on voltage regulation. As the number of grid-connected inverters grows, their use as VAR compensators will aid grid voltage regulation while reducing the need for costly capacitor banks. Control strategies for grid-connected solar inverters to supply reactive power in addition to active power for various loads and varying irradiance are discussed in this paper. The special case of inductive or capacitive load connections will result in a significant change in bus voltage, which will exceed the system voltage specification, resulting in poor system stability. To ensure grid-connected voltage stability, the distributed control strategy is proposed to control the reactive power output, and active power reduction is used as a backup strategy to control the voltages in the PV system [4, 9, 10]. The problems of large-scale PV grid connection, as well as active power regulation, reactive power control, and low voltage crossing methods, are summarised in [2, 3, 5, 11].

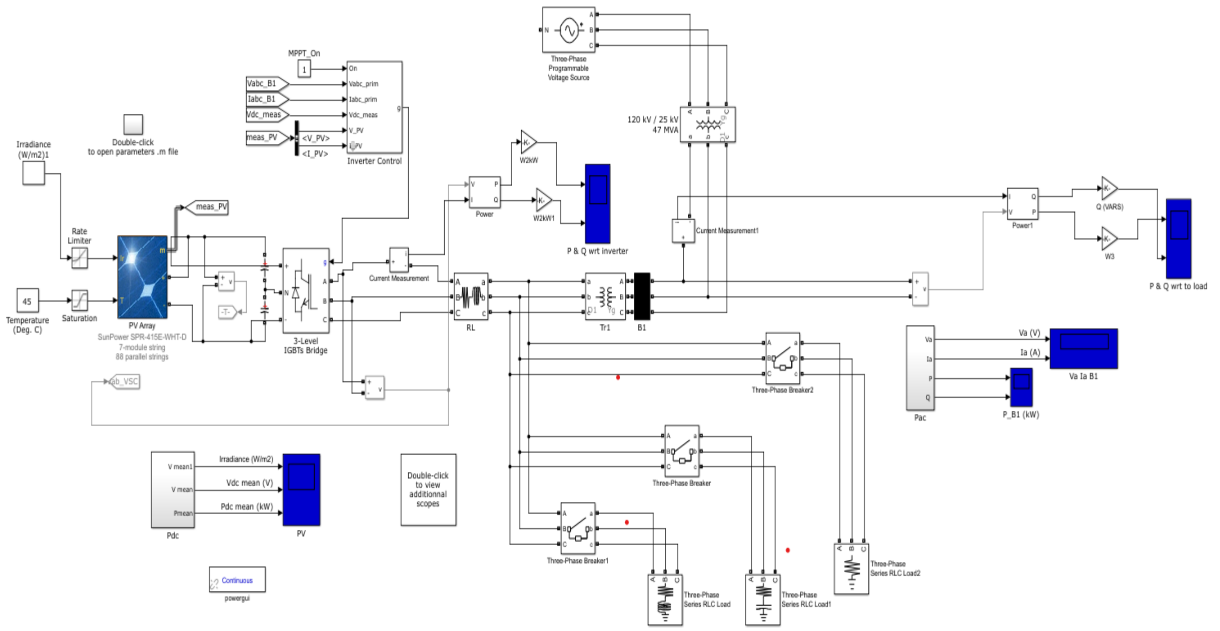

Fig. 1: Model for grid tied PV and its control schemes

In this paper, we studied a grid-connected photovoltaic generation system that includes a PV array, power electronic converters, controllers, local loads, and the utility grid (Fig. 1). The paper presents an investigation into the system's detailed modelling. A voltage source inverter connects the PV array to the utility grid, converting the solar modules' DC output voltage into an AC. The inverter's DC input must be constant, which is controlled by a dc link capacitor. In Matlab/Simulink Software, the proposed model of the entire components and control scheme is simulated. The validity of the models and the effectiveness of the control methods have been confirmed by all simulation results.

