Hybrid algorithm for reactive power control in grid integrated Photovoltaic inverters

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***Abstract*—This paper develops a coordinated reactive power control system for grid integrated solar photovoltaic (PV) inverters. The proposed algorithm combines the reactive power control capabilities of PV inverter with flexible AC transmission devices for stabilizing the PV system during grid faults. The proposed control method works as per a predefined hierarchical structure by prioritizing the reactive power control with PV inverters. The complete methodology is realized by testing them with a two-stage single-phase grid-connected PV system simulated in MATLAB/Simulink software. The simulation results verify the accuracy of the classification algorithm and depict the effectiveness of the proposed controller in both the under and overvoltage situations.**

***Index Terms*—Grid-connected Photovoltaic System (GCPVS), Fault Ride Through (FRT), Islanding Classification, Reactive Power Control.**

I. INTRODUCTION

One of the fastest growing and cheap energy resources among the available renewable energy sources is solar Photovoltaic (PV) systems. The major advantage with PV systems is, they can be connected to all kind of grid systems, irrespective of the voltage level. This process of grid integration of photovoltaic (PV) systems resulted in new challenges such as violation of voltage profile, and reverse power flow [1], [2]. Therefore, grid codes and grid standards are required for the successful and safe operation of GCPVS [3]. Generally, grid codes address all significant concerns associated with the power grid and guarantee its safe operation and performance. Any issue violating the grid code will lead to various faults on DC side as well as AC side resulting into unstable system operations [4]. One of the major effects of all these faults is the voltage instability at the point of common coupling (PCC). In order to achieve voltage stability, the power system needs to be operated within an acceptable voltage range even under disturbances. There have already been numerous research works done to find out different possible remedies to deal with issues related to unwanted voltage problems, and they are classified into mainly system, plant, and interactive level. The system level deals with remedies that target the grid side, whereas the plant level deals with PV plants or customer side. The interactive side focuses on in-between and installed at different locations in the grid along with components of the plant, and it requires the communication structures to link to the decision-making units. Conventionally, OLTC transformers are also used to maintain the voltage profile by installing at the high voltage side of the transformer with tap changing mechanism [5]. To enhance the LVRT capability during a fault when the overvoltage occurs at the DC-link voltage, a control schemes for two-stage GCPVS is realized in [6]. In the regard of severe voltage fluctuations, various custom power devices like Dynamic Voltage Restorer (DVR), UPQC, STATCOM, TCR are introduced as a solution to power quality problems [7]. On the distribution feeder side, to protect the sensitive load from voltage sags, DVR is used. DVR control system detects voltage sag and also govern the depth of sag and any associated phase shift [8], [9]. DVR provides the most implicit solution, according to the IEEE519-1992 and IEEE1159-1195 standards typical duration for voltage sag and swell is 10ms to 1min, using DC/DC boost converter for low and high power and series injection transformer which is connected in series with the load to fix sag and swell in single-phase distribution system [10]. Based on the p-q theory to compensate for the harmonic content of nonlinear loads and also injecting reactive power to eliminate the change in load conditions [11], [12]. Furthermore, due to the high quantity of PV systems existence in power systems, the flow of power is not unidirectional

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anymore. This changes the active and reactive power responses of low voltage grids to voltage variations in medium voltage grids. The changes in the voltage-power characteristics affect the operation of above-mentioned controllers. So, to overcome this, a coordinated control algorithm which addresses the impact of high penetration of PV systems on low voltage and medium voltage grids is necessary. Consequently, it is necessary to find a coordinated reactive power control method that can effectively regulate the voltage profile at PCC with the high density of PV systems.

In this paper, a two-stage, single phase GCPVS is developed, and a machine learning based islanding classification is proposed. Once the condition of the system is observed, necessary action is taken by the proposed FRT algorithm. The FRT strategy is based on the Coordinated Reactive Power Injection algorithm that has been developed for controlling the voltage sags and swells. Further sections of the paper are organized as follows: in section II, Grid requirements for integrating PV systems in to grid were studied; in Section III, Reactive power compensation modes is presented; in section IV, the implementation of islanding classification algorithm and Coordinated Reactive Power control algorithm is carried out on a simulated system, and the results are discussed, and the research is concluded in section V.

