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Implementation of a Two Stage Grid Connected Solar PV System with Reactive Power Compensation under Dynamic Load Conditions

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Abstract: The increasing deployment of non- conventional energy sources to the grid poses many challenges to the utility. One of the key challenges is proper reactive power compensation on the grid side as any unbalance in the reactive power on the grid side will cause voltage variations at the point of common coupling (PCC). This paper presents design of three-phase, two-stage-grid-connected solar PV system with reactive power compensation control under the varying load conditions at the PCC. The research work recommends the integration of compensating device in the grid connected distribution system so as to supply variable reactive power as per load demand and to reduce dependency on the grid. The entire modelling is done on MATLAB and the various simulation results are obtained by varying the active and reactive power of the load. The simulation results obtained shows the efficacy of the proposed control algorithm in the studied system and it is observed that with proper coordination between grid, solar PV inverter and the compensating device the power requirement of the load is fulfilled.

***Keywords:** Active Power, DC Link Voltage,Grid, Solar PV, Static Synchronous compensator (STATCOM), Reactive Power.*

1. Introduction

The past few years have been witness to depletion of fossil fuels, rise in prices of conventional energy sources and environmental pollution globally which has pushed the electricity generation with alternative energy sources. Among them the wind and Solar energy plays the main role in power generation than other alternative sources of energy. The generation from wind and solar started 3 decades back but was not that popular because of the high implementation cost. But with the development in the power electronics technology there is reduction in the cost of converters and more spread of renewable sources particularly solar and wind [1]. The benefits of power generation from solar energy not only have zero impact on environmental pollution but it is also convenient for remote areas where it is not convenient to transmit electricity from conventional grids.

There are two configurations for solar PV grid connected inverters. One is a single stage configuration in which the generated power from the solar PV is directly fed to the inverter for dc-ac conversion and then to the grid. Other is two stage configurations in which the power generated from solar panel is first boosted using dc-dc converter and then converted to ac via dc-ac converter. The two-stage configuration is mainly used where solar panel output voltage is low although no of components are more than single stage configuration.

For grid current control there are various control strategies utilizing p-q theory and d-q theory with phase locked loop (PLL) [5].

There are lot of challenges that are faced by the utility in grid connected distributed generation system. Some of the challenges are variations in voltage at point of common coupling, power quality issues, voltage ride through capability (VRT), frequency regulation, reactive power management etc [4]. Any unbalance in the reactive power on the grid side will cause voltage instability and thus drops in buses and lines. Reactive Power compensation devices like SVC or STATCOM may be used then.[2]

STATCOM i.e Static Synchronous Compensator is a static power electronic device that supplies or absorbs reactive power as per the system's requirement. It is mainly used for voltage control and power factor correction in electrical power systems. By continuously regulating the reactive power, STATCOM helps in maintaining a stable voltage profile and power quality improvement of the grid-connected system [3]. A STATCOM supplies reactive power to the grid when the inverter voltage is higher than the grid voltage. Thus, the excess reactive power is injected into the grid, helping to regulate the voltage and improve power factor. But if the grid voltage is more as compared to the inverter voltage, STATCOM will consume extra reactive power. By absorbing excess reactive power from the grid, it helps maintain voltage stability and power quality. The STATCOM dynamically

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adjusts its reactive power output depending on difference in the voltage of the grid and inverter. Thus, it ensures that voltage at PCC remains stable. In the existing literature the integration of STATCOM in grid-connected PV systems (GCPV) is extensively discussed. [6-13]. The integration is possible with different control schemes on smart inverter [15].

The work presented in this paper provides a study on reactive power compensation when a dynamic load is connected to a three-phase grid-connected PV system (GCPV). The study includes an analysis of the system's performance both with and without the implementation of a compensating device, such as a fixed capacitor or STATCOM (Static Synchronous Compensator). The objective is to assess the effectiveness of reactive power compensation in meeting the load demand and enhancing the overall system efficiency in grid connected PV system. For the different cases taken to study the reactive power compensation in a three-phase GCPV system STATCOM is found to be most suitable as it is able to adjust itself as per the dynamic load conditions as well as under the fault conditions.

The paper is arranged in the manner that Section II provides the design description, providing detailed explanations of the design process. Simulation Results and their analysis is in Section III. Section IV provides conclusion of the work, summarizing the key findings and implications of the study.