2. PHOTOVOLTAIC SYSTEM

A photovoltaic system is made up of many strings of solar cells connected in series and in parallel to provide the desired output voltage and current. Fig. 2 shows the equivalent circuit of a PV, which can be used to calculate the nonlinear I-V characteristic. As a result, the cells are connected in series and parallel to form an array with the desired voltage and power levels. The current through the parallel diode in the single diode equivalent model can be given as:

$$I_D = I_0 \left[\exp\left(\frac{q(V+IR_S)}{\alpha KT}\right) - 1\right] \quad (1)$$

By using Kirchhoff's law in equivalent circuit of PV output current can be written as:

$$I_{pv} = I_{ph} - I_D - I_r \quad (2)$$

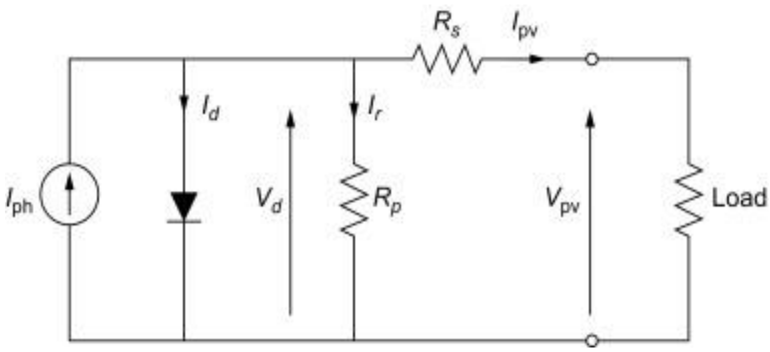

Fig. 2: Equivalent structrure of PV cell

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(V+IR_S)}{\alpha KT}\right) - 1\right] - \frac{V+IR_S}{R_P} \quad (3)$$

Where, I_{ph} is light current

I_0 is diode reverse saturation current

I_r is current in the parallel branch

R_s is the series resistance

R_p is the parallel resistance

α is the diode ideality factor

k is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K)

T is the cell temperature in degrees Kelvin

q is the electron charge

Fig. 3 shows the mathematical model of PV array that includes both series and parallel modules. The data in Table 1 is used to value all of the model's parameters. Fig. 4 shows the output characteristics of the PV array with temperatures and solar radiation.

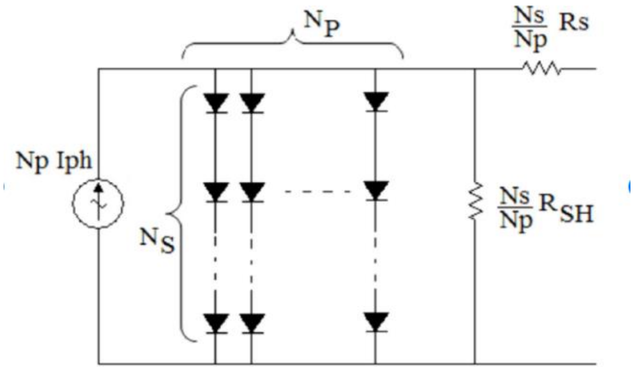

Fig. 3: Mathematical model of PV array

where N_S and N_P are the series and parallel cell numbers, respectively. When cells are connected in series, the output voltage is increased, and when they are connected in parallel, the output current is increased. TABLE 1 shows the data used by PV array. Fig. 4 shows the output characteristics of a PV array at various temperatures and solar radiations.

TABLE 1. Parameters of PV Array

Panel used	SunPower SPR-415E-WHT-D
No of cells	128
Maximum Power	414.801
Open circuit Voltage	85.3
Short circuit current	6.09
Solar intensity (W/m^2)	1000
Diode ideality factor	0.87223
Shunt resistance	419.7813
Series resistance	0.5371

The dc-link voltage is regulated by an external control loop. The DC link voltage of a grid-connected inverter is stabilized with DC-link capacitors. The injected voltage to the grid rises as the drawn energy from PV rises. As a result, the DC link voltage can be kept constant.