II. CONTROL OF SINGLE-PHASE GRID-CONNECTED INVERTERS

An overview of grid conected system is represented in fig. 1. The Control of Single-Phase Grid-Connected Inverters consists of two cascaded control loops, the outer loop and the inner loop [13]. The outer loop controls the power injected to the grid using the DC-link voltage management, whereas the inner loop is the current controller, which handles the power quality issue and needs to respond faster than the outer power loop [13]. In the current controller, a Proportional-Resonant (PR) controller is used [14] since it can track a sinusoidal reference signal without a steady-state error at the resonant frequency. This is because PR controllers have a high gain around the resonant frequency [13], [14]. In general, the transfer function of the inverter is realized by a delay introduced from the PWM generation and the sampling [14]. Then, the difference between the inverter output voltage and the grid voltage is fed to the grid filter transfer function resulting in the grid current fed back to the PR controller. There are various control structures for the outer power loop, depending on the application. However, one commonly used control structure is the DC-link voltage controller. A voltage regulator is adapted to maintain the required DC voltage level whereas the current injected into the grid is regulated by the current controller. The reference value of DC link voltage can be regulated by a voltage control loop, which manipulates the value of injected grid current. DC voltage generated by PV system regulates dc-link voltage via control loop and produces a current reference for injected grid current. DC voltage regulator is generally controlled by a PI controller. The major disadvantage in single phase grid cone ted inverters is that, the active and reactive power of cannot be regulated by manipulating the value of direct axis current (i_d) and quadrature axis current (i_q) in the $d-q$ frame as performed for a three-phase inverter. Hence a grid synchronizer is required to generate a grid current reference for controlling active and reactive power control /citeChen2013. Grid information such as the grid voltage and its phase angle are required parameters for the synchronization controller. Among various synchronization techniques, PLL based methods are popular [15].

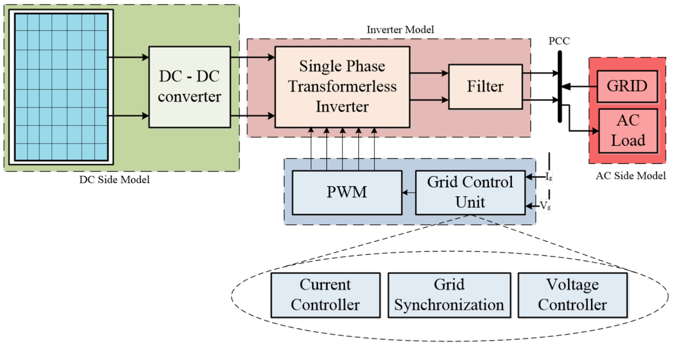

Fig. 1. Overall structure of grid integrated PV system.

III. REACTIVE POWER COMPENSATION

Taking into consideration voltage regulation is considered as an utmost concern for grid connected PV system. To restrain the system from completely failing and creating any major blackout either on grid side or at the PV side the unbalanced faults should be quickly compensated otherwise causing an unstable system which results in Voltage sag or swell. In accordance with FRT capabilities during the grid fault there are basically four reasons for the inverter to disconnect which are-

- Extreme DC link voltage
- Overcurrent at ac side
- Desynchronization of grid voltage and
- Imbalance in reactive power injection

A. Reactive power control during grid faults

Four different type of reactive power control methods that have been proposed by [16]:

1) Fixed power factor,
2) Steady receptive power,
3) Control factor control subject to the dynamic power infusion cos’(P),
4) Neighborhood responsive power control reliant on voltage Q(U).

The last method is of the interest for this study as the Q(U) technique utilizes the local voltage information to stabilize the weak bus voltage. This study centers around the voltage control by the PV inverter utilizing Q(U) technique. This activity keeps up the satisfactory voltage range at the PCC by giving the reactive power into the system from PV inverter. An organized voltage control calculation is created After changing

PV inverter and Static synchronous compensator a coordinated voltage control algorithm is generated.

1) PV inverter control method - Q(U): : As of now referenced before, the reactive power capacities of solar powered inverters can be utilized to maintain the voltage level inside the determined capping. Expectedly, some reactive power control techniques for PV inverter has been considered, and in this examination, Q(U) technique is actualized as it directly utilizes local voltage data that is a result of the power gereration and utilization. In this way, the total reactive power absorption or production of the inverters will be significantly diminished for voltage supporting as differentiated with the other reactive power control techniques, for example, fixed $\cos\theta$ and $\cos\theta(P)$ techniques [17].
The given equation (1) can be effectively implemented in the inverter controllers and be altered remotely to control the weak bus voltage by giving reactive power from the PV inverter [17]. Due to given equation (1) the reactive power flow algorithm by PV inverter is established.

