Intelligent Control of Solar Inverter for Grid Power Factor Enhancement through STATCOM Operation

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***Abstract*—In this research paper, the key contribution is to design a new control algorithm so that we can use PV Inverter as a STATCOM thereby maintaining PCC Voltage and achieving the power factor correction of the grid. This PV Inverter has three modes of operation: PV-Mode, STATCOM-Mode & Partial PV-Mode. In PV-Mode the inverter will generate only the active power and the grid supplies the reactive power needed for the load. In STATCOM- Mode the inverter will use its full resources to exchange the dynamic reactive power need of the grid for critical conditions in the power system, while in partial PV-Mode it will generate active power as well as reactive power. Instead of using conventional P-Q control, here the controller is designed combining the DC-link voltage and PCC Voltage controllers. The detailed modeling of the controllers are done in MATLAB SIMULINK.**

***Index Terms*—Photovoltaic Inverter, FACTS, PV-STATCOM, Power factor correction, Voltage regulation.**

I. Introduction

Our world is currently rapidly running out of fossil fuels, so to meet our fundamental needs, we are switching towards using renewable energy sources. PV sources are the most widely used and accessible renewable energy source. The key equipment for converting solar DC power into AC is Smart Inverter. Due to this inverter, it is possible to feed the loads so easily [1]. Although the inverter's primary function is to convert DC electricity to AC voltage due to the advancement of power electronics technologies the inverters have so many versatile functions. It can supply the load with active power while also making up for the grid's requirement for reactive power [2], [3].

In the conventional grid, due to the nonlinearity of loads, there are voltage fluctuations and power quality issues on the utility side as well as the customer side. So, to maintain the voltage we need some reactive power compensation devices like FACTS devices [10]. Basically in this paper, we are more focussed on STATCOM(Static synchronous compensator). As we all know a STATCOM Plant is very costly, so we tried to develop a controller for the PV Inverter so that it will work as STATCOM during the voltage fluctuations in the grid and maintain the nominal voltage [4]. The time of response of the STATCOM Controller is matched with the response time of actual STATCOM(1-2 cycles) [6]. The main component of STATCOM is the voltage source converter(VSC). It can add as well as absorb reactive power from the grid.

This paper suggests an innovative voltage control technique for the grid-connected photovoltaic inverter to improve transient stability and, as a result, the power transfer capability. Revisions are presently being made to grid connectivity standards to make smart inverter functionalities more widely adopted. The inverter is meant to serve both during the day and at night as a STATCOM [3]. The technology that uses a PV solar farm as a STATCOM is known as "PV-STATCOM" [4]. It utilizes the entire solar farm's inverter capacity at night and the remaining capacity during the day following the production of actual power, both squandered in a typical solar farm [3].

In this paper, the three modes of operation are described. In PV mode it will generate only active power while the grid will supply the reactive power of the load. When some critical disturbance occurs in the grid, the solar panel will cease its active power generation and provide full support for the reactive power compensation to the grid as long as it needs, and then autonomously it will start the active power generation again when the disturbance is over. Whereas in Partial PV-Mode, the inverter will supply active power along with reactive power. This partial mode is mainly for the power factor correction [7] and this will come into the picture when the reactive power need of load is less than the overall capacity of the inverter. This overall control method is being modeled in MATLAB Software and being tested for various load conditions.

Below is an explanation of the remaining sections: The system modeling along with its parameters are explained in Section II. Section III describes all the results and discussions that are being verified in MATLAB. Section IV describes the conclusion part followed by references in the next section.

II. System Modeling and parameters

A. PV System

The majority of renewable energy, as we all know, originates from solar power. Voltage source converters(VSCs), an essential component of all DERs, are needed to integrate solar power into the conventional grid. We also know that each solar cell produces relatively less voltage, so a boost converter is used along with the MPPT technique. In the MPPT technique, I have used the ”Perturb and Observe” method to extract the maximum voltage from the solar PV. The L and C parameters of the boost converter are designed in such a way as to provide the correct output voltage.