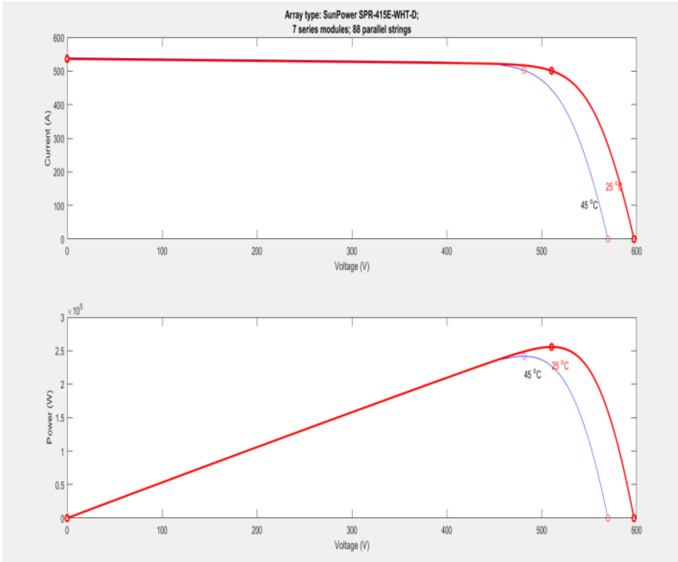

Fig. 4: Characteristics of PV cell

3. MPPT ALGORITHM

In order to determine the maximum power point, many MPPT techniques have recently been developed. Due to high accuracy at MPP, variable step size P&O are the most important used MPPT techniques. The principle behind variable step size P & O algorithms is that when the operating point is far away from the MPP, the algorithm increases the size of the increment, resulting in faster MPP tracking, whereas when the operating point is close to the MPP, the step size increment is too small, resulting in very small oscillations around the MPP, contributing to increased PV system efficiency. Step size used in the MPPT algorithm is given by the following equations:

$$\text{Step 1} = \left(\frac{N}{I}\left|\frac{dP}{dV}\right|\right) A_1 \tag{4}$$

$$\text{Step 2} = \left(\frac{N}{I}\left|\frac{dP}{dV}\right|\right) A_2 \tag{5}$$

With $A_1 < 1 < A_2$

N is the scaling factor and A_1, A_2 are normalizing coefficients.

4. PQ CONTROL METHOD

A common DC/AC inverter connects the PV array to the ac grid via a dc-link capacitor. To make the inductance current track the sinusoidal reference current closely, the inverter is used in current control mode with a PWM switching mechanism. Internal and external control are the two most important aspects of control.

I_d and I_q grid currents are regulated by an internal control loop (Components of active and reactive current). The dc voltage controller's output is the I_d current reference. In addition, the proposed system employs dq0 transformation equations, a PLL algorithm for grid synchronization, and active/reactive power calculation. Park transformation transforms the grid voltages and currents from abc to a dq frame, and rotational frequency ωt is generated with PLL.

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = T_{dq0} * \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (6)$$

Where,

$$T_{dq0} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (7)$$

Consider an inverter connected to the network via a resistor R and inductance L (which represent a simplified model of a transformer) in order to grasp the general principle of control method which as indicated in Fig. 5.
The basic circuit equation for the grid connection to the grid can be written as follows using transformation theory:

$$\frac{d}{dt}\begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} - \begin{bmatrix} R_g/L_g & \omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} = \frac{1}{L}\begin{bmatrix} V_{gd} - e_d \\ V_{gq} - e_q \end{bmatrix} \qquad (8)$$

where V_g and I_g represent the voltage and current of the grid, R_g and L_g are resistance and inductance of the grid and e is the inverter voltage.

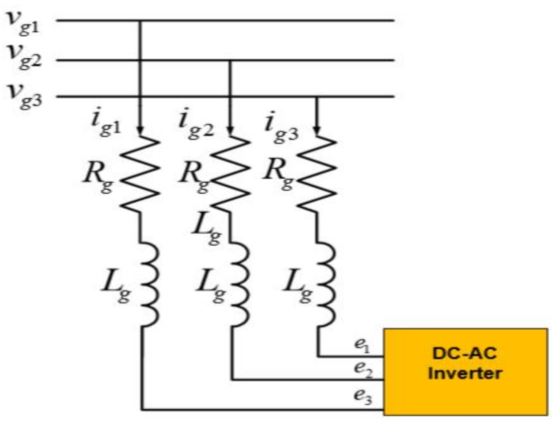

Fig. 5: Grid-connected inverter circuit

The dq reference frame theory is responsible of power control for grid-connected inverters, which results in power determination in a reference frame. The active power control and reactive power exchange components, I_{dref} and I_{qref}, are controlled to achieve active power control and reactive power exchange, respectively, and are commonly used to influence a desired power factor. The grid's active and reactive power can be expressed as follows:

$$P_{dq} = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \qquad (9)$$

$$Q_{dq} = \frac{3}{2}(-v_d i_q + v_q i_d) \qquad (10)$$

where v_d and v_q represent the direct and quadrature grid voltage components, respectively, and i_d, i_q represent the inverter's direct and quadrature output current components. These currents are determined by the amount of power requested and the voltages measured at the connection point. Before calculating the currents, this voltage is transformed in the dq frame. The active power is proportional to i_d and the reactive power is proportional to i_q.
A reference generator block is used after the values of direct and quadrature axis components are obtained from the PLL for grid current. The values of reference current in both the direct and quadrature axis are generated in this reference generator system. The current reference calculator uses the following equations to generate the values of I_{dref} and I_{qref}:

$$I_{dref} = \frac{2}{3}\frac{P_{ref} V_d + Q_{ref} V_q}{V_d^2 + V_q^2} \qquad (11)$$

$$I_{qref} = \frac{2}{3}\frac{P_{ref} V_q + Q_{ref} V_d}{V_d^2 + V_q^2} \qquad (12)$$

5. SIMULATION RESULT

The effect of PQ control on the grid-connected voltage when an inductive or capacitive load is connected to the grid and for different irradiances is investigated in this paper. An inverter bridge module, a voltage and current detection module, a phase-locked loop module, a coordinate transformation module, a control module, and an SPWM module are all included in the proposed control strategy.

