Enhancement of Fault ride through strategy for single-phase grid-connected photovoltaic systems

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Abstract- **Increasing efficiency and decreasing cost of Photovoltaic (PV) panels has led to the rise of many PV Plants. Considering their evolution, Grid standards require PV systems to remain connected and support the grid by providing reactive power during a fault. In order to achieve this, a control system that provides Fault-Ride-Through (FRT) capability for grid-connected PV systems is proposed. The FRT requirements, i.e., injecting a minimum 2% reactive current for every 1% change in the voltage, and limiting the current overshoot of the voltage source converter switches are met by the designed controller. During a fault, when the active power of the PV plant is decreased, the controller allows reactive power to be injected into the grid. In case the fault prolongs over a certain stipulated time as described by grid codes then the PV system is disconnected from the grid until the fault is cleared. Simulations verify that the proposed control system achieves the FRT requirements when providing FRT for symmetrical and asymmetrical faults.**

Keywords **– Grid-Connected PV system, Fault ride through, Reactive power compensation, Grid codes**

I. INTRODUCTION

With the increase in renewable energy installation over the years, power saturation has been an issue with the grid. Because of grid power saturation, several problems occur due to insufficient power from renewable energy. Solar energy is highly unpredictable because it depends upon the irradiance obtain from the sun. At times, shading may occur causing power output to be zero. It is difficult to forecast the power output from renewable and connect the grid as per the power requirement. Grid integration remains a significant issue at large and improvement is required for more reliable operation and reduction in running cost. Many of the governments have stepped in by making a stringent grid code for interconnection to protect the grid from collapsing altogether. Grid codes comprise of standards required for connecting with the grid. It fixes the limits within which variation of certain nominal factors such as voltage, power factor, and frequency are varied.

Many of the researchers have proposed various control for inverters for obtaining the maximum efficiency. Transformerless inverter topology has been the most efficient inverter topology in recent years. An overview of different transformerless inverter topologies is present by Islam et al. [1]. An overview of control techniques implementation on the transformerless inverter is presented by Khan et al. [2]. While controlling the inverter switching pulses, reactive power injection also needed to be considered for fault clearance of the system. Kabiri et al. [3] in his work presented a control strategy utilizing sequence frame for current regulation for continuous adjustment of real power and elimination of reactive power oscillation. Mojallal et al.[4] presented research that utilizes a slide mode control methodology for recovering after a fault has occurred. Hossain et al. [5] in his research has proposed, and intelligent reactive power injection method where DC-DC converter switching is controlled by fuzzy during faulty condition and an in normal condition incremental conductance are implemented to achieve maximum power. Lammert et al. [6] wok presented a brief study of dynamic voltage support capability along with a recovery rate for active current. The implementation takes place at the local voltage control unit. In research by Nagata et al. [7] independent component analysis is used for voltage sag and swell detection. Sharma et al. [8] contribution to the method of managed reactive power exchange with the grid so even in case of high degree of the unbalanced power system can operate in clusters.

Yang et al. [9] in his research presented a modified control algorithm with an aim to enhance low voltage ride through (LVRT) for a grid-connected PV inverter. In case of a fault, flux coupled is triggered at fault current limiters. Yang et al. [10] has presented in his research an overview of LVRT and compared different grid codes across the world and discussing the evolution of grid codes over time. Sadeghkhani et al. [11] proposed an LVRT method that claims to improve the power quality of the entire microgrid. Droop control is proposed to address reactive power injection in the system in case of voltage sag. Shetwi et al. [12] proposed current limiter and DC chopper brake control to absorb the excessive DC voltage and limit it. The control strategy also ensures reactive power ejection in case of a fault.

All of the above issues pointed out by various researches, In this paper, an reactive power compensation strategy is implemented, when there is a variation in voltage or frequencies at PCC. Voltage recovery process is monitored and if the voltage or frequency is not recovered in stipulated time as per the grid code then the trip signal is generated, disconnecting the PV system with the grid. In section II, control of grid connected system is presented. Section III overview of reactive power injection and proposed method is explained. whereas, in section IV, fault ride through is explained along with the grid codes. Section V presents the

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result of the simulation work and section VI concludes the results.