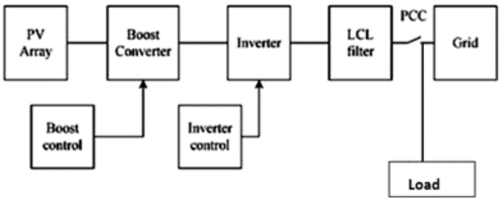

Fig 1. Block diagram of the implemented system

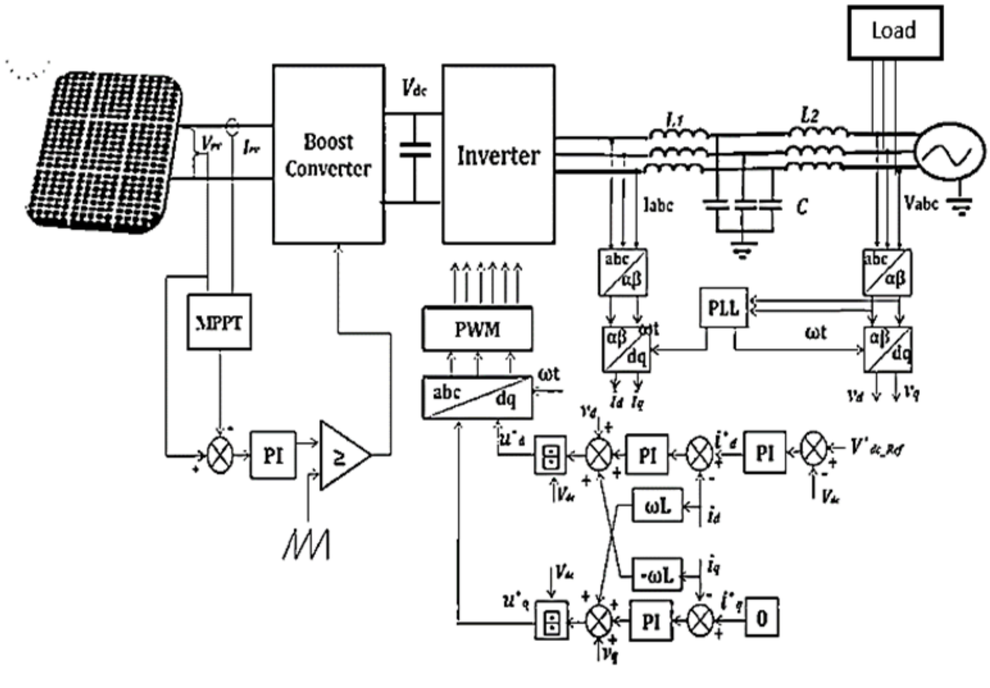

Fig 2. Implemented System

2. Design of System

The system design incorporates grid connection of 100-kW solar PV panel. The solar PV configuration consists of series connection of 47 modules and parallel connection of 10 modules, resulting in a total power generation capacity of 100 kW. To overcome the solar PV panel's low power output, boost converter is first connected to it. The boosted voltage output is obtained from converter. The boosted DC voltage is then fed into a voltage source converter (VSC), which transforms the DC voltage into AC voltage. This allows for the integration of the solar PV power into the grid as AC power. The voltage source converter (VSC)'s output which is AC, after passing through an LCL filter, is connected to the grid at PCC. This ensures that AC power generated by the system is seamlessly integrated with grid at designated connection point. LCL filter at the inverter's output ensures grid with a harmonics-free supply. This filter helps mitigate harmonics and ensures a clean power supply is delivered to the grid. Fig 1 represents the block diagram of the implemented system, which includes linear load connection at PCC.

Table 1 provides the boost converter parameters.[3]

The inductance (L) and capacitance (C) values in the boost converter design can be determined using the following equations.[24]

$$L = \frac{Vin(Vo-Vin)}{\nabla I \times fs \times Vo} \qquad (1)$$

$$C = \frac{Io(V-Vin)}{\nabla V \times fs \times Vo} \qquad (2)$$

where

V_{in}-voltage input

V_o-voltage output

∇V-voltage ripple

f_s-switching frequency

Due to the intermittent nature of PV panels, the maximum power obtained from them exhibits continuous variation Implementation of Maximum Power Point Tracking (MPPT) technique is thus very crucial in order to have maximum power from the PV panel under all varying weather conditions. The MPPT technique allows for the optimization of power extraction from the PV panel. There are number of techniques that are discussed in the literature for same each having its merits and demerits [23]. In this work Perturb and Observe method is utilized because of its simplicity and easy implementation.

Table 1: Boost Converter Parameters [3]

Vin, Input voltage	250-350V
Vo, Output voltage	600V
Power Rating	100 kW
Switching Frequency	5kHz
Voltage Ripple(ΔV)	1%
Current Ripple(ΔI)	5%
C	4000𝓊F
L	1.25mH
Kp, Ki	0.005,0.001

The implemented system is represented by a comprehensive schematic, which is depicted in Figure 2.

In the system there are two separate control loops: one for the boost converter control another for inverter control. To control the boost converter, the voltage and current of the photovoltaic (PV) system are initially sensed and provided as inputs to the MPPT algorithm. The MPPT algorithm calculates a reference voltage based on the sensed PV array voltage, and this reference voltage is compared to the actual PV array. The error signal generated is then fed into a proportional-integral (PI) controller to produce a reference signal. This reference signal is subsequently sent to a pulse width modulation (PWM) generator, which produces the control signal for the boost converter [3]. This is shown in Fig 2.

To ensure proper inverter control, the grid voltage and inverter current are monitored. The inverter incorporates two control loops: outer control loop is for voltage and an inner control loop is for current [25-26]. In the voltage loop, the DC reference voltage is compared to the DC link voltage and error signal is generated. The generated error signal is then fed into a proportional-integral (PI) controller to produce a reference current (I_d) for the inverter. Since the inverter is operating at unity power factor, the Iq reference current is typically set to zero, which means no reactice current component is there in inverter output. In the current control loop, the reference current I*d is compared with the inverter actual current I_d. The error signal is directed to a PI (Proportional-Integral) controller, which processes the error and produces reference voltages $v_d^*$and v_q^*. The voltage control signal $v_d^*$and v_q^* is generated using following equations.[20]

$$v_d^* = v_d + Ri_d + L\frac{di_d}{dt} - wLi_q$$
(3)

$$v_q^* = v_q + Ri_q + L\frac{di_q}{dt} - wLi_d$$
(4)

The voltage control signals $v_d^*$and v_q^* are then compared with V_d and V_q components of grid voltage. The error signals are combined with Vdc (DC-link voltage) and converted to abc voltage. These abc voltages are then fed into a PWM (Pulse Width Modulation) generator, which generates the control signals for the three-phase inverter. The output from inverter is fed to LCL filter before connecting it to the grid.

