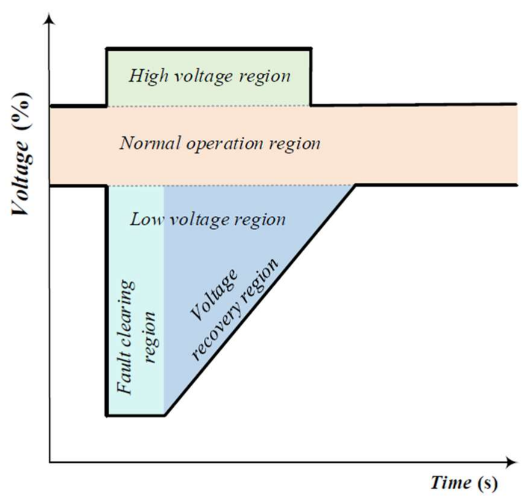
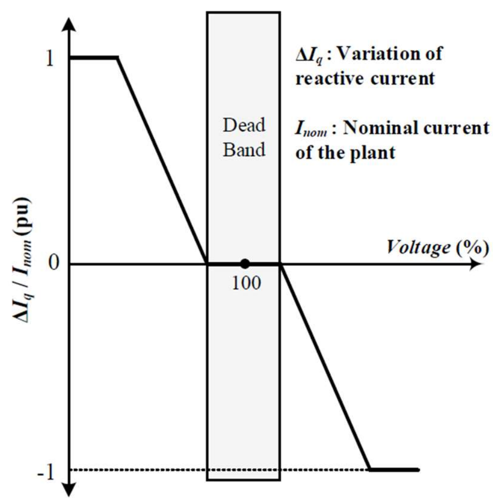
Grid Code for Voltage FRT Operation

The power system network is formed by a coherent interaction of multiple generating units, loads, and storage devices with distinct characteristics through a complex set of transmission and distribution lines. The transition from passive to active network through rapid deployment of renewable energy units led to the need for rules and regulations that dictate the way these generating units interact with the network. Grid code is an operative collection of regulations to coordinate the inclusion of and interaction among different generating units in an interconnected power system network. The grid code for voltage FRT operation falls into the category of dynamic operation of the network. In the recent years, most of the countries published or have updated their grid code related to the voltage FRT operation of the SPV units. The voltage FRT requirements are often embedded in the grid code through a voltage versus time curve and a reactive current variation versus voltage curve that dictates the operation of the generating unit during short-term voltage disturbances in the network.





a) Voltage vs time b) reactive current variation vs voltage

Fig.1 Voltage FRT characteristics for a generating unit

The voltage versus time curve is indicative of the extent of voltage sag and the duration of impact that the generating unit should withstand to avoid disconnection during the short-term voltage deviations. Typical voltage versus time curve is shown in Fig.1a. Broadly, the voltage versus time curve can be divided into the following regions (i) normal operating region; (ii) low-voltage region; and (iii) high-voltage region as shown in Fig.1a. The normal operating region specifies the voltage limits within which the generating unit can continue its intended operation. Typically, the voltage limits for this region are 90–110%. The low-voltage region corresponds to the voltage limits below normal operating region and within the characteristic curve within which the generating unit needs to stay connected to the network irrespective of the drop in voltage. This region can be further classified as (a) fault clearing region and (b) voltage recovery region. The fault clearing region represents the phase during which the network voltage undergoes a significant dip in the voltage resulting from a fault and settles at a voltage level depending on the severity and type of the fault. The time duration of this region and the allowed voltage sag mainly depend on the maximum time taken by the protection system to isolate the faults and the severity of the fault. Post successful isolation of the fault, the network voltage starts recovering back to the normal operating region. The region within the low-voltage region other than the fault clearing region is generally referred as the voltage recovery region. The rate of recovery of voltage in this region depends on the strength of the network, reactive power capability, generation–load mix, etc. High voltages in the network typically occur due to switching transients and/or sudden disconnection of loads. The region above the normal operating region and below the voltage FRT characteristics is the high-voltage region that bears the same operational norms as their low-voltage counterpart.