II. GRID-CONNECTED SYSTEM CONTROL

PV system application is the most leading power supplying method when it comes to residential load. The figure 1 depicts the overall layout of PV based grid connected system. The DC-DC converter is implemented to boost the output obtained from the solar panels and which is in an acceptable range of inverter input. Maximum power point tracking is implemented for achieving a peak efficiency of the panel at a given value of irradiance and temperature. In the case of grid fault or disturbance in voltage or frequency, the grid must be disconnected from the system at Point of common coupling (PCC) [13] as depicted in the figure 1.

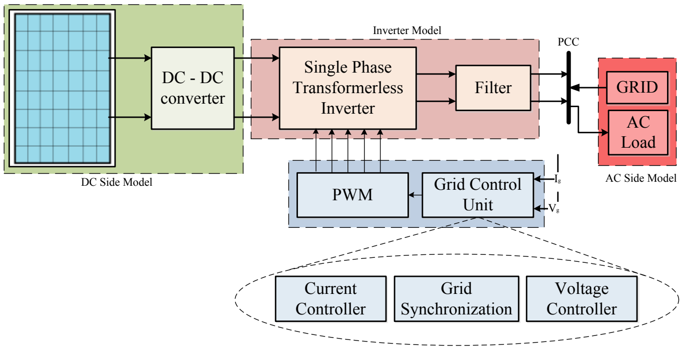

Fig. 1. Control configuration of the grid-connected system

For maintaining the balance in case of disturbance a reactive power injection strategy is implemented in the grid integration control of the inverter. For the implementation of reactive power control, the strategy is developed in dq- frame [14]. Orthogonal signal generation system is required to create quadrature component for real value of grid voltage v_{grid} and current i_{grid}. The reference value of active and reactive power provides a reference to the reactive power control unit and depending on them the reactive power is injected through the iq component of the current. Apparent power is taken into account to control the limit of reactive power in the system [15].

III. REACTIVE POWER INJECTION

In the case of voltage sag and swell in a grid-connected photovoltaic system, reactive power needs to be injected by the grid to maintain the voltage profile of the feeder [16]. As the designing of PV is performed with a reasonable margin and can operate under partial loading condition, there is scope for reactive power control. Apparent power rating dominates the capability of reactive power in PV inverter.

$$|Q_{in}| \leq \sqrt{S_r^2 - P_{in}^2} \qquad (1)$$

Where Q_{in} is the instantaneous reactive power to be injected to the grid and P_{in} is the instantaneous active power delivered by the grid to PV inverter. S_r is the rated apparent power of PV inverter. From the equation, it can be deduced that the power derating enables more reactive power injection the system.

In certain grid such as Germany high penetration of PV system [17] is required for activation grid control via reactive power as most of the distribution networks are of medium or high power. Recently even for the low voltage smart PV system, reactive power requirement has gone up for increasing PV capacity and providing voltage control using reactive power management techniques.

Control implementation by injecting reactive power tend to improve the voltage profile at the point of common coupling (PCC). Voltage profile tends to improve with the exchange of reactive power taking place between grid and PV system [18].

There are three methods related to reactive power control: -

Independent reactive power (Q) control- the control of reactive power is independent of active power obtained at PCC. In this method, reactive power is supplied the system with the help of FACT devices.

Voltage (VAR) based Control- Grid voltage obtained at PCC enables the exchange of reactive power to control the voltage level at PCC. Voltage sag and swell is detected in the process, and depending on them the reactive power injection is made into the system. Droop control is the most implemented method when it comes to voltage-based control.

Power factor-based Control- Active power is monitored, and a balance between active and reactive power is made to obtain a constant power factor of the system.

In the proposed voltage at PCC is fed to sag swell detector which detects the variation in voltage of the inverter. In the case of sag or swell reactive power, injection strategy is used to balance the power factor to unity and maintain the balance between active and reactive power as depicted in the figure 2. The power reference out of the reactive power injection technique in case of grid sag can be calculated by the following:

$$P^* = \frac{3}{2} V_{grid} I_d \tag{2}$$

$$Q^* = \frac{3}{2} V_{grid} I_q \tag{3}$$

Where V_{grid} denotes the grid voltage amplitude. During normal condition required active power is lower than the maximum power delivered by PV. The inverter must vary the active power value to obtain maximum PV power delivered during normal condition.

