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Reactive Power Control by Single Phase Single Stage Solar PV Inverter

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***Abstract*: As solar inverters have the ability to inject reactive power along with the active power, a reactive power control methodology to inject and control the reactive power flow into the grid is presented in this paper. A detailed modelling about the components used in this technique is mentioned in the below sections. This paper also discusses about the reactive power capability curve in relation with the inverter current carrying capability and constant reactive power injection method. The system is simulated using the MATLAB/SIMULINK software for constant reactive power injection method and results are presented.**

***Index Terms*: reactive power, power capability curve, Solar PV array, inverter.**

I. INTRODUCTION

In the recent world of electricity, the development of non-conventional resource of energy is rapidly increasing due to the ever-growing demand of electricity. Considering the power quality issue and environmental impact, many techniques evolved to extract maximum amount of power from renewable resources also. One of the major resources for producing electrical energy from renewable energy resource is the solar energy through which DC energy can be extracted and can be converted into AC quantity using additional devices. Due to the limitations in solar PV arrays the usage of solar energy for producing electricity is very less. Knowing the abilities of renewable resources, present day engineers are using these resources and integrating the power grid for improvement of power quality of the system. Among the renewable resources, solar energy has a major role in improving the power quality issues of grid. The PV arrays produce DC energy by utilizing the insolation from sun, the DC energy is converted into AC form by using inverter circuit. As electrical loads are predominantly inductive loads, they tend to consume more amount of inductive reactive power from the grid side and the performance of the grid will be affected due to such condition. So, there is a need to regulate the reactive power flow in the power system network as this may affect the voltage regulation also. Formerly, the reactive power injection/absorption is done through the FACTS devices for mitigating power quality issues. There are different types of FACTS devices like series, shunt, series-series, series-shunt which are used based on the requirement. But the problems aroused due to the usage of FACTS devices like sizing, cost, area of installation . made the power engineers to think the other way which yielded a solution in terms of solar inverter, as the inverters are capable of producing the reactive power. Reactive power injection from the inverter along with active power injection reduces the burden on the grid and improves the performance of the total system. For this purpose, the inverters are needed to be over sized by 15-20 percent of the original rating [7]

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II. MATHEMATICAL MODELLING

A. Photo Voltaic Array

A Photo Voltaic array is modelled using basic PV cell structure which is reliant on the solar irradiance, temperature and the output voltage of the cell. The output characteristics of solar cell is calculated depending on the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) at standard test conditions (STC). Refer (1)-(5) for V_{oc} and I_{sc} respectively. Equvivalent of solar PV cell is shown in the Fig.1.

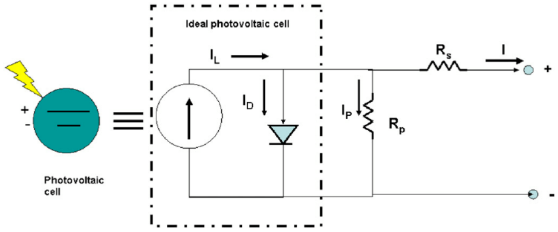

Fig.1. Equivalent Circuit of Solar PV Cell

$$Voc = Voc + Kv.(Tc - 25) \quad (1)$$

$$Isc = \frac{Iph - Id - Vpv/Rp}{1 + Rs/Rp} \quad (2)$$

$$Iarray = Ipv.Npar \quad (3)$$

$$Varray = Vpv.Nser \quad (4)$$

$$Parray = Iarray.Varray \quad (5)$$

B. Inverter Modelling

The inverter model used in the system under study is a Voltage Source Converter (VSC) which is responsible for the exchange of power between DC side and AC side [8]. The conversion is performed by the inverter with Sinusoidal Pulse Width Modulation (SPWM) technique which produces an AC current resembling the wave shape of a sinusoidal signal where the inverter output voltage

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(V_{ac}) depends on the input DC Voltage and modulation index. The circuit of a single phase VSC is shown below Fig.2.