$$Q_{PV}^{ref} = \begin{cases} Q_{max} & V_{grid} = V_{l1} \\ \frac{Q_{max}}{V_{l1}-V_{l2}}\left(V_{grid} - V_{l1}\right) + Q_{max} & V_{l1} \leq V_{grid} \leq V_{l2} \\ 0 & V_{l2} \leq V_{grid} \leq V_{l3} \\ \frac{Q_{max}}{V_{l3}-V_{l4}}\left(V_{grid} - V_{l3}\right) & V_{l3} \leq V_{grid} \leq V_{l4} \\ Q_{max} & V_{grid} > V_{14} \end{cases} \tag{1}$$

2) STATCOM control method: : Static synchronous compensator is the most broadly used constituent of FACTS and is normally utilized as a source to give reactive power to regulate the transmission voltage. Shunted compensation with the AC system is primarily the reactive power compensation. Due to the use of semiconductor switches rather than mechanical switches [18], the Voltage Source Converter (VSC) is much faster and also has a wide range of control while the reactive power compensation by the STATCOM is depend on it. In the given module the insights regarding the STATCOM are introduced.

Operating Principle: A STATCOM consists of a voltage source converter along with a capacitor on the DC side and a shunt connected transformer as depicted in fig. 2.

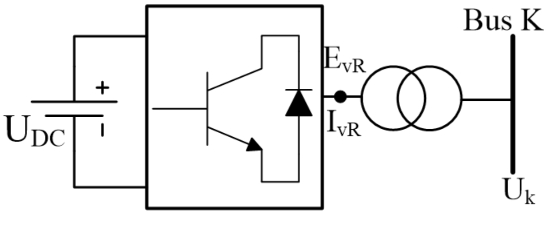

Fig. 2. Schematic representation of STATCOM.

Generally, the STATCOM can be utilized as synchronous voltage source if its output voltage can be regulated as wanted as displayed in fig. 2. Now the speculation is that there is no trade of active power among STATCOM and the grid, and the procedure is lossless, so the voltage of the STATCOM controller and the grid voltage is in phase. The course of current across the STATCOM is reliant on the voltage change among the grid and the STATCOM. If the compensator voltage size is lower than the voltage at the junction, reactive power will be absorbed by the STATCOM. Then again, if the condition is inverse, reactive power will be conveyed to the grid [19]. This concept is introduced in the given fig. 3.

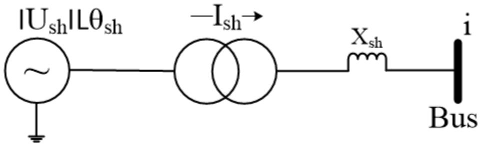

Fig. 3. STATCOM equivalent circuit.

A STATCOM infuses reactive current to provide backing the grid voltage if there would be an occurrence of under voltage and act as an overexcited generator or capacitor. Despite what might be expected, when the STATCOM is consuming reactive current it reduces the grid voltage and STATCOM acts as an under excited generator or inductor. The power flow constraints of STATCOM are provided by the given equations.

$$P_{sh} = U_i^2 g_{sh} - U_i U_{sh}(g_{sh}\cos(\theta_i - \theta_{sh}) + b_{sh}\sin(\theta_i - \theta_{sh})) \tag{2}$$

$$Q_{sh} = -U_i^2 b_{sh} - U_i U_{sh}(g_{sh}\cos(\theta_i - \theta_{sh}) - b_{sh}\sin(\theta_i - \theta_{sh})) \tag{3}$$

in which U_i and θ_i are the voltage of the bus and the angle of the bus voltage to which the STATCOM is connected. U_{sh} and θ_{sh} are the voltage and the angle of the STATCOM and $g_{sh} + jb_{sh} = 1/Z_{sh}$. *Control mode:* In case of STATCOM various method are implemented to provide reactive power control. The reactive power flow can be adjusted either by droop control or by reactive power injection or by controlling the power factor of a STATCOM. In the research presented in this paper main aim is to control the voltage at PCC with the help of STATCOM in cases where PV inverter is not capable of maintaining the voltage to the preferred limit. Voltage is controlled based on droop characteristics control. Different modes of operation are designed. The voltage at PCC is maintained at a constant level by balancing the voltage error between the grid voltage and reference value via reactive power injection. Hence form equation (2) reactive power exchange for STATCOM can be defined. A lossless STATCOM ($g_{sh} = 0$ and $\theta_i = \theta_{sh}$) is assumed to simplify the equation. Assumption regarding no supply of active power through STATCOM ($P_{sh} = 0$) is also made. After the assumption are taken into consideration the equation (3) becomes

$$Q_{sh} = -|U_i|^2 b_{sh} + |U_i||U_{sh}|b_{sh} \tag{4}$$

Where measured bus i voltage is denoted by U_i, at the output of STATCOM U_{sh} is the output voltage observed. STATCOM resistance is denoted by X_{sh} and reactive power injected by STATCOM into the grid is represented by Q_{sh}.