The LCL filter values are obtained using the following relations. [23]

$$L_1 = \frac{V_{DC}}{6f_{sw}\nabla I_{Lmax}}$$
(5)

$$L_2 = \frac{\sqrt{\frac{1}{Ka^2}}+1}{C_f w_{sw}^2}$$
(6)

where L_1 is grid side inductance and L_2 is inverter side inductance. The Capacitance value C_f is obtained with the relation

$$w = \sqrt{\frac{L_1+L_2}{L_1L_2C_f}}$$
(7)

where

V_{DC}- DC link voltage

fsw -Switching frequency

The values of L_1, L_2 and C_f obtained are mentioned in Table 2 along with other data taken for implementation.
At PCC a three-phase linear load is also connected. AC source is connected as a utility grid in the system.

3. Simulation Results

The work involved the implementation of a 100kW two-stage GCPV inverter with a linear load connected at PCC using MATLAB Simulink. The different parameters values used in the design are provided in Table 2.

There are four cases that are considered in the simulation work.

Case 1: Grid connection to the solar PV inverter with a linear load at PCC but with no compensating device.

Case 2: Grid connection to the solar PV inverter with load and Shunt Capacitor at PCC.

Case 3: Grid connection to the solar PV inverter with load and STATCOM at PCC.

Case 4: In this particular case Line-to-Ground(L-G) Fault is simulated at the PCC with a connected STATCOM.

Quantity	Value
Grid Voltage (RMS Value)	415V
frequency	50 Hz
LCL filter inductances (both inverter side and grid side) L_1 and L_2	500𝑢H each
DC Link Capacitor	3227𝑢F
LCL Filter Capacitance (C_f)	100𝑢F
Inverter’s switching frequency	10kHz
Linear Load (R-L series)	P(100kW), Q(100kVAR)
Kp, Ki	10,20

Table 2: Different Parameters Values Used in Design

The detailed study for each of the case follows below:

Case 1: Without any compensating device

A linear load with rating of P(100kW), Q(100kVAR) is connected to the solar PV grid-connected system at the PCC. The solar PV panel generates 100 kW for 0.2s then after because of fall in radiations(500kW/m^2) on the PV panel it generates 50 kW i.e from 0.2s to 0.4s solar PV Panel is generating only 50kW. Fig 3 and Fig 4 shows variation of radiations on PV panel and the PV power output.

As can be seen from Fig 4 from 0 to 0.2s grid is receiving 100 kW from solar PV inverter but 0.2s onwards it is receiving only 50kW from solar PV inverter.

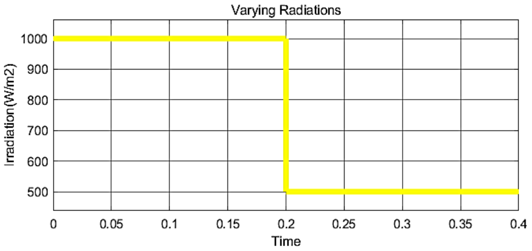

Fig 3. Irradiations on PV Panel

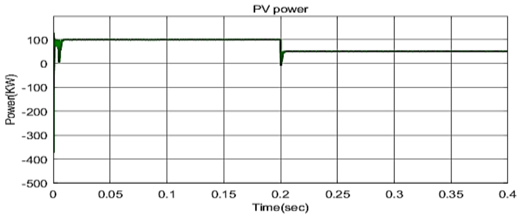

Fig 4. PV Power Output

Thus load real power demand of 100kW is taken care of by the solar PV inverter for about 0.2s and grid during this time will not provide any active power to the load but after 0.2s when the solar radiation falls and solar PV inverter is supplying only 50kW then remaining 50kW is supplied to the load by the grid to fulfil load demand of 100kW as shown in Figs 5 and 6.As the solar inverter supplies solely active power to the grid the entire reactive power requirement is fulfilled by the grid. This can be observed from simulation plots for reactive power of the inverter, load and grid as shown in Figs 5-7. The inverter operates at a unity power factor in the implemented system, meaning that it supplies only active power. Figure 8-10 illustrates the voltage and current waveforms for the inverter, grid, and load. The DC link voltage is effectively maintained at the desired level of 700V, as depicted in Fig.11.