B. Study System

In this paper, the chosen study system contains Solar PV which is associated with the Grid at the PCC Bus.

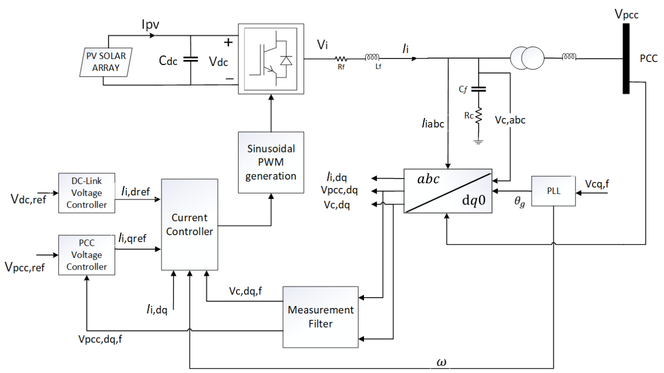

Fig. 1. Proposed System

The proposed system is described in figure 1. In this system, a 208 V line-to-line voltage in the distribution system is connected to a 10 kW photovoltaic solar system via an isolation transformer. At PCC a parallel RLC Load is connected whose ratings are like this P=8 kW and Q=6 kVAR. A switching frequency of 10 kHz is used by the PV system which uses a 10 kVA IGBT-based VSC. To reduce the harmonics that the inverter produces, an LC filter is used. Here, Rf is the combined resistance of the filter inductor and resistance offered by IGBT in the ON state. Lf denotes filter inductance. The reactance of the filter inductor is chosen to be between 0.1 and 0.25 pu to reduce the VSC current ripple. The capacitor used in the filter is represented by Cf. Along with this a damping resistor Rd is used to dampen out the oscillations in inverter current.

The time of response of a normal STACOM is around 1-2 cycles. This criterion is also fulfilled by the PV STATCOM as we will see in the results section.

A solar farm serves as the STATCOM in a PV-STATCOM [6]. After active power generation, it uses the inverter’s remaining capacity to adjust the power factor and supply the required reactive power [4]. In both devices, VSC plays an important role. In this paper, the controller of the inverter is designed in such a way that it delivers as well as absorbs reactive power. It will adjust the grid’s power factor if the reactive power required is less than the inverter’s capability. Because in any system if we reduce the reactive power supply from the grid then its active power transmission will be improved and this will improve the grid power factor. This is the main aim of this paper.

C. Operation Modes

In this paper three modes of operation are described as follows:

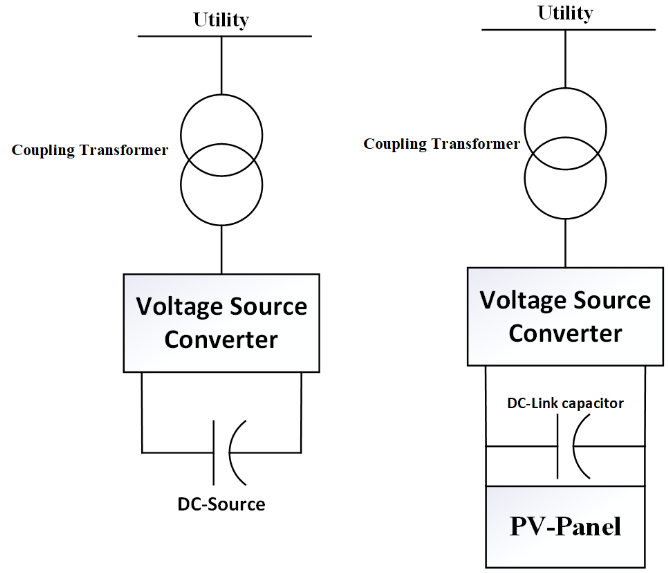

Fig. 2. PV-STATCOM and Conventional STATCOM

I. PV-Mode (M=0): This is how solar photovoltaic systems operate simply. In this instance, it will only produce active power, the production of reactive power will be 0. Thus, the grid is the only source of reactive power delivery to the load. This mode will work only during daytime.