In the event of high or low voltages in the network, the network requires suitable reactive power to counteract the cause. This requirement is represented by a reactive current variation versus voltage curve as shown in Fig.1b. The reactive current variation versus voltage curve depicts the requirements for reactive current exchange during network voltage deviations in a view to stabilize and quickly regain normal operating condition of the network voltage. Going the distributed way, during network faults, few grid codes mandate the reactive current compensation from the distributed generating units. Typically, a fall in network voltage should be counteracted by an appropriate injection of reactive current by the generating unit and vice versa. The dead band in Fig.1b corresponds to the network voltage limits for which no reactive current compensation is required. This region generally aligns with the normal operating region of the voltage versus time curve. Beyond the dead band, droop settings are in place to determine the required reactive current variation as a ratio of nominal current of the generating unit against the voltage level. The generating unit may either curtail the real current or be oversized to meet this reactive current requirement.

Voltage FRT Characteristics in IEEE 1547:2018 standard

Most of the available distributed generation technologies like SPV, wind, fuel cell, hydro generation, and energy storage technologies are classified into abnormal performance category (APC) I, II, and III with respect to the voltage FRT operation. The basis for this classification is not straightforward, yet it depends on both technical and non-technical factors like generation type, capacity, type of application, future penetration of generation technology, grid configuration, generation technology use case, impacts on environment, emissions, and sustainability. The methodology and an example classification of the existing distributed generation units are presented in Appendix-B of the IEEE 1547:2018 standard. Based on this classification, unique voltage versus time curve is published for each APC. The fundamental difference lies in the voltage and time settings of the voltage versus time characteristic curve. Inverters sourced by SPV units either fall into APC-II or III depending on the level of penetration with APC-III having the most wider voltage versus time settings.

The voltage versus time curve is sub-divided into multiple performance regions in IEEE 1547:2018 for each APC. The low-voltage region (below 0.88 pu) and high voltage region (above 1.1 pu) are further divided into mandatory operation region, permissive operation region, and momentary cessation region. It is important to note that the presence of a particular performance region within the voltage versus time curve depends on the type of APC. The performance regions and the requirements for the distributed generation unit while operating in that performance regions are elucidated below.

• Mandatory Operation Region: The generating unit shall stay in synchronization and shall continue to exchange energy with the network. For APC-II and III, the generating unit shall not reduce its total apparent current during the disturbance period below 80% of the pre-disturbance value or of the corresponding real current level subject to the available real power, whichever is less. Active and reactive current oscillations in the post-disturbance period that are positively damped are acceptable.

• Permissive Operation Region: The generating unit shall stay in synchronization and may continue to exchange energy with the network or may cease to energize. If the generating unit rides through a voltage disturbance with cease to energize function, the generating unit shall restore output of real current to at least 80% of pre-disturbance real current level within 0.4s once the permissive operation region is surpassed. Active and reactive current oscillations in the post-disturbance period that are positively damped are acceptable.

• Momentary Cessation Region: The generating unit shall stay in synchronization and shall cease to energize. The restore output conditions are same as described for permissive operation region.

The structure of the voltage versus time curve for APC-II is presented in Fig.2. The high-voltage region comprises only permissive operation region, whereas the low-voltage region is sub-divided into mandatory operation region and permissive operation region. The momentary cessation region is absent in APC-II characteristics. The summary of different performance regions is depicted in Fig.3.