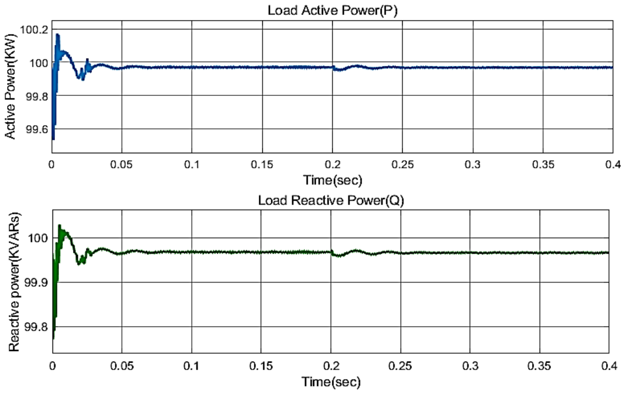

Fig 5. Load Active and Reactive Power

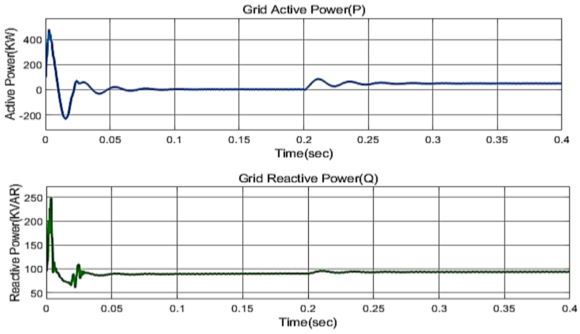

Fig 6. Grid Active and Reactive Power

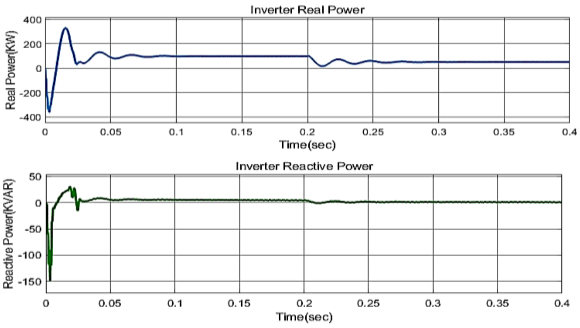

Fig 7. Inverter Active and Reactive Power

Case 2: With Shunt Capacitor

In the second scenario, a shunt capacitor with a capacity of 100kVAR is connected to the grid at the PCC with the same load connected i.e 100kW and 100kVAR. In this particular case, the shunt capacitor fulfills the reactive power demand of the load, eliminating the need for the grid to supply any reactive power. Figures 12 to 15 depict the demonstration of this case.

The active power of the load, which is 100 kW, will be shared between the grid and the solar inverter. From 0 to 0.2s the solar inverter will feed active power to the load i.e 100kW and from 0.2 to 0.4s the grid and solar inverter both will share active power demand of the load equally (50kW each) as shown in Fig 13-15.