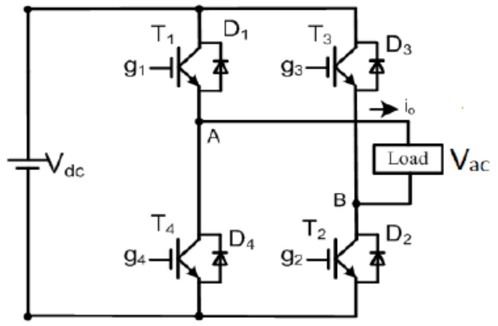

Fig.2. Circuit diagram of single-phase inverter

C. Capability curve

The curve which shows the capacity of an equipment up to which the equipment can deliver without wear and tear. Here the inverter operation is analyzed in terms of active and reactive power. In this analysis from the literature [2], [3] the voltage, current, power limits play a major role.

Voltage limits: The dc voltage can be varied from the initial value to the maximum value so as to extract the maximum possible power from the solar PV array. However, it also has some limitations over the dc voltage for which V_{min} at the inverter input terminals that allows the ac voltage to be inside the permissible range as mentioned in the grid codes, refer to (6).

$$Vmin = 2\sqrt{2}V \qquad (6)$$

When the inverter is working at the Maximum Power Point, the minimum acceptable solar insolation to maintain the voltage above the minimum voltage range is also calculated, refer to (7).

$$Gmin = \left(\frac{Vdcmin - Vocstc}{Kv} + 25 - Ta\right) X \frac{800}{Noct - 20} \qquad (7)$$

Besides this limit, the upper limit for the dc voltage (V_{max}) should also be a constraint, as it is depending on open circuit (OC) voltage of panels connected in series. If the dc voltage is higher than the maximum voltage of the array, there will be no power supplied from the solar panel. So, care should be taken while designing these parameters, the maximum open circuit voltage of the PV array mainly depends on the minimum temperature limit possible at the chosen location. Refer to (8)

$$Vocmax = Vocstc + Kv.\left(Tamin + Gmin.\frac{Noct - 20}{800} - 25\right) \qquad (8)$$

$$Vmax = Vocmax.Nser \qquad (9)$$

The maximum PV inverter voltage which is obtained from the PV array imposes the restrictions on the active and reactive power feed-in capability of the inverter, refer to (10).

$$P^2 + (Q + Vg^2/X)^2 = (Vg.Vi)/X \qquad (10)$$

Current Limits:

The maximum inverter current (I_i) injection by the inverter under the given circumstances imposes the limits for P and Q, which the PV inverter feeds into the grid. The limits of power injection can be expressed as the equation of the circle, refer to (11).

$$P^2 + Q^2 = (Vg.Ii)^2 \qquad (11)$$

$$Ii = \frac{\sqrt{P^2 + Q^2}}{Vg} \qquad (12)$$

Where, V_g is the grid voltage, I_i is PV inverter current and P, Q represent the active and reactive power of the network at the PCC, respectively. From the above voltage and current limits, the PQ limits can be shown graphically as below in Fig.3.

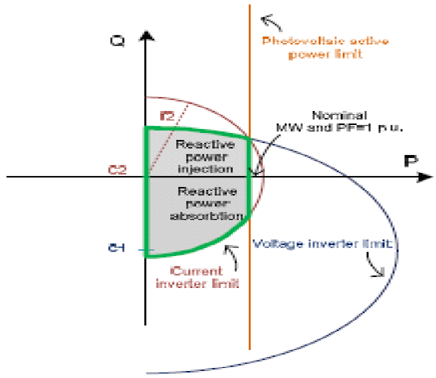

Fig.3. Capability curve of inverter

The restriction of reactive power can be calculated using the two circle equations that dominates the power capability curve. If the $S^2 = P^2(G, T) + Q^2$ dominates the PQ curve then reactive power (Q) will depend on the active power (P) variation which was stated in the previous equations. In case the curve is dominated by the equation refer to (13), then the factors affecting the injection of reactive power limit can be dc voltage and modulation index (MI) refer to (14).

$$P^2 + (Q + Vgrid)^2/X = (Vgrid.Vconv)^2/X \qquad (13)$$

$$Q = \frac{Vgrid.Vdc.M}{X} \qquad (14)$$

Considering the variations in dc voltage at the input side of the inverter, Q can be referred to (15)

$$Qmpp(G,T,Vdc) = \frac{Vgrid.Vmpp(G,T).M}{X} \qquad (15)$$

As V_{dc} influences the alteration of modulation index (MI), means that Q remaining constant as the dc voltage is almost constant at any given instance.

In order to feed-in the Q required to the grid, MI can be imposed which sets the output voltage value of the converter (Vac). Thus, MI varies only between maximum and minimum limits (M_{min} and M_{max}) which again depends on the ac voltage limits set by the grid codes.