Test 1: Irradiance is constant at 1000W/m2

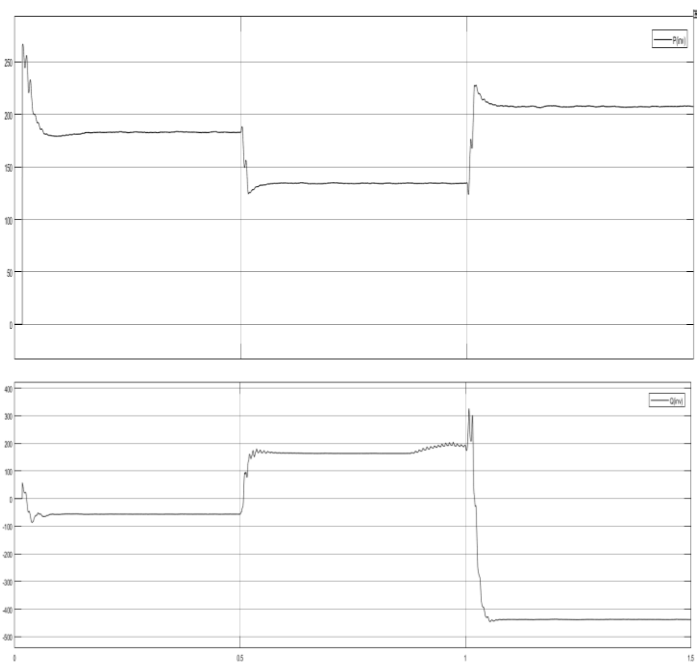

Fig. 6: Active and reactive power by the inverter

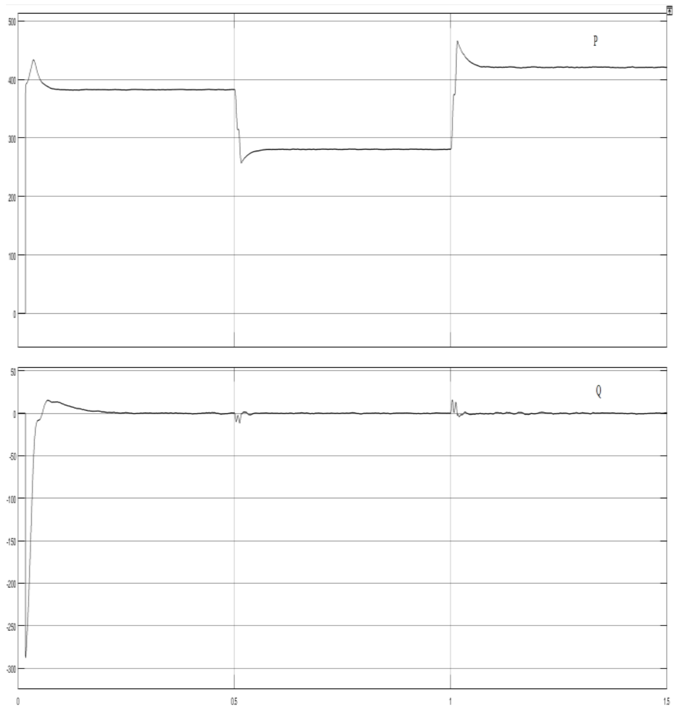

Fig. 7: Active and reactive power from the grid

Reactive power to the load is supplied from the inverter as shown in Fig. 6. In the proposed scheme inductive load is connected between 0.5 to 0.1 and capacitive load is connected between 0.5 to 1 with the help of breakers. It is clear from the graph that for inductive load inverter is supplying reactive power and for the capacitive load it is absorbing reactive power means reactive power is positive for the interval 0 to 0.5 and negative for the interval 0.5 to 1. Active power is supplied according to MPPT.

Fig. 7 shows the active and reactive power supplied from grid. From the powers graph of grid, it is clear that reactive power from grid is always around zero.

Test 2: Irradiance is varying as 1000 W/m^2, 800 W/m^2, 600 W/m^2, 400 W/m^2 and 200 W/m^2.