II. STATCOM-Mode (M=2): This mode is generally active at night time because there is no active power generation of solar farms at night. But at the time of critical loading conditions, the voltage will fluctuate very much so this mode can be operated in daytime also. To maintain the nominal voltage at PCC in this scenario, solar PV ceases producing active power and swaps dynamic reactive power with the grid.

III. Partial PV-Mode (M=1): This mode will work only during the daytime because, here the solar PV will generate reactive power along with active power. When the grid needs power factor correction this mode will be turned on automatically by the mode selector.

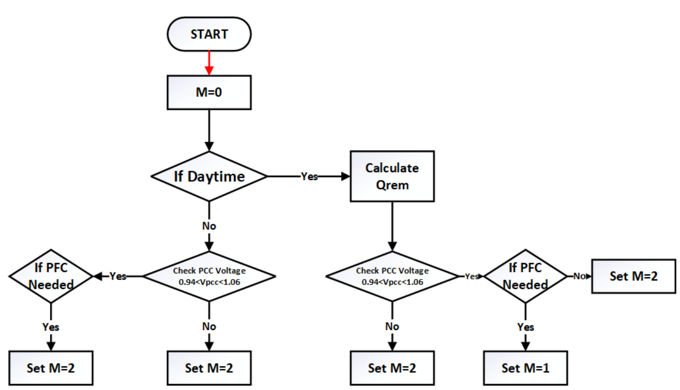

Fig. 3. Operation Mode Flowchart

D. PV-STATCOM Controller

1) PLL(Phase Locked Loop):): It is employed to coordinate the inverter output with grid frequency which is 50 Hz. As the control will be easy in dq_0 format due to the static behavior of the frame of reference, so all the abc parameters are converted into dq_0 . The PCC Voltage's q component is regulated to 0 for the decoupling of the reactive as well as the active powers.

$$V_{\mathrm{pcc}_q} = V\sin(\omega_0 t + \theta_0 - \chi) \tag{1}$$

$$\frac{d\chi}{dt} = \omega(t) \tag{2}$$

Where V is the PCC Voltage magnitude, ω_0 is the system frequency, and angle θ_0 represents the initial phase angle. Voltage controlled oscillator(VCO) is used for converting the frequency into phase angle.

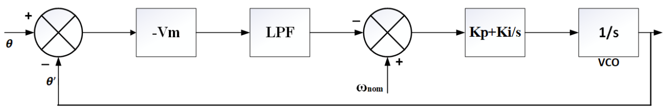

Fig. 4. PLL

2) Current Control: The main target of the current controller is to generate the modulation index of the PWM Signals. The following describes the true power and reactive power of solar PV:

$$P = \frac{3}{2}(V_{\mathrm{pccd}} i_{\mathrm{invd}} + V_{\mathrm{pccq}} i_{\mathrm{invq}}) \tag{3}$$

$$Q = \frac{3}{2}(-V_{\mathrm{pccd}} i_{\mathrm{invq}} + V_{\mathrm{pccq}} i_{\mathrm{invd}}) \tag{4}$$

From the PLL operation, it is seen that $V_{\mathrm{pcc}d}$ =V and $V_{\mathrm{pcc}q}$=0 so from the above equations we can see that active power is monitored by I_{invd}, I_{invq} controls the reactive power, where I_{invd} and I_{invq} are the inverter current outputs in $dq0$ form. The reference of this controller comes from the outer voltage control loop which is the voltage controller of the DC-Link and PCC.