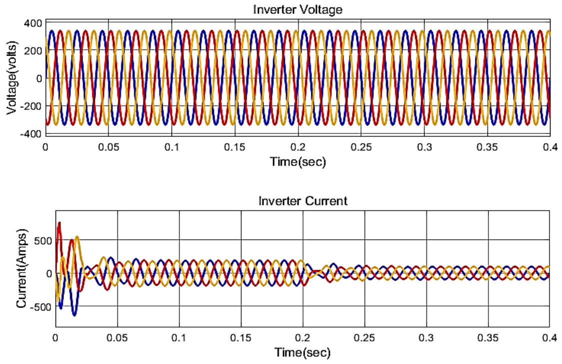

Fig 8. Inverter Voltage and Current

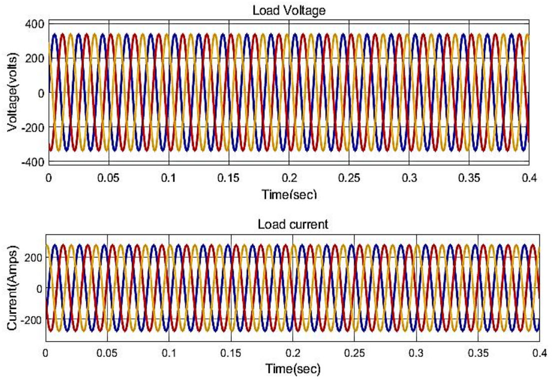

Fig 9. Load Voltage and Current

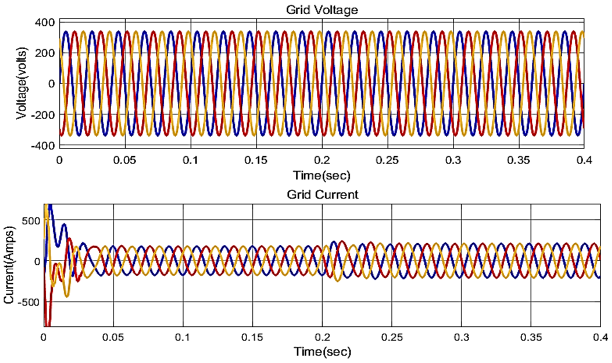

Fig 10. Grid Voltage and Current

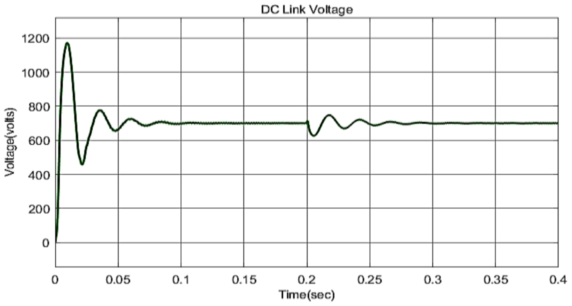

Fig 11. DC Link Voltage

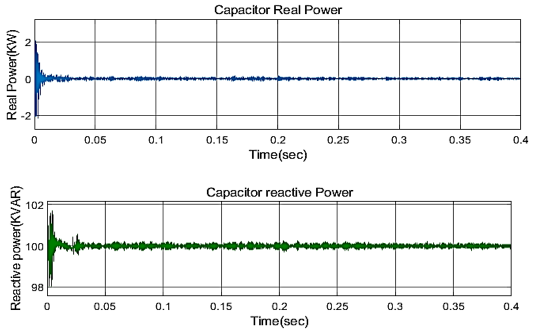

Fig 12. Capacitor Active and Reactive Power

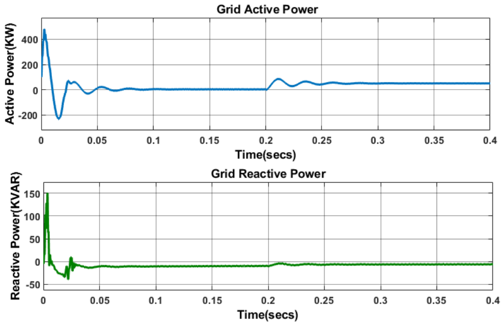

Fig 13. Grid Active and Reactive Power

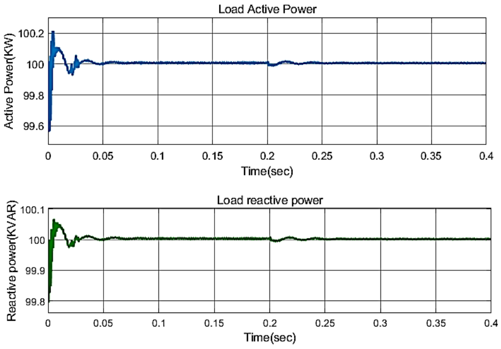

Fig 14. Load Active and Reactive Power

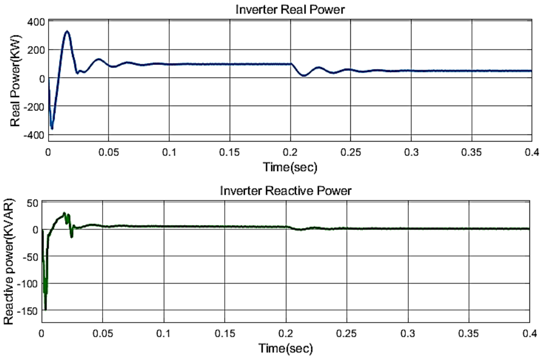

Fig 15. Inverter Active and Reactive Power

In this case, due to the shunt capacitor reactive power is supplied from it and no reactive power is drawn from the grid. Shunt Capacitor if supplies the reactive power that exceeds the required amount, there is an excess of reactive power available, that reactive power will be taken by grid and if it is less then what is required by the load then grid will supply remaining reactive power.

Table 3 provides a summary of the power distribution among the solar PV, grid, and capacitor.

Table 3: Active and Reactive Power Sharing with Shunt Capacitor

Element	Active Power(P)	Reactive Power(Q)
Solar PV Inverter	100kW (0 to 0.2s), 50kW (0.2 to 0.4s)	0 kVAR
Grid	0kW (0to 0.2s), 50kW (0.2 to 0.4s)	0kVAR
Shunt Capacitor	0 kW	100kVAR
Load	100kW	100kVAR

The voltage and current waveforms for capacitor, load and grid are also shown from Fig 16-18.

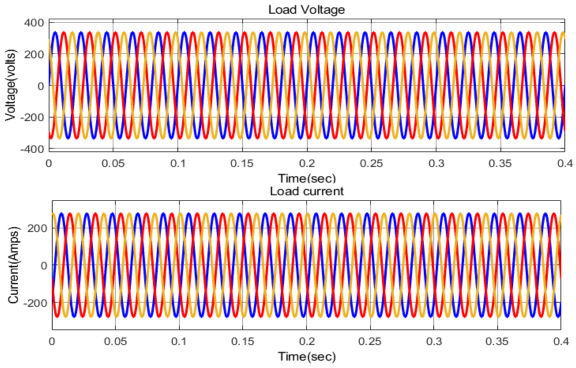

Fig 16. Load Voltage and Current Waveforms

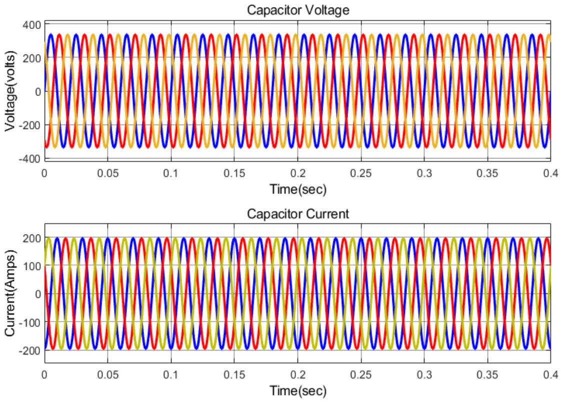

Fig 17. Capacitor Voltage Waveform and Capacitor Current Waveforms

The waveforms clearly indicate the absence of current. from the grid up to 0.2s since load is taking current from inverter but after 0.2s more current is supplied by the grid as the inverter current reduces due to fall in radiation on solar PV panel.

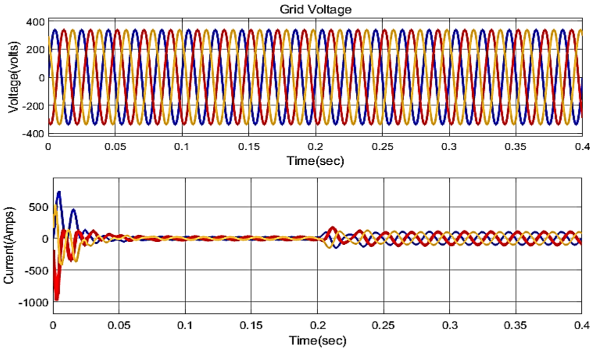

Fig 18. Grid Voltage and Current Waveforms

When the load reactive power increases to 150kVAR then as shunt capacitor can provide only 100kVAR the remaining 50kVAR will come from the grid. In this scenario, the grid also contributes to reactive power in addition to active power. This result of Fig 19-21 clearly shows this. Thus, reactive power sharing is done by shunt capacitor and grid both incase shunt capacitor capacity is not sufficient.