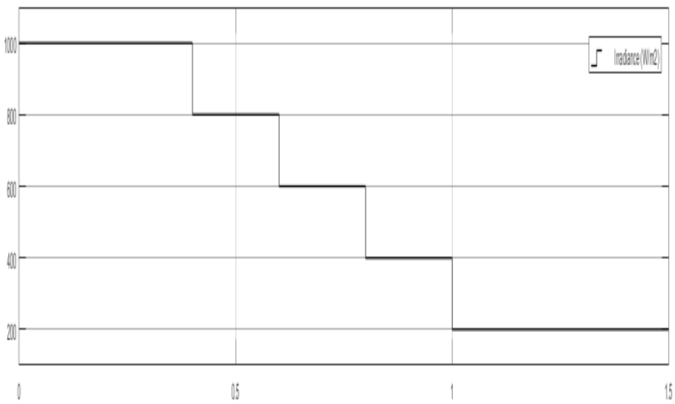

Fig. 8: Varying irradiance

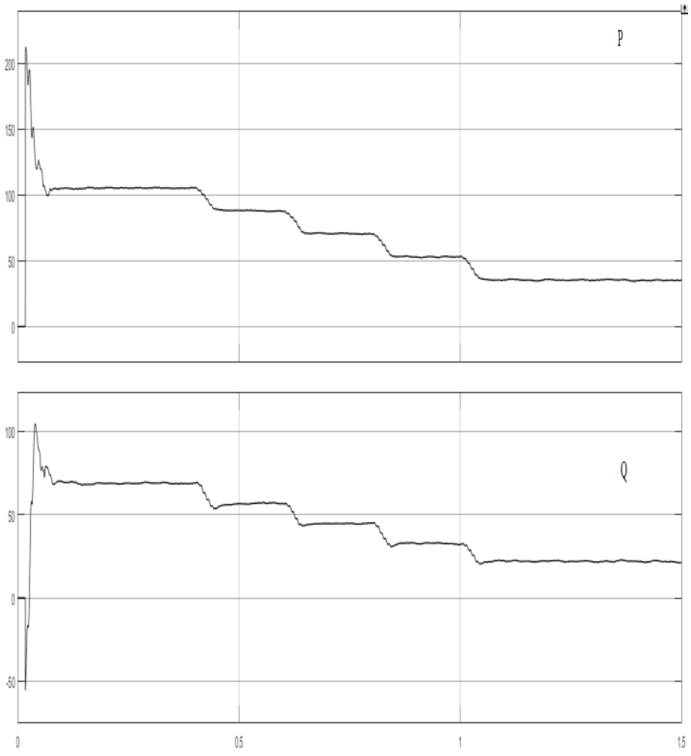

Fig. 9: Active and reactive power from the inverter

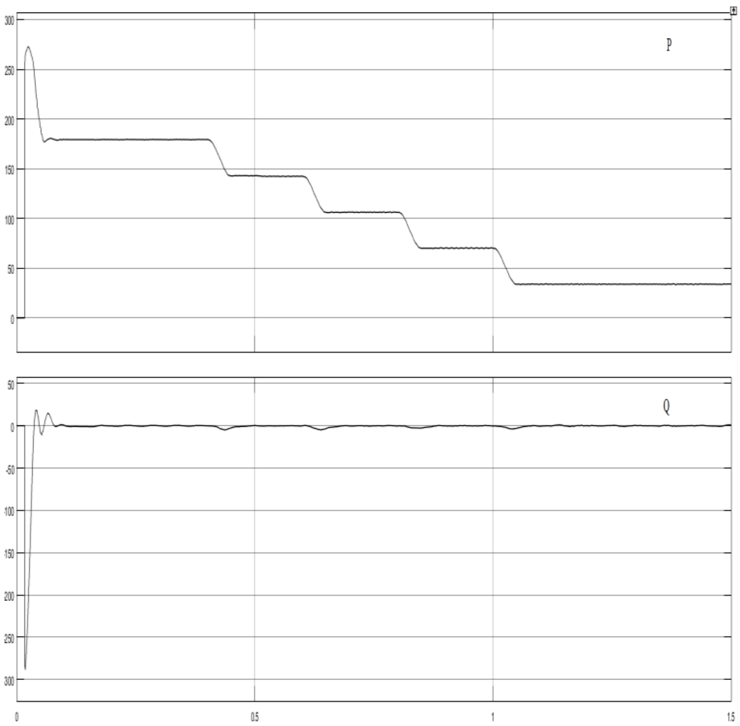

Fig. 10: Active and reactive power of grid

Fig. 9 shows the behaviour of active and reactive power supply from inverter for different values of irradiances. The irradiance is adjusted in 200-unit steps from 1000 to 200 W/m^2.

The active power fed by the inverter follows the MPPT operation to extract and pump maximum power to the grid. The inverter's reactive power varies in proportion to the active power in order to maintain a constant power factor of 0.83. Active and reactive power values for various time intervals are taken from the active and reactive power plots of Fig. 9 are shown in TABLE I. Fig. 10 shows the active and reactive power supplied by the grid and from the graph, it is clear that reactive power is always around zero which is a desirable condition.

TABLE 2: Active and Reactive Power Values

Time interval	Active Power (kw)	Reactive power (kVAR)
0.1 -0.4 sec	120	80
0.4-0.6 sec	94	61
0.6-0.8 sec	75	50
0.8-1 sec	53	35
1-1.5 sec	24	16

From the above table, it is clear that in this mode of operation power factor is fixed to 0.83. The results show that the grid-connected inverter helps the grid when there is a need for reactive power for loads.

6. CONCLUSION

A grid-connected photovoltaic inverter system with reactive power compensation is presented in this paper. In the PV inverter, the need for reactive power generation has been discussed. After sudden access of an inductive or capacitive load, the PV inverter's reactive power is used to stabilize the grid-connected voltage. The simulation results show that the proposed control method can maintain grid-connected voltage stability after a sudden inductive or capacitive load access which verifies the proposed method's correctness and effectiveness. In MATLAB, a Simulink model of a three-phase dual-stage grid-connected solar PV inverter is developed. The operation of a PV inverter in both active and reactive power generation modes has been simulated.

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