III. METHODS TO CONTROL REACTIVE POWER

As inverter is a current-limited device, the choice of designing the inverter control system is left to the manufacturers depending on their own requirement.

There are two possible ways to design an inverter one way is either by making the maximum current capacity available for real power or the other is by holding some

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current capacity as reserve so that the inverter has some reactive capability at its rated real power, operating alike a conventional synchronous generator. In power system network basically, the inductive loads are thoroughly used and these inductive loads absorb active and reactive power from their respective system depending upon their performance. Real power is the one which does the useful work but reactive power just helps in transferring the real power to the demand side so it has to be ensured that for an efficient operation of power system the reactive power flow must be minimized.

The reactive power compensation principle is stated as the compensation of load and regulating the voltage. The main objectives of reactive power compensation are to improve the system performance and balance the system. Reactive power compensation dynamically has been a rare practice in consequence of the developing technology in the power system sector.

The active power injection into the grid is rather easy compared to the reactive power injection, as finding reference value for reactive power is a typical task. One of the most important and popular methods in the reference generation is the instantaneous theory of reactive power. The other methods include Constant power factor operation, Dynamic power factor operation PF(P), Q(V), AC-bus voltage regulation, Constant reactive power [5], [6]. In this paper the reactive power control using constant reactive power method is discussed in detail.

Constant reactive power method

In this method, the reactive power is kept at a constant rate. Regardless of the PV generating active power and the status of grid requirements on the reactive power, the inverter will supply the reactive power as per values prescribed by the operator.

In this paper a single-phase single stage PV inverter model is presented in Fig.4. The output of PV array is fed to single phase IGBT inverter and is controlled by the gate pulses obtained from the control strategy applied to it. The control strategy mainly consists of three stages namely MPPT technique, DC voltage control and AC voltage control. The three stages are explained below in detail.

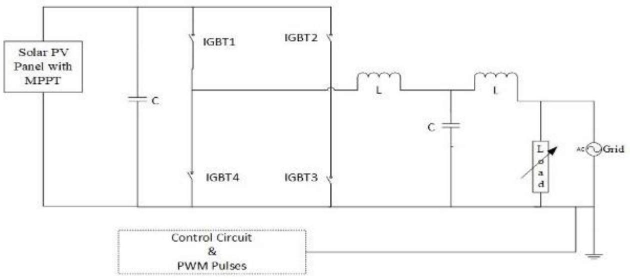

Fig.4. Circuit diagram of single-phase single stage solar inverter

MPPT technique

For tracking the maximum power from the solar panel many techniques are available. one of the common methods used for extracting maximum power is Perturb and Observe (P&O) algorithm **[1]**. This methodology uses only two numbers of sensors one for dc voltage and other for dc current. MPPT is an algorithm which tries to balance the maximum power transfer theorem. The changes in voltage and power are measured and based on the sign of these two quantities, the duty cycle is varied so as to harvest maximum power from the solar PV panel and also automatically adjusts the reference signal of DC bus. The program is developed in such a way that it harvests maximum power and also maintaining a fixed value of DC voltage at the output of the PV panel irrespective of variations in conditions such as solar insolation, ambient temperature and surroundings which affect the performance of solar panel. The MPPT tracker should be able to produce effective output with non-linear and time variant systems. MPPT flowchart is shown in Fig.5.

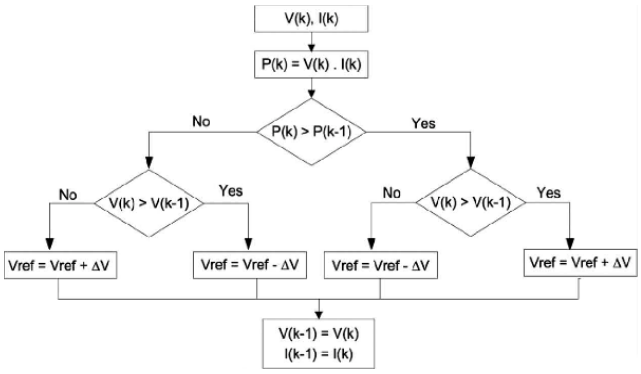

Fig.5. MPPT algorithm (P&O) technique

Voltage Controller:

The DC voltage is regulated using the reference voltage obtained from MPPT controller, the Dc link voltage is compared with a reference value of 400 V and the error is calculated which acts as input to the PI controller which gives the I_{dref} for controlling the active power.