From figure 1 we can see that the equivalent voltage equations in dqo format at the filter capacitance node are

$$L_f \frac{di_{invd}}{dt} = L_f\omega(t) i_{iinvq} - R_f i_{invd} + \frac{V_{\mathrm{DC}}}{2} m_d - V_{\mathrm{pcc}_d} \tag{5}$$

$$L_f \frac{di_{invq}}{dt} = -L_f\omega(t) i_{invq} - R_f i_{invq} + \frac{V_{\mathrm{DC}}}{2} m_q - V_{\mathrm{pcc}_q} \tag{6}$$

where V_{dc} is DC-Link voltage, m_{dq} are modulation indices, $V_{\mathrm{pcc}dq}$ are PCC Voltages and $I_{\mathrm{inv}dq}$ are inverter currents. After these terms, the coupling factors are decoupled using the control equations u_{d} and u_{q}. The sum of the control signals added generates the modulation indices which are as follows:

$$m_d = \frac{2}{V_{\mathrm{DC}}}\left(u_d - L_f\omega_0 i_{invq} + V_{\mathrm{pccd}}\right) \tag{7}$$

$$m_q = \frac{2}{V_{\mathrm{DC}}}\left(u_q + L_f\omega_0 i_{invd} + V_{\mathrm{pccq}}\right) \tag{8}$$

now again after converting these modulation indices from $dq0$ to abc, these signals will go to the PWM converter and they will generate the gate pulse for the three-phase inverter.

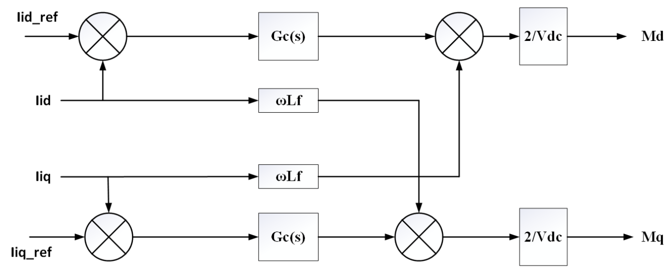

Fig. 5. Inner Current Controller

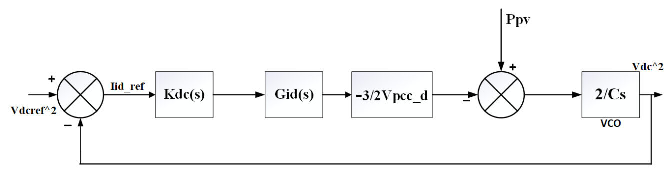

Fig. 6. Outer Voltage Controller

3) DC-Link Voltage Control: The PV power equals the AC side power when all inverter and DC link losses are taken into account, i.e.

$$P_{\mathrm{dc}} \approx P_{\mathrm{pcc}} = \frac{3}{2} V_{\mathrm{pcc}d} \cdot i_{\mathrm{invd}} \tag{9}$$

The PV-STATCOM inverter's DC side power is determined by:

$$P_{\mathrm{PV}} = P_{\mathrm{dc}} - P_{\mathrm{cap}} + P_{\mathrm{dc}} \tag{10}$$

The photovoltaic power (P_{pv}), capacitive power (P_{cap}), and direct current power (P_{dc}) are defined as follows:

$$P_{\mathrm{pv}} = \text{Photovoltaic Power}$$
$$P_{\mathrm{cap}} = \text{Capacitive Power}$$
$$P_{\mathrm{dc}} = \text{Direct Current Power}$$

In figure 6 the outer voltage controller is described which is the same as the DC-Link voltage controller. In a normal PV Controller, the $V_{\mathrm{dc}ref}$ is given by the output of the MPPT Controller whereas in a PV-STATCOM Controller $V_{\mathrm{dc}ref}$ is provided by the open circuit voltage of the PV Panel (V_{oc}). This is because in STATCOM-Mode the active power of solar PV is zero and it will compensate only the grid reactive power. But when the disturbance is over it should change its reference from V_{oc} to V_{MPP} that corresponds to the maximum voltage output of solar PV.