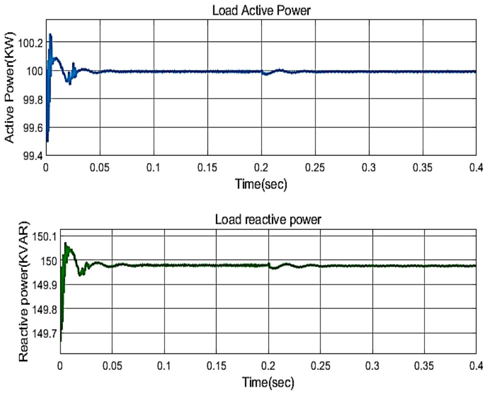

Fig 19. Load's Active and Reactive Power

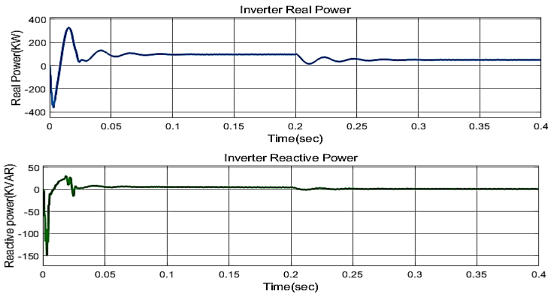

Fig 20. Inverter's Active and Reactive Power

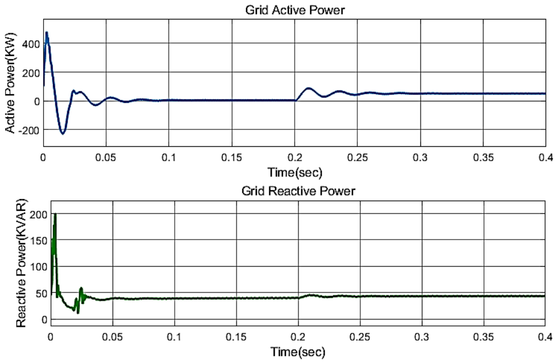

Fig 21. Grid Active and Reactive Power

Figure 22-23 illustrates the voltage and current waveforms for both capacitor and load.

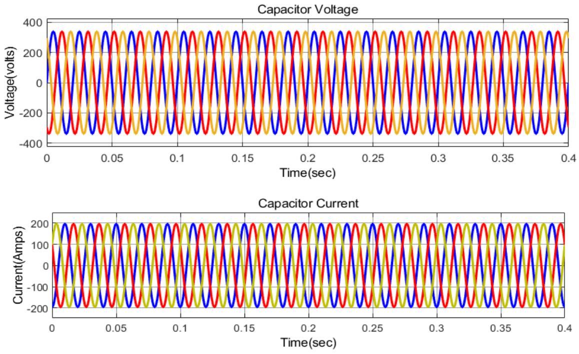

Fig 22. Capacitor voltage and current waveform

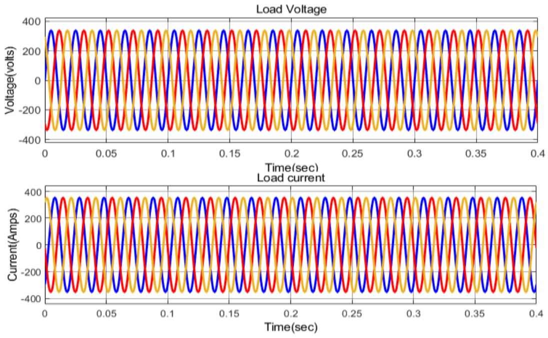

Fig 23. Load voltage and current waveform

Case 3: With STATCOM

A STATCOM i.e Static Synchronous Compensator is fast acting device that can source or sink reactive current as per load demand [29]. The STATCOM consists of a regulated voltage source converter (VSC) linked to an energy storage device, specifically a capacitor. On one end, it is connected to the grid via a reactor that acts as a filter. [28]. A simplified STATCOM configuration is shown in Fig 24[1].

By adjusting voltage source converter (VSC)'s voltage level with respect to the bus voltage, the integration of STATCOM with the PV system can effectively optimize the flow of reactive power. [14]. Thus, in case 3 we have connected the STATCOM to the grid at the PCC.

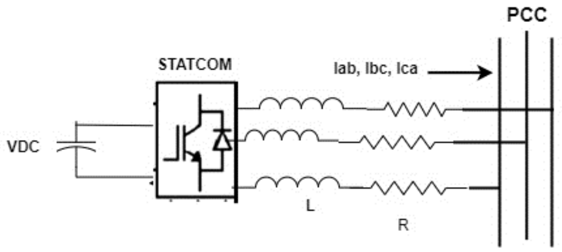

Fig 24. STATCOM simple configuration

In this implementation, the STATCOM effectively handles the reactive power demands of the load. Since only 100kW is generated by solar PV inverter so grid and solar inverter together will supply 200kW required by load. But this continues up to 0.2s only. After 0.2s as radiation falls on solar PV panel its output reduces to 50kW and thus 0.2s onwards solar inverter will provide 50kW and remaining 150kW will come from grid. The entire reactive power demand of the load i.e 100kVAR will come from the STATCOM. So, Grid in this case only supplies active power and zero reactive power. This can be seen in Figs 26-29 below. Also, DC STATCOM voltage is set at 800V as required as shown in Fig 25. Power distribution in this case is summarized in Table 4.