Current Controller

The grid current is transformed by using transformation techniques (Park Transformation) [4], refer to (16), (17).

$$Vd = V\alpha * Cos(\theta) + V\beta * Sin(\theta) \quad (16)$$

$$Vq = -V\alpha * sin(\theta) + V\beta * cos(\theta) \quad (17)$$

The obtained transformation values are compared to the output from the voltage controller which is taken as reference and the error acts as input to the PI controller.

Case-1: The I_q is compared with a reference value zero which makes Iq as zero and the both the error values of Id and Iq are combinedly send to the PI controller. As reactive power is controlled by reactive component of current (Iq), in this case the Q is not fed or absorbed only active power will be fed into the grid.

Case-2: In this case the q-component of grid current is compared with a fixed reference such as -0.6 Pu and Iq is made to follow the reference value prescribed in the control algorithm, then both the error values of Id and Iq are fed to a PI controller. In this case the Q is fed into the grid as the reference of reactive component of current is maintained at a specified value. As like in the above cases shown the simulation was carried out for both positive and negative values of reference for reactive component of grid current and the following observation is made:

1. If the reference for the I_q is maintained as zero then neither reactive power injection nor the absorption takes place, the inverter delivers only active power.
2. If the reference for the reactive component of current is made positive then reactive power absorption takes place as the inverter tends to operate in inductive mode.

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3. If the reference for the reactive component of current is made negative then reactive power injection takes place as the inverter tends to operate in capacitive mode.

The PI controller output is then taken as reference for the PWM generation. The output obtained is then converted to the per units using the nominal values and then the converted per unit value is divided with the Vd & Vq converted to obtain the modulation index which gives us the references for the pulse generation.

IV. SIMULATION RESULTS & DISCUSSION

The simulation was carried out for a 5.5KW single-phase single stage PV solar inverter as shown in the figure below. The inverter topology uses IGBT switches with sinusoidal PWM technique and carrier frequency of 5 KHz. The simulation was carried out for variable irradiance ranging from 1000w/m^2 to 200w/m^2 in steps of 200 units per second. The results are shown in Fig.6 & 7. for case-1 and 2 respectively.

case-1: Iq is set to zero

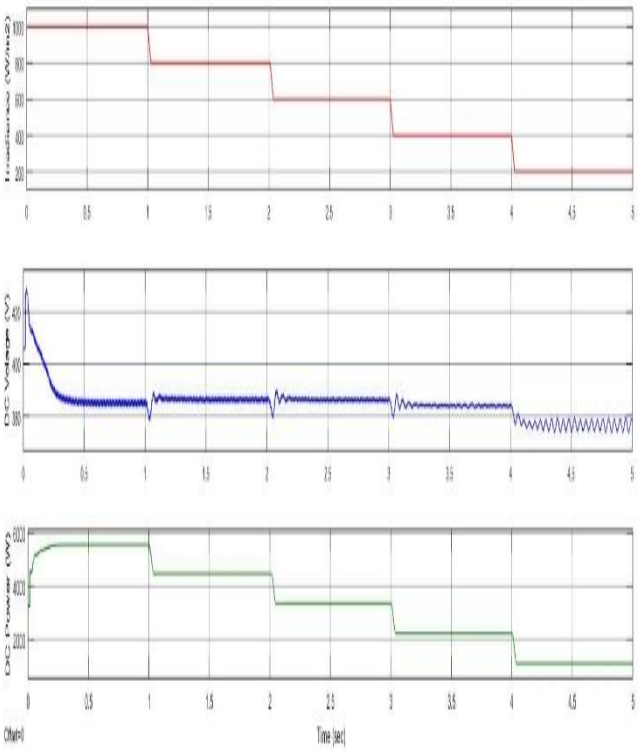

Fig.6. (a) Irradiance, DC voltage, PV power.