B. Proposed algorithm for coordinated voltage control

The proposed algorithm was developed with an aim to control voltage and provide stability to distribution grid. The proposed method has been developed with an aim to control grid voltage of two levels.

- LV grid voltage control
- MV and LV grid voltage control together.

1) Scenario I: Low voltage (LV) grid voltage control algorithm:: The condition of LV grid is considered as a scenario I for simulation. Only low voltage control is taken into consideration by controlling PV inverter and STATCOM. A hierarchical control method is implemented to control the flow of reactive power through PV inverter and STATCOM. The corresponding flow chart is represented in fig. 4. It can be observed that when the voltage drops then the PV inverter is first layer of control action as reactive power is either injected or absorbed by the inverter. When the first layer of control is not enough for the voltage regulation then the STATCOM comes as a second layer of control action. The additional reactive power is injects/absorbs with the help of STATCOM corresponding bus of the LV network in order to stabilize the bus voltage.

2) Scenario II: Medium voltage (MV) and LV grid voltage control algorithm:: For simulation the current scenario is considered as scenario II. Both LV and MV networks are considered where STATCOM is used for control of MV network and for LV network both STATCOM and PV inverter are implemented. Hierarchical mode of control is implemented for reactive power control of the device. The flow chart in the fig. 4 display the implementation of the controller. It can be observed that when the voltage drops then the PV inverter and STATCOM control acts as reactive power control and it either injected or absorbed reactive power as per requirement like scenario I.

But, MV mode of operation is not a subsequent mode of operation as it always takes place after LV network action. The MV based control get activated independently and STATCOM stabilize the voltage at MV node. If the reactive power is generated at LV side than firstly it examines the MV grid and then MV network control acts depending upon the situation. Or else both LV and MV network control will act independently to bring voltage to a specified limit.

IV. SIMUATION ANALYSIS AND RESULT

For testing the performance of the proposed methods, a distribution network was simulated on MATLAB/Simulink platform. Grid operates at 50Hz single phase with 11kV voltage magnitude. 1kW distributed PV system is interacting with the grid. A string of 14 series and 1 parallel TRINA SOLAR TSM-250 PA05.08 module is connected to generation end working under standard test condition. H bridge inverter is connected along with LCL filter and the system parameters are depicted in table 1. For testing the efficiency of the developed

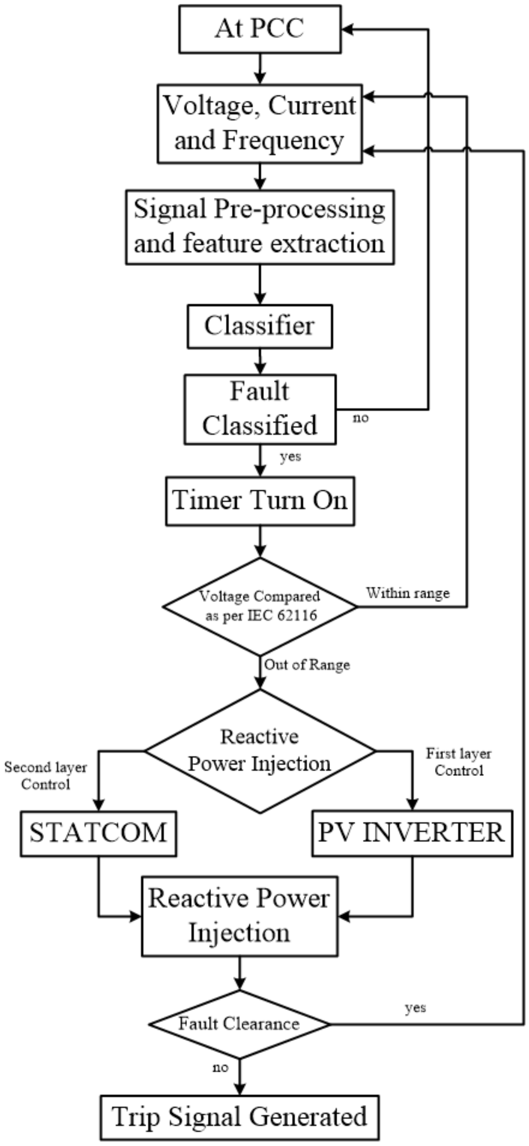

Fig. 4. Flow diagram for proposed FRT process.