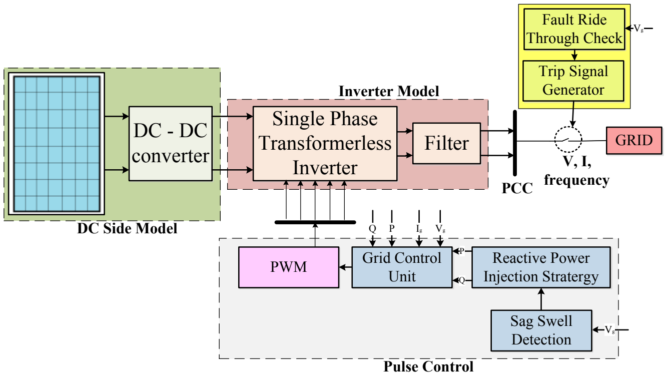

Fig. 2. A grid-connected system with Reactive power compensator and Fault ride through

IV. FAULT RIDE THROUGH

Grid codes are responsible for defining the fault ride through the system. As per the grid code, it is required that the system operates within the defined safety limits. It ensures that continuous operation of a PV plant even when there is a severe disturbance in grid voltage. PV plant may witness a serve dip in voltage at PCC in case of a fault [13]. At the instance, the power factor is balanced by maintaining the ratio between active and reactive power. In case if the fault persists and the grid voltage falls below or above the prescribed voltage range as per the grid codes then after two seconds of the fault starting time the PV system is disconnected with the grid [19]–[21]. In case of load variation during the operating condition if the voltage is twice the nominal voltage for more than 0.2 sec, then the tripping signal is sent to the circuit breaker disconnects the grid as per national grid code, India[22].

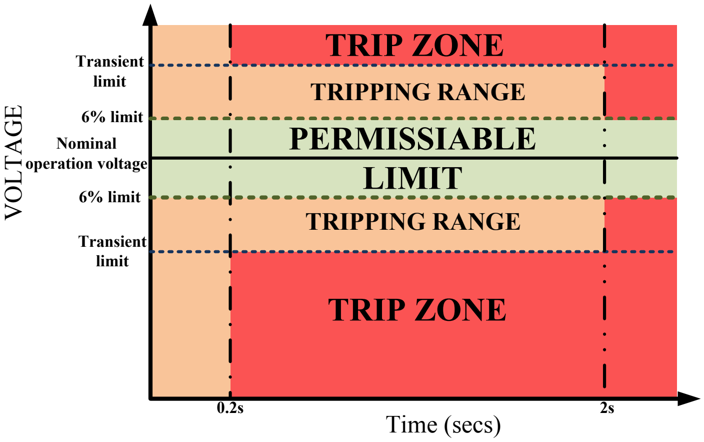

Fig. 3. An operational layout for voltage fault ride through

In the figure 3 given below, the range in green denote operating range which is, ±6% from the nominal voltage. In this range, the PV system operates flawlessly without generating any trip signal. In the yellow range, the system moves to a dangerous range as the system may trip if the control algorithm explained earlier can't recover the system in the time that is, 0.2 sec for operational transient and 2 sec for a regular fault condition. When the system surpasses the prescribed time limit, the system moves into the red zone, and the trip signal disconnects the PV from the grid.

For normal operation, the following method is used to generate the trip signal in 2 sec.

$$u_{norm} = \begin{cases} 1\ [-6\%\ of\ v_n < v_{grid} < +6\%\ of\ v_n] \\ 0\ [+6\%\ of\ v_n < v_{grid}\ or - 6\%\ of\ v_n > v_{grid}\ ] \end{cases} \tag{4}$$

Where u_{norm} is the trip signal under a normal operating condition, v_n is the nominal voltage of the system, and V_{grid} is the voltage of the grid. Initially, the trip signal is high, so the system relates to the grid. As soon as the fault is injected the trip signal falls to zero in two second and grid is disconnected from the PV system. In case of load variation while operation the transient voltage value is deduced by the following method.

$$u_{trans} = \begin{cases} 1\ [-50\%\ of\ v_n < v_{grid} < +50\%\ of\ v_n] \\ 0\ [+50\%\ of\ v_n < v_{grid}\ or - 50\%\ of\ v_n > v_{grid}] \end{cases} \tag{5}$$

Here u_{trans} denotes tripping signal under transient condition.