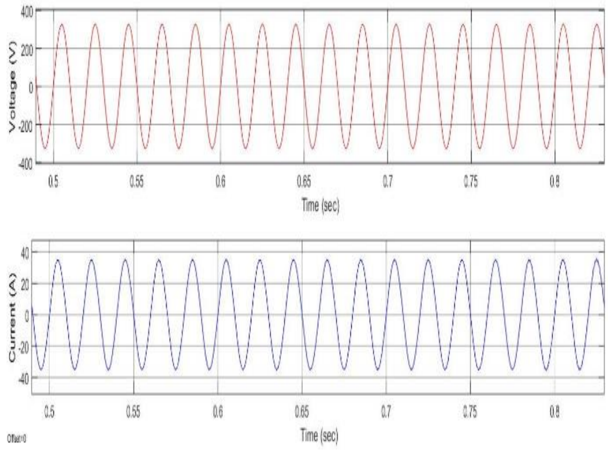

Fig.6. (b) grid voltage and current

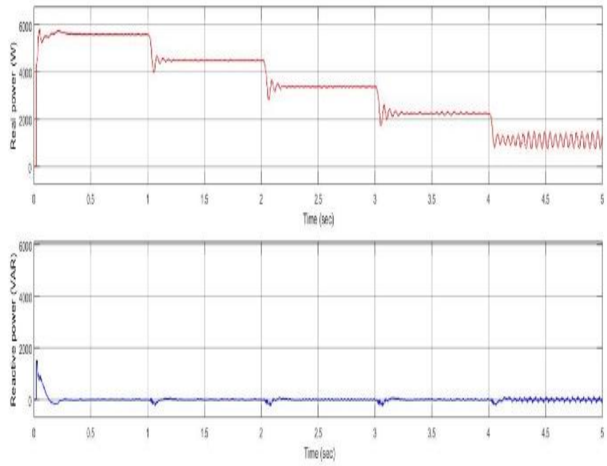

Fig.6. (c) Active and reactive power

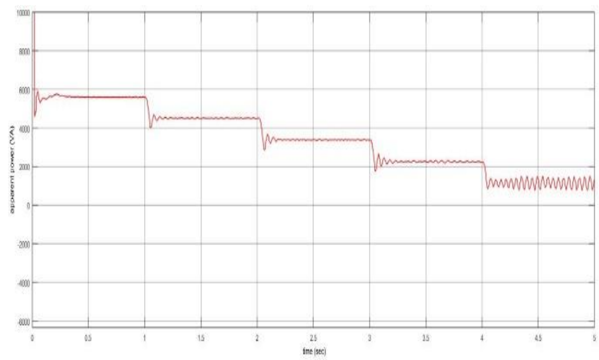

Fig.6. (d) Apparent Power

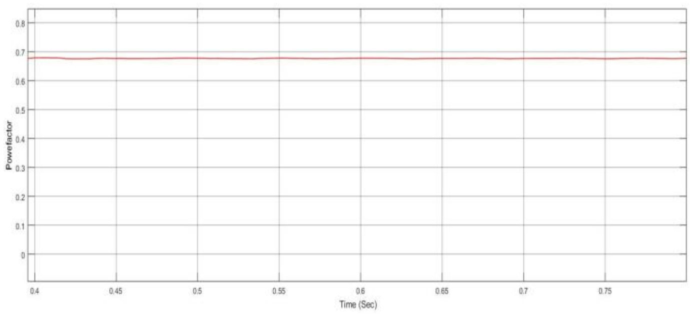

Fig.6. (e) Power factor of grid.

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Case-2: Iq is set to -0.6 (reactive power delivering)

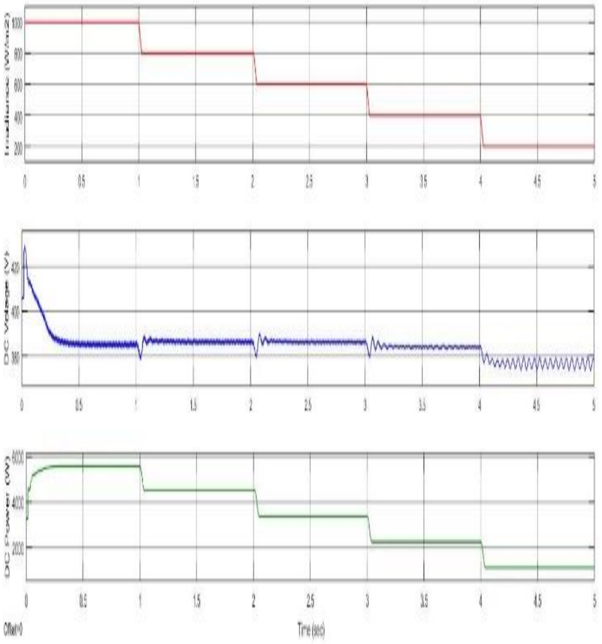

Fig.7. (a) Irradiance, DC voltage, PV power.