4) PCC Voltage Control: The main aim of this controller is to uphold the PCC Bus voltage by generating the Reactive power reference for the current controller i.e. I_{qref}. The PCC Voltage is described as:

$$V_{\mathrm{pcc}} = L_g \frac{di_{\mathrm{g}}}{dt} + V_{\mathrm{g}} \tag{11}$$

where V_{pcc} is the PCC voltage, i_{g} is the grid current, and L_{g} denotes the grid equivalent inductance and V_{g} denotes grid voltage in three phase frame. The PCC Voltage magnitude is denoted by V. So it is given as:

$$V_{\text{pcc}-d} = -L_g \omega_0 i_{\text{gq}} + L_g \frac{di_{\text{gd}}}{dt} + V \tag{12}$$

where L_{g} = grid equivalent inductance, V_{gdq} = grid current in $dq0$ form.

5) Operation Mode selector: This Mode is used for switching between the different types of modes.

M=0: PV-Mode

M=1:Partial PV-Mode

M=2:STATCOM Mode

These modes will be decided based on the PCC Bus Voltage magnitude and the requirement of reactive power of the grid.

III. Simulation Results & Discussions

Here all the MATLAB simulation results of the different modes of operation will be discussed in detail and the different conditions will be tested for different load situations.

A. Response of PV-STATCOM in PV-Mode

In figure 7 it is shown that when the PV is operating in M=0 i.e. in PV-Mode, the active power requirement of the load is being delivered by the PV. In this case, PV is supplying 9.5 kW as well and the load active power is 8 kW so the rest 1.5 kW is feeding back to the grid in the opposite direction.

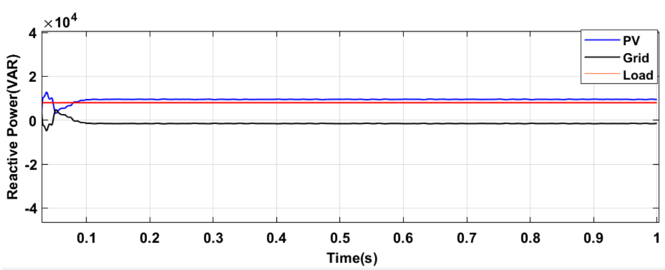

Fig. 7. Active Power sharing in PV Mode

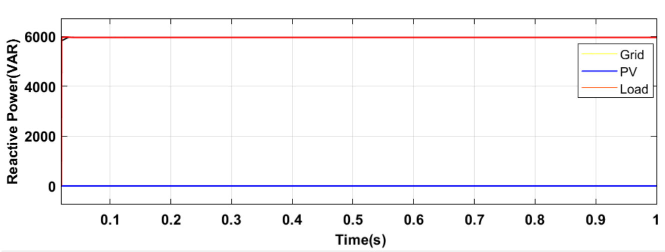

Fig. 8. Reactive Power sharing in PV Mode

As shown in figure 8, Since the PV Solar Farm's reactive power is zero when in PV Mode, the load's reactive power is 6 kVAR and is only provided by the grid. This is a result of the solar PV's open circuit voltage being used as the outside voltage controller's reference.

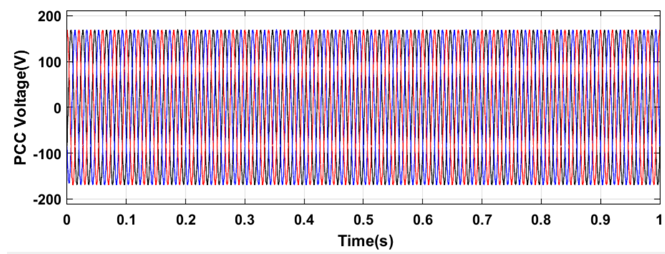

Fig. 9. PCC Voltage in PV-Mode

As the main aim of PV-STATCOM is to maintain the PCC Voltage which is around 169.8 V. So in this mode the voltage at PCC Bus is maintained at its nominal value.

The 2nd main motive of this paper is to improve the Grid PF. In Figure 10 It is shown that the grid power factor is around 0.721. This is the Grid PF in normal condition so to improve this PF the novel controller will be used which is discussed in previous sections and results will be displayed in the upcoming section.