When the frequency is taken into consideration for fault ride through, as per the report of the central electricity regulation committee, India, a variation of only 3% is permissible [23]. If the frequency is greater then or less, then the prescribed limit then in two seconds a trip signal will be generated disconnecting the grid with the PV system.

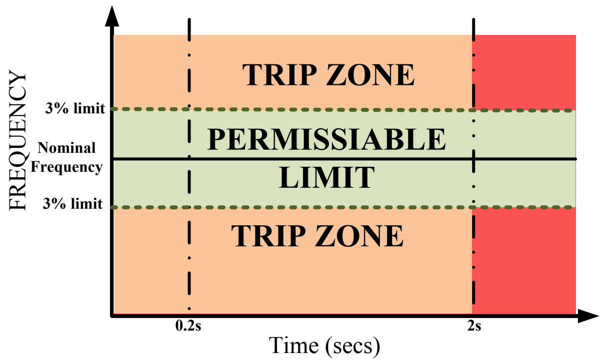

Fig. 4. An operational layout for frequency fault ride through

In the figure 4, the operating range of frequency is marked in green whereas the trip zone is in red. The area in orange is the recovery zone; hence if the system recovers in time, then the trip signal may not be created.

For frequency-based operation, the following method is used to generate the trip signal in 2 sec.

$$u_{freq} = \begin{cases} 1\,[-3\%\ of\ f_n < f_{grid} < +3\%\ of\ f_n] \\ 0\,[\,+3\%\ of\ f_n < f_{grid}\ or -3\%\ of\ f_n > f_{grid}\,] \end{cases} \qquad (6)$$

Where u_{freq} is the frequency trip signal, f_n is the nominal frequency of the system, and f_{grid} is the frequency of the grid. Initially, the trip signal is high, so the system is a connection with the grid. As soon as the frequency cross the prescribed limit, the trip signal falls to zero in two second and grid is disconnected from the PV system.

V. SIMULATION RESULTS

The grid-connected PV system was simulated using MATLAB 2017b. Different sections were designed by using mathematical analysis as depicted in table 1. A 1kW solar array was implemented using the datasheet of Topsun Energy.

Table1: Overall System Description for 1kW solar inverter

Section of the System	Parameter	Values
Photovoltaic Topsun solar (250W) X 4	Power (P_{max})	250 watts
	Short circuit current of the module (I_{sc})	14.6A
	Open circuit voltage of module (V_{oc})	22Volts
	Maximum Power Point current (V_{mpp})	13.9A
	Maximum Power Point Voltage (V_{mpp})	18 Volts
DC-DC Boost Converter	Duty cycle	0.6
Inverter (Transformerless topology)	Topology	H5
	Bus Voltage	400V
	Output Voltage	230V
	Tolerance Voltage Limit	6%
	THD Tolerance limit	5%
Grid (Single Phase)	Grid Frequency	50Hz
	Line to line voltage	220 volts
	Line to Neutral Voltage	220 volts
	Grid Impedance	0.11Ω, 0.35mH

A balanced Vrms 240V AC is considered as the nominal voltage at Vpcc. Even in the case of variation in load the output voltage attempts to recover with the help of reactive power injected to the system by controlling the pulse of the inverter. As represented in the figure 5 the power factor is maintained as when the active power value is reduced the system starts to inject reactive power to recover the system from the fault.

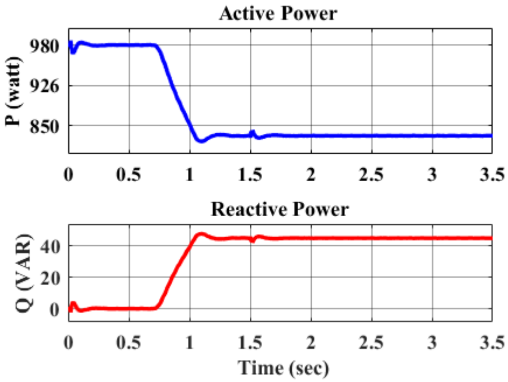

Fig. 5. Active and reactive power flow with fault at t=0.7 sec

As by the national electrical code presented by Bureau of national standards, India, a variation of up to 6% in output voltage is acceptable [22]. Hence in case of voltage sag taking place which is above the limit of 6% of nominal voltage, a trip signal is generated 2 seconds after the fault has occurred as depicted in the figure 6. The trip signal will cause the circuit breaker to disconnect the faulty system from the grid until the fault is cleared. If the fault gets cleared or the reactive power recovers the system voltage within two seconds, then the system will operate normally without any trip signal generation.