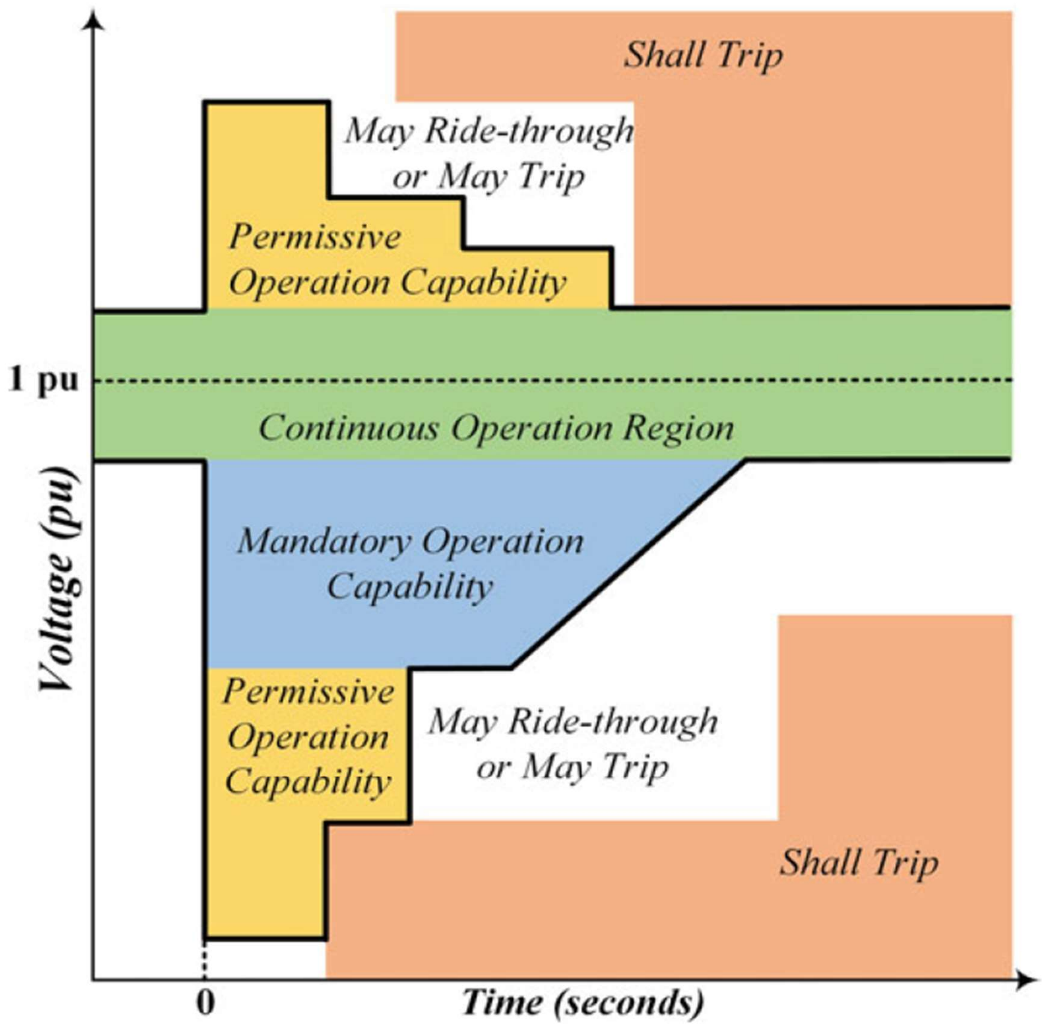


Fig 2. Structure of voltage versus time curve for APC-II.