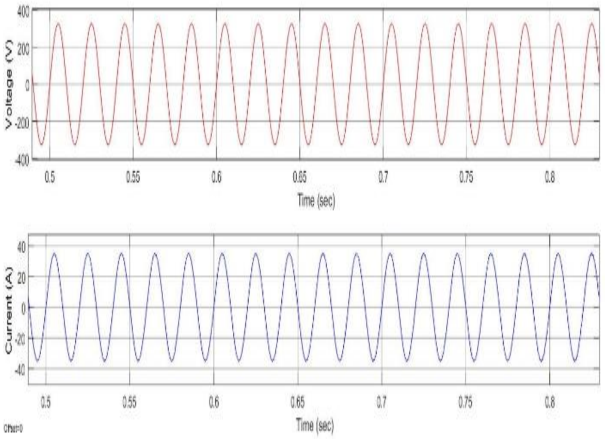

Fig.7. (b) grid voltage and current

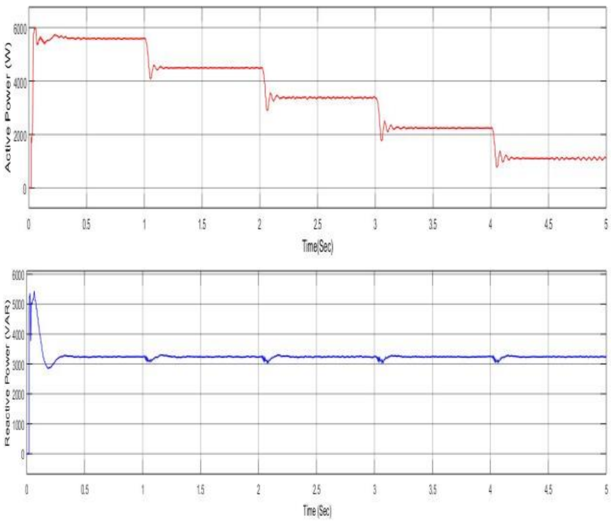

Fig.7. (c) Active and reactive power

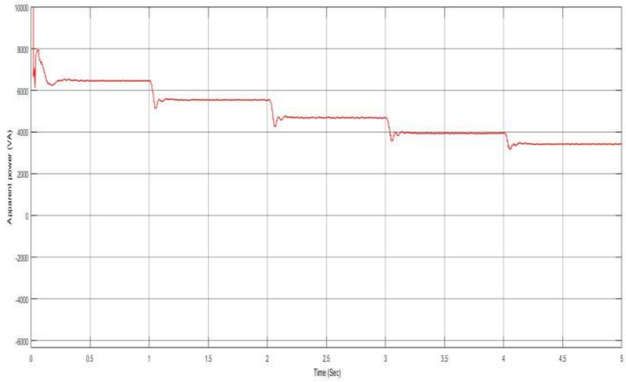

Fig.7. (d) Apparent Power

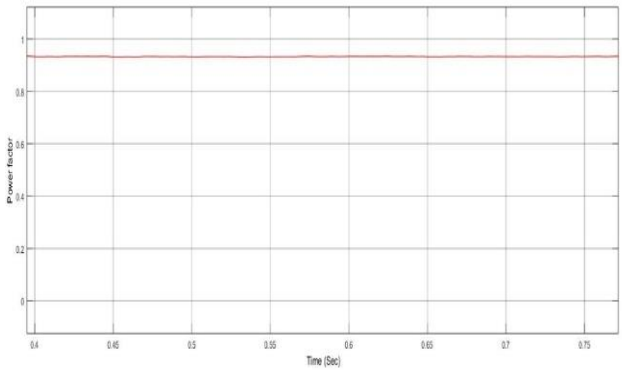

Fig.7. (e) Power factor of grid.

V. CONCLUSION

Single phase single stage PV solar inverter has been simulated in MATLAB/Simulink software for constant reactive power method and the results are discussed above, shows improved performance and better power factor at the grid side when the inverter was operated other than unity power factor (Iq reference is not kept at zero).

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