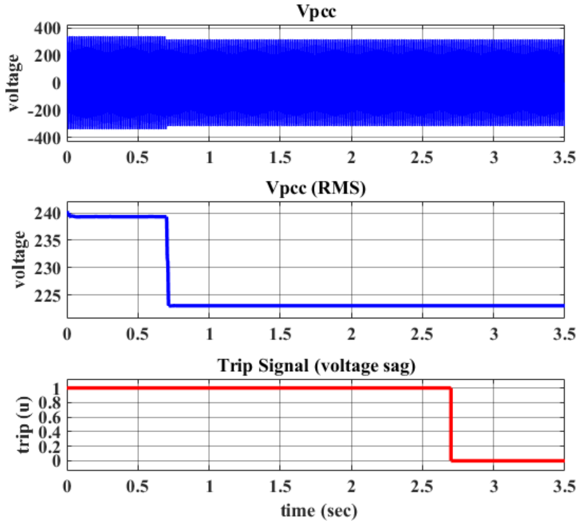

Fig. 6. Vpcc, Vpcc RMS and Trip signal for voltage sag condition

Like above, if the voltage swell is present and the fault within 2 seconds a trip signal is generated, as depicted in the figure 7. It disconnects the grid from the faulty PV system.

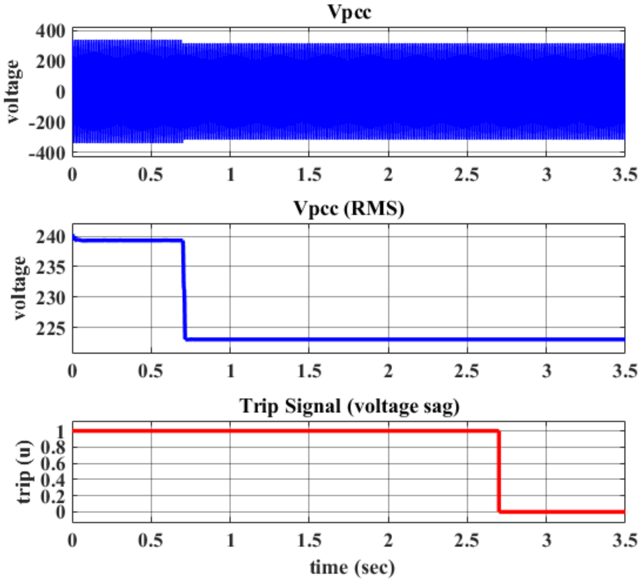

Fig. 7. Vpcc, Vpcc RMS and Trip signal for voltage swell condition

Sudden variation in load or disconnection of a certain section from the grid may lead to a transient in the voltage beyond the permitted limit by IEC 62116 [24]. In case of transient fluctuation in voltage level during operating condition, the trip signal is generated in 0.2 sec if the transient is not stabilized by then depicted in figure 8. Hence if the transient doesn't stabilize within the prescribed time limit, the grid will disconnect the system.

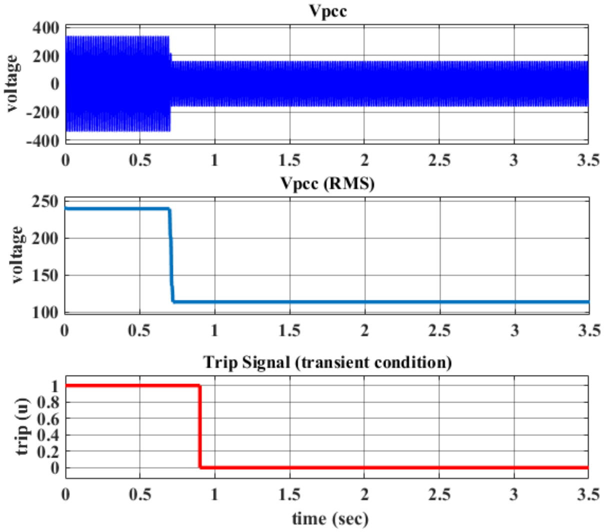

Fig. 8. Vpcc, Vpcc RMS and Trip signal for low voltage transient

If the voltage transient even causes the voltage to increase above a certain range, like before a trip signal will be generated in 0.2 sec from the transient disconnecting the PV system from the grid as shown in the figure 9.