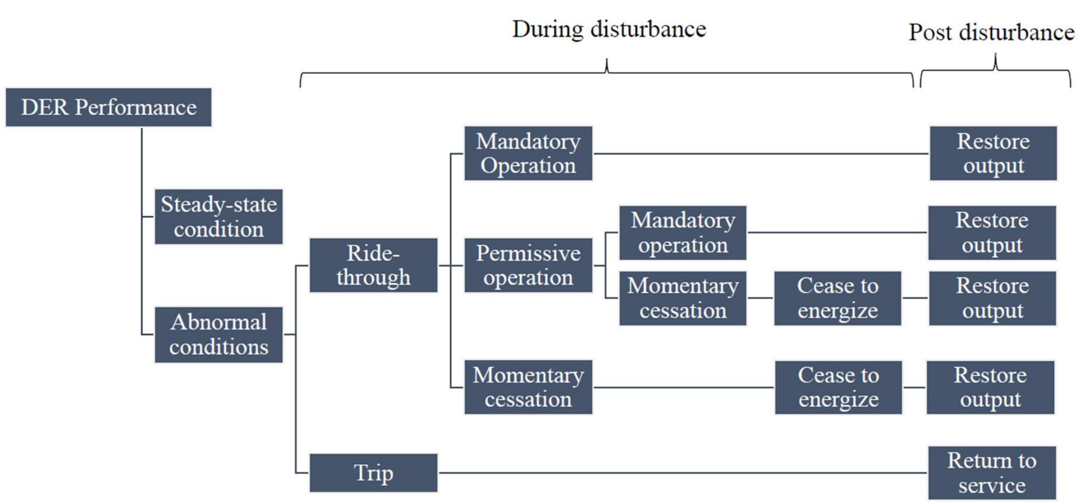


Fig3. Overview of performance regions for voltage FRT operation

Grid-Connected SPV Generating Unit

Grid codes are mandating fail-proof voltage FRT operation from the generating units. It is therefore the need of the hour to understand the operation and different aspects related to the grid interaction of the generating unit. The layout of a grid connected SPV generating unit along with its control strategy is depicted in Fig.4. Typically, grid-connected SPV unit involves a two-stage power conversion, i.e., first DC-DC and then DC-AC, often performed by DC-DC converter and two-level inverter, respectively. The DC-DC converter is often controlled to tap maximum power from SPV panels by taking the voltage and current at the panel terminals as feedback. Maximum power point tracking (MPPT) controller hosts the tracking algorithms like incremental conductance, perturb & observe, fractional open-circuit voltage, etc. The resulting effect of the MPPT algorithm is an uncontrolled variation of the DC bus voltage. Therefore, the two-level inverter is often controlled to stabilize the DC bus voltage at a pre-set reference value by transferring the incoming maximum power from PV panels to the utility grid. Often, voltage and current variables from the point of common coupling (PCC) are measured and processed for further control. While PCC voltage is used for synchronizing the output of inverter with that of the PCC, the PCC current is used to control the power flow through the inverter. The DC bus voltage controller takes DC bus voltage as input and generates a real power reference (P^*_{inv}) in a process to control the voltage to a predefined reference value. Similarly, the SPV system can either host an AC voltage controller that generates the reactive power reference (Q^*_{inv}) or a predefined reactive power/current versus voltage curve that defines the level of reactive power/current required with respect to variations in PCC voltage. Post reference power generation, the information of the real and reactive powers will be converted to an apparent current reference (i^*_{inv}) and is passed on to the AC current controller that compares the reference current with the actual current (i_{inv}) measured from the PCC and generates modulation signals for generating the switching pulses for the SPV inverter. The entire system therefore behaves as a grid-following entity with maximum power transfer from SPV panels to the utility grid at any point of time. This two-stage grid-connected SPV unit is required to provide voltage FRT operation as mandated by the grid code.

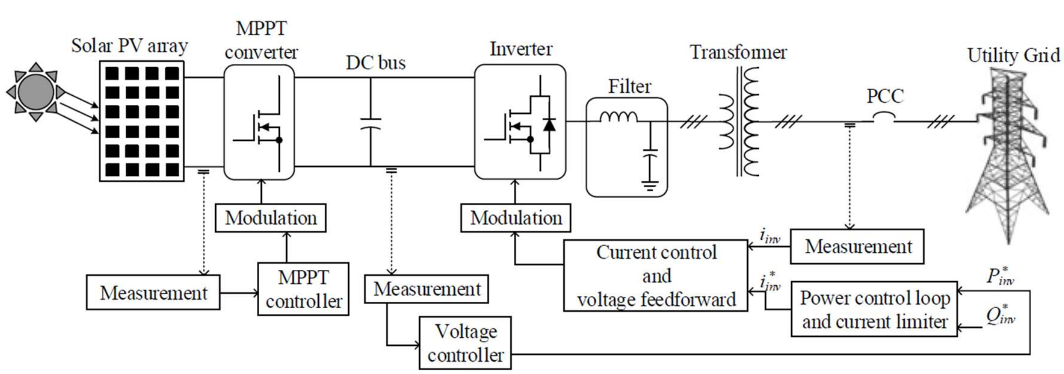
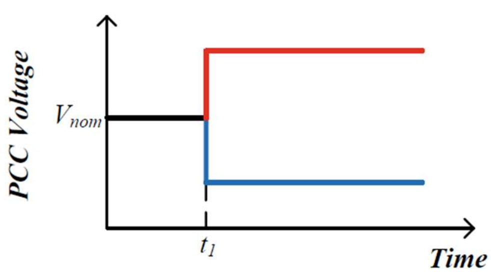