TABLE I
SIMULATION PARAMETERS FOR TWO-STAGE SINGLE PHASE GRID-CONNECTED PV SYSTEM

Parameter	Representation	Value
PV array Power	P_{PV}	1kW
DC-Link Voltage	V_{dc}	400V
Switching Frequency	f_{sw}	5000Hz
Converter Side Inductance	L_f	3.809mH
Variation in converter current	$\triangle I_{max}$	10% of the maximum converter current
Grid Side Inductance	L_g	1.081mH
Capacitance	C_f	5.622uF
Resonant Frequency	f_{res}	1735kHz
Damping Resistor	R_f	0.54ohms
Voltage at PCC	V_{PCC}	230V

algorithm four different mode of fault was created. Once the fault is detected by many different islanding techniques as present in literature [20], [21], an attempt is made to clear the fault. Reactive power is either injected in case of voltage drop below the certain limit or reactive power is absorbed if the voltage rises above certain voltage level. The voltage at point of common coupling (PCC) is monitored for the purpose of control. The fault is detected based on voltage at PCC and then as per IEC 62116 standards it is determined if the system is out of range and what is the range of recovery time permitted for that range of fault. Voltage regulation is taken care of with the help of STATCOM and PV inverters by injecting or absorbing reactive power for stabilizing voltage. At the end, a trip signal is generated if the fault is not cleared after injecting reactive power within due time.

- *Case 1: More than 6% overvoltage at PCC:*

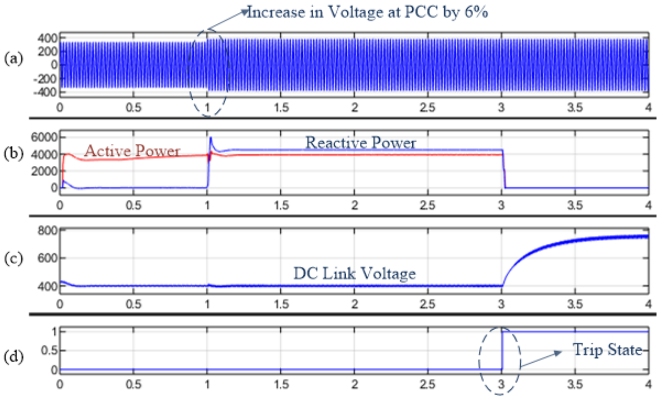

Fig. 5. Characteristics of the GCPV system for Overvoltage (6%>Nominal Voltage at PCC) fault.

  In the fig. 5, it can be observed that a LG fault is executed at t=1 sec which causes the system to go in over voltage. The voltage at PCC increase beyond 6% of limit as per grid standard. An oscillation is observed at P_{PCC} and Q_{PCC} because of negative sequence component. Average active power drops from 1p.u. to 0.8p.u. whereas reactive power rises ty 0.8p.u. to 1p.u. Q is injected in the system and at t=1.2 sec V_{DC} return to the normal value. according to IEC62116 if the value of voltage at PCC is not regulated in limit within two second from the fault then a trip signal is generated to disconnect the faulty region. Hence in (d) subsection of figure, a trip signal is observed as fault is injected externally so the system is unable to recover in time.

- *Case 2: More than 50% overvoltage at PCC:*
  The nature of fault is like the above case just that the voltage is exceeding the nominal voltage limit by 50% hence the stress on the system is very high. As per the standards in such case the trip signal is generated just after 0.2 sec of fault detection which can be observed in the fig. 6.