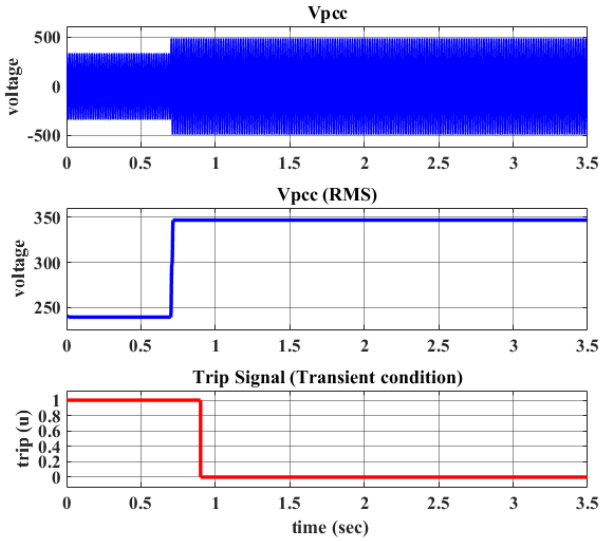

Fig. 9. Vpcc, Vpcc RMS and Trip signal for high voltage transient

In case of frequency variation, a drop-in frequency below 3% of the nominal value will result in trip signal generation within 2 seconds from the fault time as shown in the figure 10. If the frequency gets stabilized before the 2 seconds, then no trip signal will be generated.

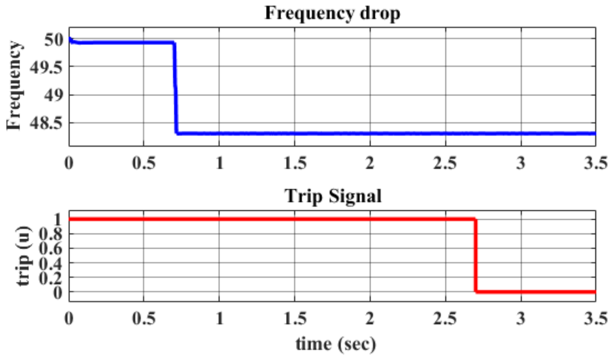

Fig. 10. Frequency and Trip signal for frequency drop condition

Like above, if the frequency rises above 3% of nominal value then within 2 seconds a trip signal is generated, as depicted in the figure 11. It disconnects the grid from the faulty PV system.

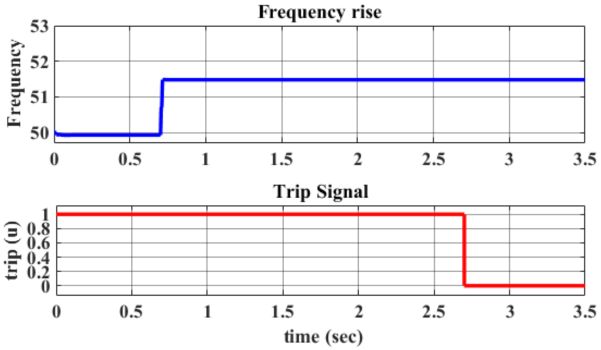

Fig. 11. Frequency and Trip signal for frequency rise condition

Fault ride though assures that the system operates within the permissible range of operation and in case the range is compromised either the system is recovered within the prescribed time limit, or the PV system is disconnected from the grid.

VI. CONCLUSION

This paper developed a control system that provides fault ride through capability for single-phase grid-connected photovoltaic systems. For different faults that occur at the grid side of the system, a variation of voltage level and frequency can be observed at PCC. The developed control system was able to meet the requirements set by recent standards and inject the required reactive current under stipulated time.

The control system was successfully able to ride through symmetrical and asymmetrical faults from the PCC. The control system met the FRT requirement which requires the PV plant to remain connected during a fault as required by the FRT characteristic curve. The PV Plant proportionally injects more than 2% reactive current for every 1% change in PCC voltage within the time limit upon detection of a fault.

If the fault is not cleared in stipulated time as per the grid codes, the PV system is disconnected from the grid until the fault clearance is achieved or maintenance is performed to clear the fault.

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