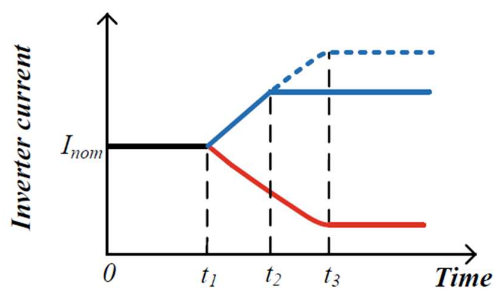
Fig4. Grid-connected SPV generation unit along with its control

Voltage Fault Response of SPV Generation Unit

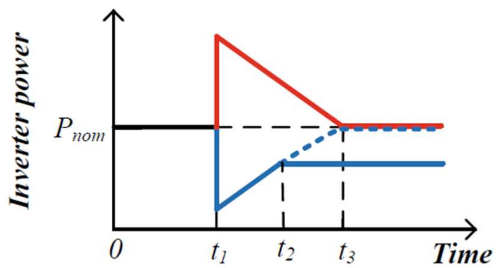
The requirements of the voltage FRT operation apply at the PCC and are achieved by tweaking the control logic of the inverter and appending suitable hardware components. Inverters are current limited devices due to the limited current rating of the switches deployed in it. Hence, at any point of time, the user needs to appropriately modify the real and reactive currents subject to the available maximum current limit. The response of different variables in a SPV inverter for both low- and high voltage symmetrical faults is shown in Fig.5. The black, blue, and red color lines indicate the response of the system to nominal voltage, low voltage and high voltage at the PCC, respectively. The subscript nom of the variables used in Fig.5 represents its nominal/rated value. A sudden drop in the PCC voltage at time t_1 in Fig.5a results in an increase in the inverter current by virtue of its constant power operation as shown in Fig.5b. If the rise in current is well below the current limit of the inverter switches, the inverter power and DC bus voltage return back to the nominal value irrespective of the low voltage at the PCC as shown in blue dotted lines in Fig. 5c and d. On the other hand, if the increase in current is beyond the inverter current limit, the inverter control hard limits the inverter current, and thus, there will be a power imbalance at the DC bus that results in a rise in DC bus voltage as depicted with solid blue lines in Fig.5c and Fig.5d. Similarly, the response of the SPV inverter for a high voltage at the PCC is also shown in Fig.5. The rise in PCC voltage actually demands a decrease in the inverter current to maintain constant power flow through the inverter as shown in Fig.5b. Hence, the inverter momentarily transfers higher power than the available SPV power (until the inverter reaches the new operating point, i.e., until t_3) as shown in Fig.5c by draining the energy from DC bus resulting in a decrease in the DC bus voltage as shown in Fig.5b. Please note that the DC bus voltage should be high enough to push power into the utility grid even during high voltage at the PCC; otherwise, there will indeed be a boost in the DC bus voltage due to the imbalance arising at the DC bus.