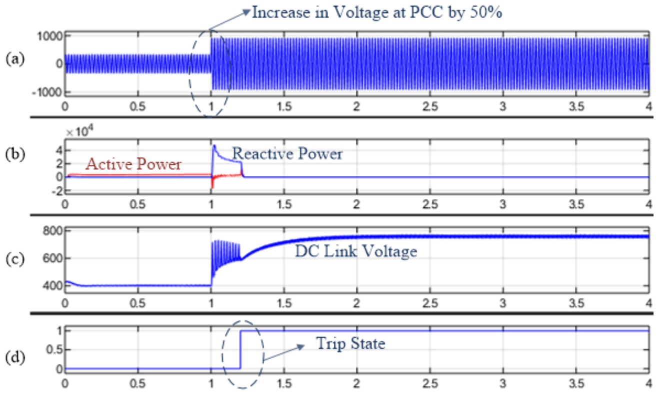

Fig. 6. Characteristics of the GCPV system for Overvoltage (50% > Nominal Voltage at PCC) fault.

- *Case 3: Less than 6% overvoltage at PCC:*
  In the fig. 7 it can be observed that a LG fault is executed at t=1 sec which causes the system to go in over voltage. The voltage at PCC decrease beyond 6% of limit as per grid standard. An oscillation is observed at P_{PCC} and Q_{PCC} because of negative sequence component. Average active power drops from 1p.u. to 0.8p.u. whereas reactive power rises ty 0.8p.u. to 1p.u. Q is injected in the system and at t=1.2 sec V_{DC} return to the normal value. according to IEC62116 if the value of voltage at PCC is not regulated in limit within two second from the fault then a trip signal is generated to disconnect the faulty region. Hence in (d) subsection of figure, a trip signal is observed as fault is injected externally so the system is unable to recover in time.

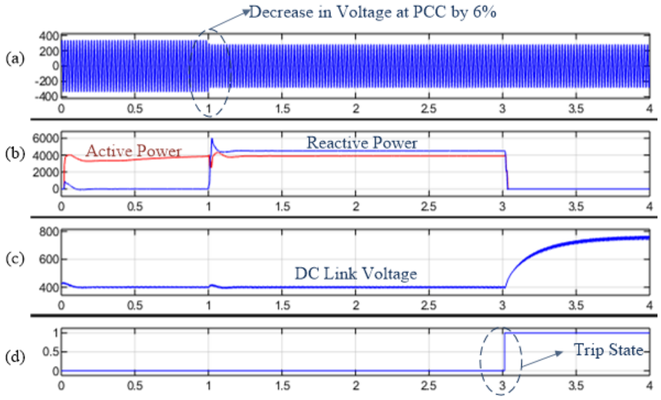

Fig. 7. Characteristics of the GCPV system for Overvoltage (6% < Nominal Voltage at PCC) fault.

- *Case 4: Less than 50% overvoltage at PCC:*
  The nature of fault is like the above case just that the voltage is below the nominal voltage limit by 50% hence the stress on the system is very high. As per the standards in such case the trip signal is generated just after 0.2 sec of fault detection which can be observed in the fig. 8.

V. CONCLUSION

This paper addressed the importance of reactive power control for large scale PV systems integration into power

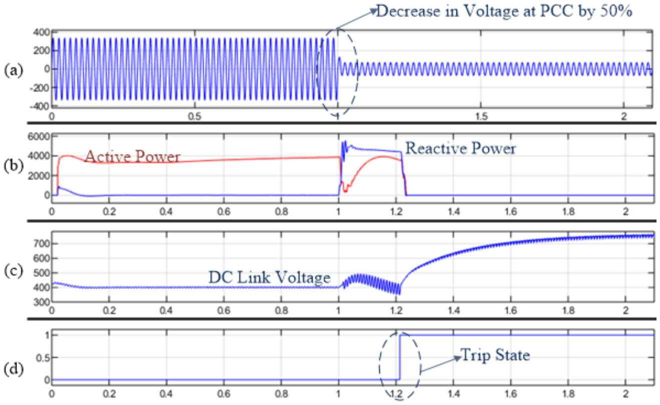

Fig. 8. Characteristics of the GCPV system for Overvoltage (50% < Nominal Voltage at PCC) fault.

distribution grids. In this regard, a coordinated control algorithm which combines the reactive power capabilities of PV inverter and STATCOM for reactive power compensation are analyzed. The developed algorithm is tested on a 4kW grid connected PV system. The results conclude that the developed coordinated voltage control algorithm efficiently regulates the bus voltages to the steady-state voltage limit according to the grid codes for both the over and under voltage situations. The STATCOM, coupled with the existing PV inverter, has shown effective reactive power compensation as well as the potential of ensuring compliance with the grid codes in terms of voltage stability. The results depicted that the developed algorithm has satisfactory performance in terms of reactive power control during grid faults.

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