Table 4: Power Sharing Arrangement with STATCOM Connection

Element	**Active Power(P)**	**Reactive Power(Q)**
Solar PV Inverter	100kW (0 to 0.2sec), 50kW (0.2 to 0.4sec)	0 kVAR
Grid	100kW (0 to 0.2sec), 150kW (0.2 to 0.4 sec)	0kVAR
STATCOM	0 kW	100kVAR
Load	200kW	100kVAR

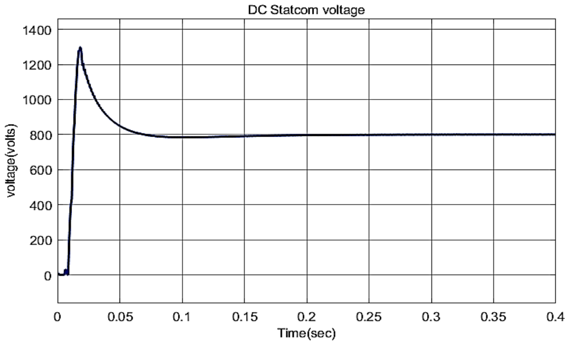

Fig 25. DC STATCOM Voltage

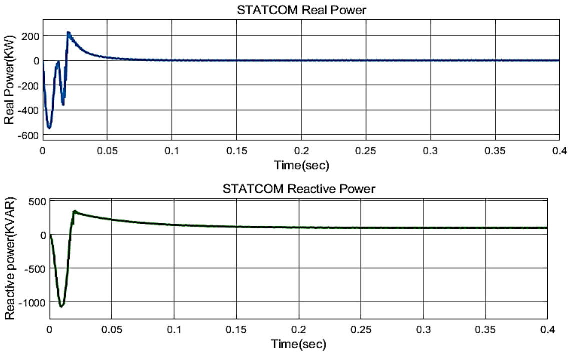

Fig 26. STATCOM Real and Reactive Power for Case 3a

The grid in this case exclusively provides active power without supplying any reactive power. which is 100kW from 0 to 0.2s and from 0.2s it is supplying 150kW so as to fulfil the load demand of 200kW.

The STATCOM, PV inverter, and grid efficiently adapt to any variations in the load's active and reactive power requirements. To validate this another case is considered with different P and Q values of load.

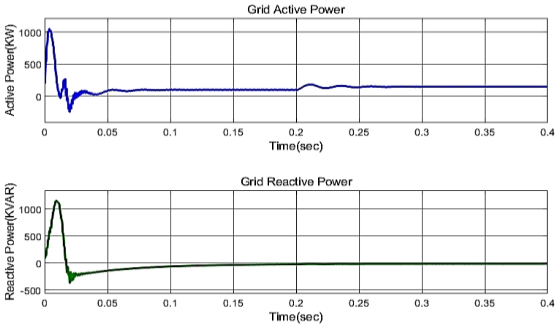

Fig 27. Grid Real and Reactive Power

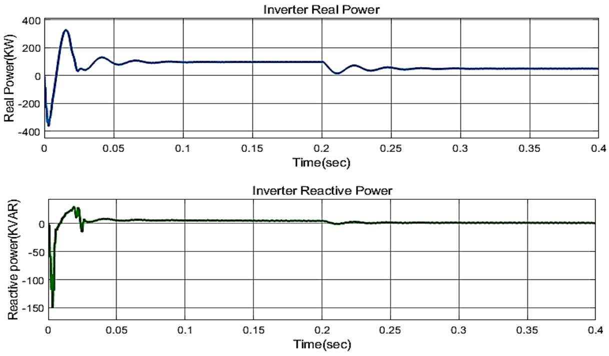

Fig 28. Inverter Real and Reactive Power

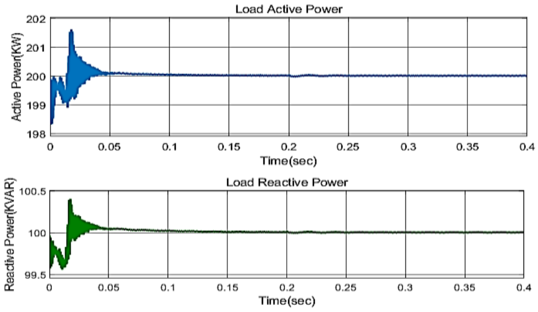

Fig 29. Load Real and Reactive Power

The grid voltage and current waveforms are as in Fig 30, while Fig.31 shows current waveform of the STATCOM.The rms value of STATCOM current is 355A and rms value of grid current is 176A from 0 to 0.2s and from 0.2 to 0.4s it is 224A.

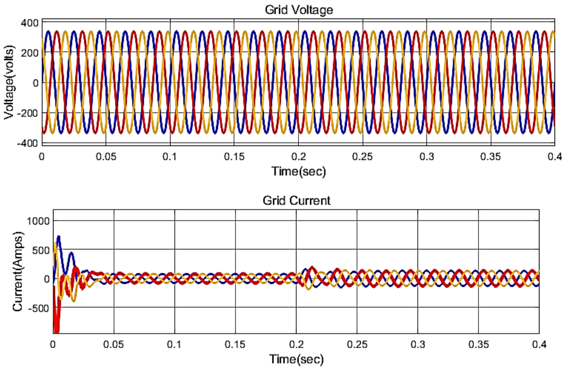

Fig 30. Grid Voltage and Current Waveforms

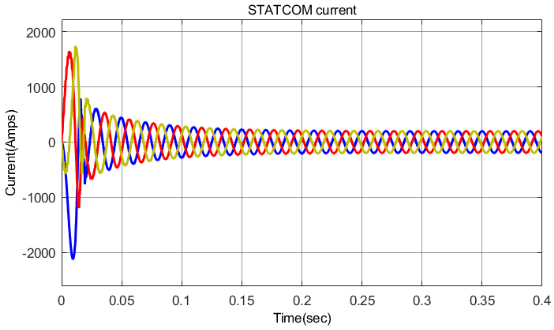

Fig 31. STATCOM Current waveform

If the load reactive power demand changes to 200kVAR the STATCOM will supply the same and again no reactive power is taken from grid. The simulations results in Fig 32 below clearly depicts this. Thus, depending on the load reactive power STATCOM provide the same while active power requirement is shared among grid and Solar PV inverter.