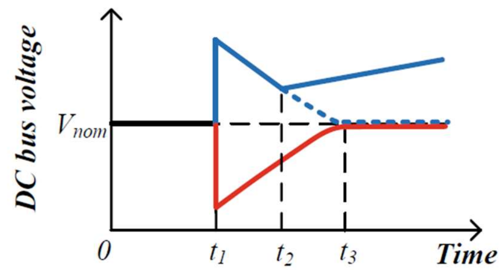
a) PCC voltage



b) Inverter current plot



c)Inverter power plot



d) DC bus voltage plot

Fig5. Response of a SPV unit to low/high voltage at the PCC

It is therefore evident that there will be serious perturbations in the DC bus voltage resulting from limitation in the switch current rating of the inverter which may lead to the tripping of SPV unit due to the stringent protection settings. The effect worsens for APC-III characteristics as the voltage versus time requirements are very wide in this case. SPV units without voltage FRT operation capability end up in tripping for short-term voltage disturbances leading to a loss of revenue for plant owners and stability issues to the utility grid (every time the unit trips and reconnects to the grid). Therefore, the upcoming solar installations should be designed adhering to the required grid code, whereas the existing solar SPV installations need to be retrofitted in terms of both system components and/or control strategy to comply with the ride through operation. The above analysis suggests that suitable hardware or control mechanism is imperative to facilitate stable and reliable voltage FRT operation from SPV units. A simple current limiting control can limit the inverter current and possible solutions based on control methods only or using both hardware and control-based methods exist for stabilizing the DC bus during voltage FRT operation. They are summarized below and are presented in Fig.6.

1. OFF-MPP control of DC-DC converter

2. Crowbar circuit at the DC bus

3. Energy storage at the DC bus.

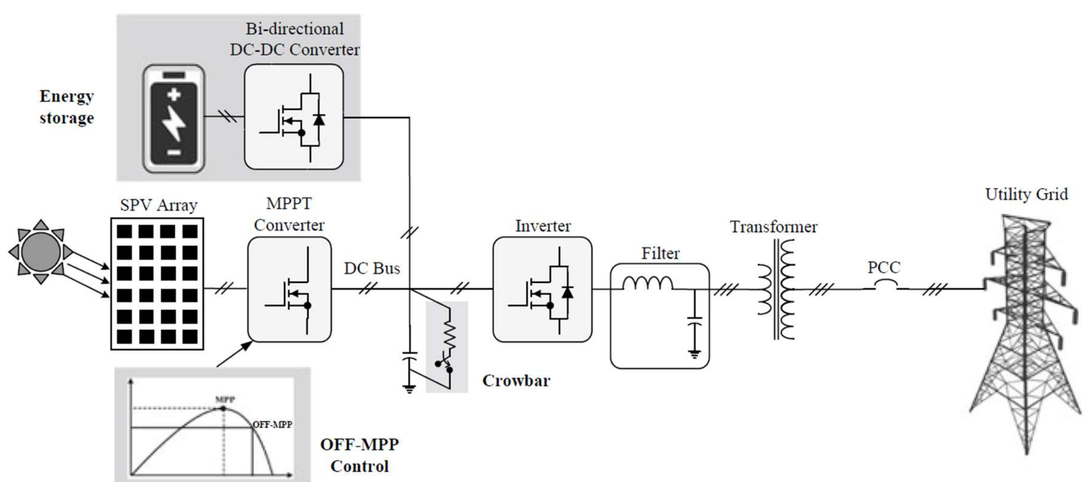


Fig.6 Methods to achieve reliable voltage FRT operation of SPV unit

Control of SPV Generation for Voltage FRT Operation

In the event of voltage FRT operation, if the inverter enters into the current limit mode and is unable to transfer the available real power, the DC bus voltage rises and settles at a new value depending on the imbalance power at the DC bus. Besides the inverter control strategy for voltage FRT operation, additional control or hardware methods are required to stabilize the DC bus voltage. Three possible methods to support the voltage FRT operation of the SPV unit by restricting the rise in DC bus voltage are discussed in detail and classified as only control-based method and both hardware and control-based method.