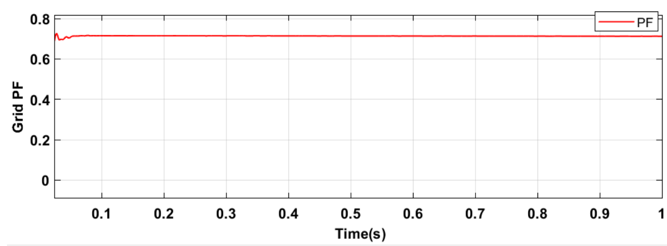

Fig. 10. Grid PF

B. Response of PV-STATCOM in STATCOM-Mode

As we know, at night time there is no active power generation from Solar PV so the PV will be disconnected from the system and the inverter will act as STATCOM. In figure 11 it is shown that when a large load is switched into the system at t=0.4s the PCC Voltage is dipped. This happens when there is no PV-STATCOM Controller. With the help of this controller, this dip in voltage is improved which is shown in 12.

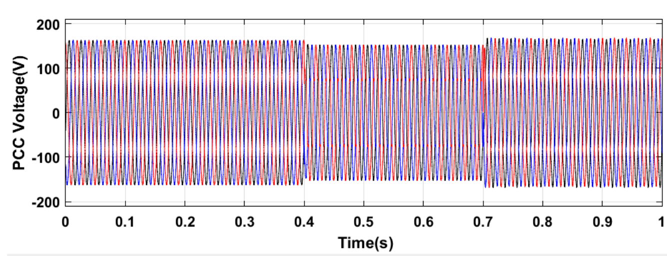

Fig. 11. PCC Voltage without PV-STATCOM Controller

In figure 12 The dip in the voltage is being maintained by the STATCOM Controller. To improve this voltage dip, the PV inverter has to supply capacitive reactive power which is shown in figure 13.

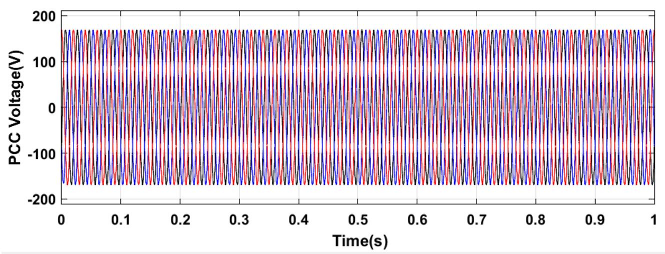

Fig. 12. PCC Voltage with PV-STATCOM Controller

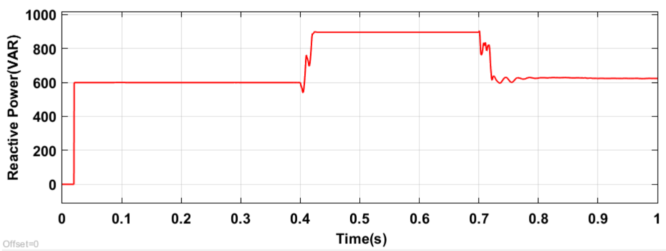

Fig. 13. Reactive Power supply by PV-STATCOM

As shown in figure 14 the grid power factor at night time is almost unity at normal conditions. This PF is achieved by the novel controller which is discussed in this paper.

C. Response of STATCOM Controller in Partial PV-Mode

This mode will work normally in only daytime because in this mode the PV will generate active power along with reactive power. So this mode will either exchange the dynamic reactive power or it will improve the grid PF in voltage flicker conditions.