The STATCOM effectively meets the reactive power demands of the load, regardless of its requirements, and no reactive power is taken or consumed by the grid in this case. This is the reason why STATCOM are preferred to be used in distribution networks specifically grid connected renewables because the connected load there has dynamic behavior.

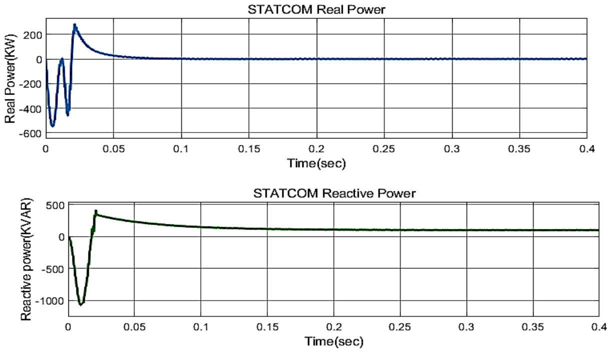

Fig 32. STATCOM Real and Reactive Power

Case 4: With STATCOM under L-G fault condition

A simulated L-G fault is conducted in this case from 0.2 to 0.3s on phase ‘a’ at PCC and the response of STATCOM is observed. Due to L-G fault around 65% voltage sag is observed as can be seen in Fig-33. It is found that STATCOM output is unaffected by the fault and it successfully provides the required reactive power of 200kVAR to the load. The STATCOM output current and DC STATCOM voltage which is 800V is shown below in Fig 34-35.

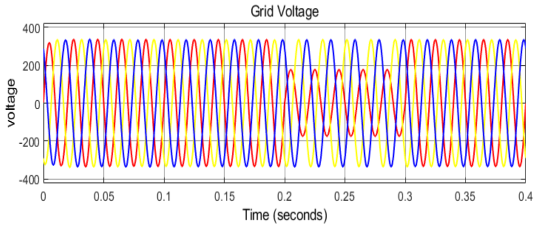

Fig 33. Voltage Sag due to L-G fault in Phase a

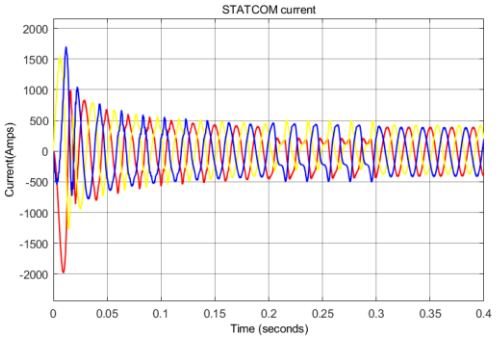

Fig 34. STATCOM current for Case 4

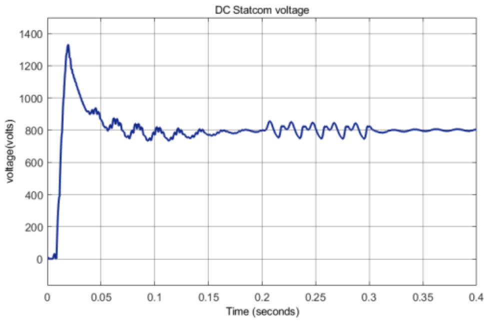

Fig 35. DC STATCOM voltage during Case 4

There is no reactive power drawn by the load from grid. Fig 36 simulations results clearly shows this.

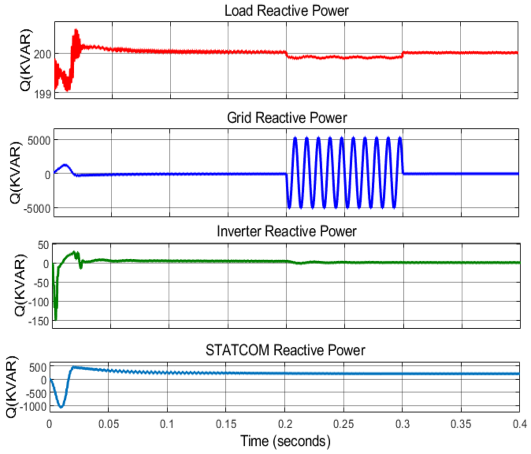

Fig 36. Reactive Power of Load, Grid, Inverter and STATCOM

4. Conclusion

The successful implementation of two stage solar PV grid connected inverter operating in three phase is done in this paper and reactive power compensation with and without compensating device is carried out in the study. It is observed that proper reactive power management is done in between grid and solar PV inverter in the absence of compensating device and also when fixed compensating device like shunt capacitor is connected on the grid side. With the fixed compensation grid should be ready to provide any extra reactive power more than the capacitor rating. But with dynamic compensator like STATCOM connected on the grid side any reactive power requirement is fulfilled by the STATCOM while the grid and solar PV system jointly contribute the active power necessary to supply the load.

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