1.OFF-MPPT control of DC-DC converter: This is only control-based method since it involves a change in the control principle of the DC-DC converter interfacing the SPV array with the DC bus. As long as the DC bus voltage is within the prescribed voltage limits, the converter is controlled by the MPPT algorithm which measures and controls the SPV terminal voltage to achieve maximum power transfer. In the event of voltage FRT operation, the control logic switches from input voltage control to output voltage control and thereby limits the power fed to the DC bus and arrests the rise in DC bus voltage. Accordingly, the operating point of the SPV array changes on the P–V curve from A to B as shown in Fig.7.

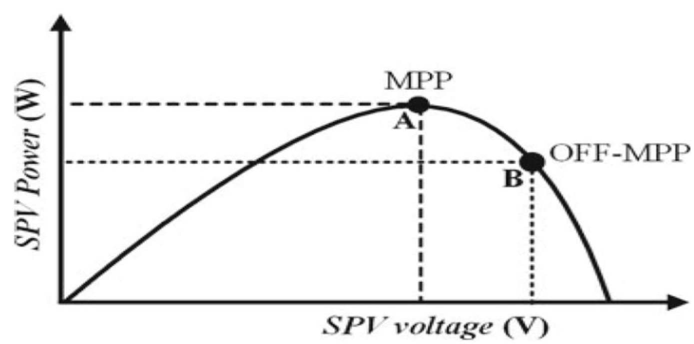


Fig7. P–V curve of SPV array with different operating points

2. Crowbar circuit at the DC bus: A crowbar is an electrical circuit used to prevent an over-voltage condition of a power supply unit, which may lead to damaging the circuits attached to the power supply unit. It consists of a suitably sized resistor in series with a high-frequency switch as shown in Fig.6. In the event of voltage FRT operation, the crowbar connected at the DC bus switches ON the resistor circuit that absorbs the excess energy at the DC bus and thereby limits the DC bus voltage close to its reference value. However, the crowbar circuit cannot arrest a fall in the DC bus voltage which might arise during high-voltage FRT operation.

3. Energy storage at the DC bus: An energy storage device at the DC bus coupled with a bidirectional DC-DC converter can arrest both positive and negative variations in the DC bus voltage (refer Fig.6). The bidirectional converter is controlled to track the DC bus voltage to a pre-set reference value through appropriate voltage and current controllers. Suitable energy storage device should be chosen to meet the requirements of power variation and energy requirement during the voltage FRT operation. In addition, energy management strategy is required to maintain the state of charge (SoC) levels of energy storage device. The energy storage option at DC bus can assist in both high- and low-voltage FRT operation.

Out of these methods, the first method is purely control logic-based while the other two methods require additional hardware along with control. However, the first two methods result in a loss of solar power, while the energy storage-based method stores the same. Also, by using suitably sized energy storage at the DC bus and by slightly tweaking the control strategy of the inverter, additional grid-supporting functions like frequency FRT and black start operation can be achieved. Proper control and energy management strategy of energy storage plays a vital role in achieving the required functionalities from the energy storage. The inverter control for achieving voltage FRT operation is described below.

The grid-connected solar PV system along with the auxiliary hardware, i.e., crowbar circuit or energy storage for facilitating voltage FRT operation is depicted in Fig.8. The SPV array is the primary source, and hence, it is always preferred to operate at maximum power point. The grid-connected inverter is prioritized to control the DC bus voltage. Accordingly, the inverter control hosts a DC voltage controller that regulates the voltage to the given set-point by injecting or absorbing required active power from the DC bus. In this regard, the voltage controller generates a current/power reference based on DC voltage deviations which is further tracked by the current/power controllers. The P_{inv} controller in Fig.8 contains the above-mentioned voltage controller that takes in the reference voltage ($v^*_{dc,pu}$) and actual voltage ($v_{dc,pu}$) of the DC bus and generates the current reference for real power control of the inverter, i.e.,$i^{(d)*}_{pcc,pu}$.