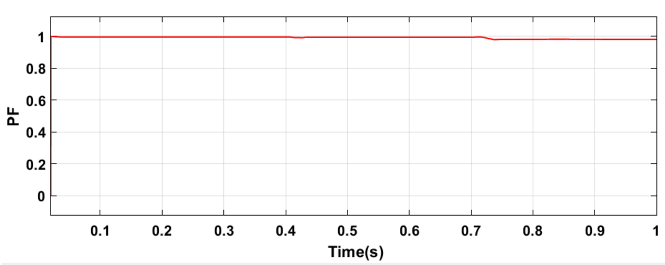

Fig. 14. Grid PF in STATCOM-Mode

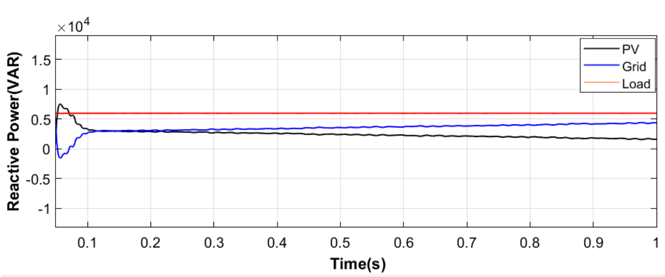

Fig. 15. Reactive Power sharing in Partial PV-Mode

In figure 15 it is shown that the Load reactive power is shared by both PV as well as Grid. In this mode PV supplies around 2.8 kVAR whereas the grid supplies around 3.2 kVAR, so the total 6 kVAR load is supplied properly.

In this mode also the voltage at the PCC is being maintained at a nominal value of 169.8 V RMS voltage.

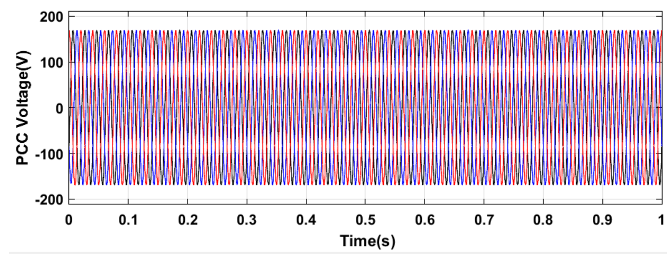

Fig. 16. PCC Voltage maintained in partial PV-Mode

As discussed above the maintained PCC Voltage is shown in figure 16. In this Mode, the main objective is to improve the grid PF, as discussed in the previous section.

Based on the switching conditions a very important result came that is initially the PV-STATCOM controller was switched off and only the conventional PV Controller was Switched ON. After $t = 0.5\,\mathrm{s}$ when we switch ON the PV-STATCOM Controller, the Grid PF which was initially around 0.721 becomes 0.91 which is shown in figure 17.

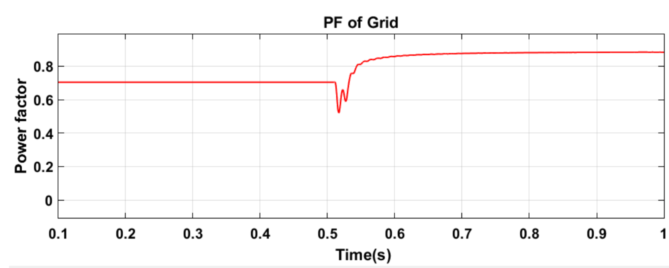

Fig. 17. Grid power factor improvement

Based on these simulation results the main objective of the controller is being verified in a very good manner.

IV. Conclusion

In this research paper, a unique control for the PV Inverter is presented to make it work like a STATCOM. In the initial papers, the inverter capacity was not fully utilized for the Reactive power compensation during the daytime, but in this paper, the inverter uses its full rated capacity for dynamic exchange of reactive power. The response time of the PV-STATCOM is matched with that of a conventional STATCOM(1-2 cycles).

The functioning of the PV-STATCOM controller is observed in different modes of operation in MATLAB (SIMULINK) software environment. This controller utilizes the solar farm on a 24/7 hours basis for STATCOM purposes. It can be used in daytime as well as in nighttime.

As we know a normal STATCOM plant cost starts from at least 4 crore, But this high cost can be saved by using the solar farm as a STATCOM. As this controller is still utilized for the distribution side network but, Research Work is going on in this area to use this technique for the Transmission System Networks also.

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