The control strategy employed to achieve voltage FRT operation from the solar PV inverter is depicted in Fig.8. The local variables, i.e., three-phase PCC voltage and current (v_{pcc} and i_{pcc}), are sensed using appropriate sensing circuit and fed to the inverter controller. A synchronous reference frame (SRF) phase-locked loop (PLL) extracts the phase angle information (ψ) of v_{pcc} which is used in calculating the dq-axis components of $v_{pcc,pu}$ and $i_{pcc,pu}$ (i.e., $v^{(dq)}_{pcc,pu}$ and $i^{(dq)}_{pcc,pu}$). The $v_{pcc,pu}$ is compared with the voltage FRT characteristics for detecting the occurrence of voltage FRT condition. Accordingly, the FRT signal is either 1 or 0. During the steady-state operation, the real current reference of the inverter ($i^{(d)*}_{pcc,pu}$) is generated using the P_{inv} controller, while the reactive current reference ($i^{(q)*}_{pcc,pu}$) can be either generated from the PCC voltage controller for static voltage compensation or can be kept zero. During voltage FRT operation, the inverter prioritizes the reactive current as per the reactive current requirement specified in the grid code, and the real current is generated adhering to the following equation.

$$\sqrt{(i^{(d)*}_{\text{pcc,pu}})^2 + (i^{(q)*}_{\text{pcc,pu}})^2} = I^{\max}_{\text{inv,pu}}$$

where $I^{max}_{inv,pu}$ is the maximum current limit of the inverter switches. Further, using current control and sinusoidal pulse width modulation technique, the switching pulses of inverter are generated. Under any circumstances, if the PCC voltage deviates beyond the voltage FRT characteristics, the Trip command is activated and the pulses to the inverter will be stopped.

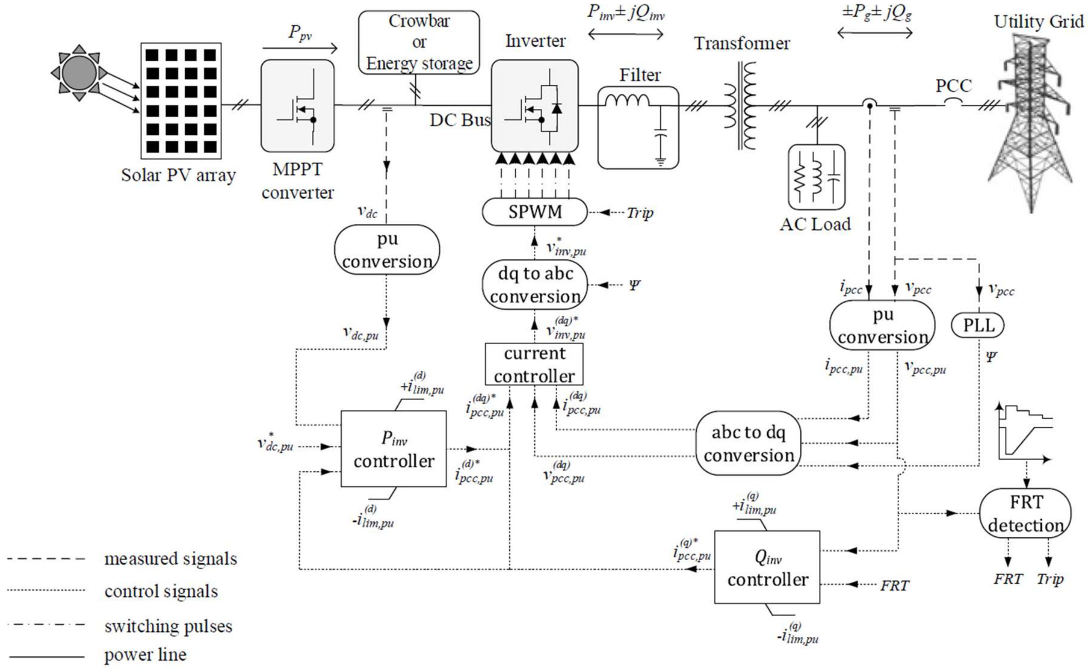


Fig 8. Schematic diagram of SPV units with voltage FRT control