Chapter 1

Introduction

1.1 Background and Motivation

The energy demand of the inflated population and continuously expanding global economy have enormously increased in the last few decades. This increased energy demand is met out by power generated through conventional energy sources; which include coal, oil and gas. Although, the fossil fuels are the primary sources of electrical power, they cause an enormous impact on the environment by injecting carbon dioxide in the atmosphere which may lead to global warming. Moreover, the fossil fuel sources are limited and it is expected that they would drain out quickly, if they are continuously used for electricity generation.

To take care of these issues, the international community have started focusing more on nonconventional energy sources known as renewable energy sources (RESs) [1],[2]. The RESs including wind, hydro, geothermal, solar, marine and biomass energies are becoming increasingly popular in distributed generation (DG) systems [3]-[5]. Among these RESs, solar photovoltaic (PV) energy conversion is the most preferred choice because of its availability, easy in installation, inexhaustibility and environment-friendly nature. The world's total installed PV capacity has reached 760 GW out of 2799 GW of total renewable energy capacity in the year 2020. By 2050, the PV global cumulative capacity is expected to contribute 11% of the worldwide electricity generation to avoid 2.3 gigatons of carbon dioxide emissions per year [6]. The PV generation is expanding with its wide acceptance due to improved manufacturing techniques, solar cell performance improvements and decreased PV panels cost [7], [8]. The PV system is one of the fastest-growing RESs integrated into the distribution system. Installing the large-scale grid-tied PV generating stations is becoming more prevalent in developed and developing countries [9]-[11]. The Government of India has also set a goal to install solar PV generation of 100 GW by 2022 [12].

A schematic diagram of grid-tied PV systems is shown in Fig. 1.1, which consists of three main parts; PV array, power electronic converters and utility grid. The characteristics of the PV arrays depend on environmental conditions e.g., solar irradiance and ambient temperature. The power electronic converters is connected between the PV array and the utility grid. The main challenges of grid-tied PV systems are related to the integration of the PV systems to the utility grid. To fulfil the flexible power control demands, the advanced control functionalities of the PV systems are required to be realized through the control schemes of power electronic converters.

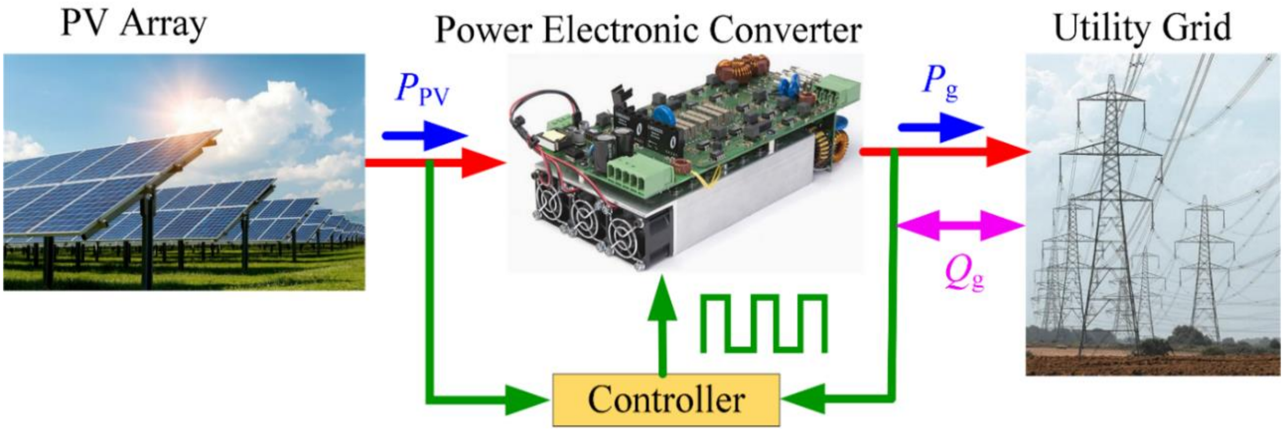
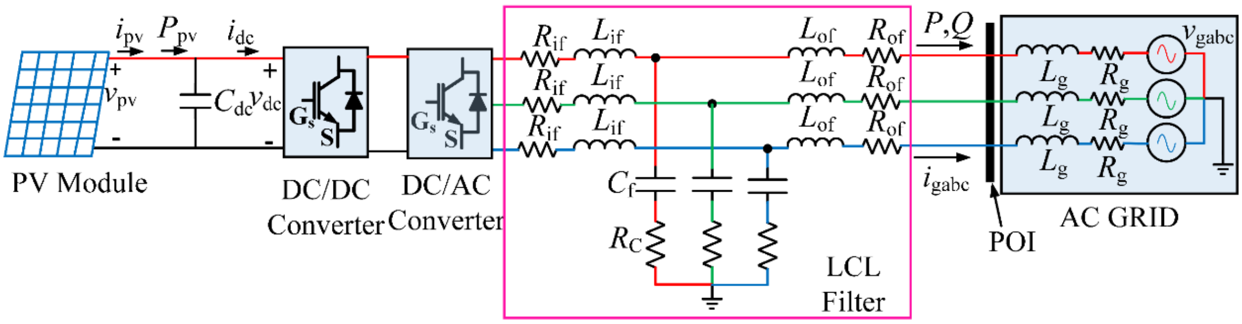
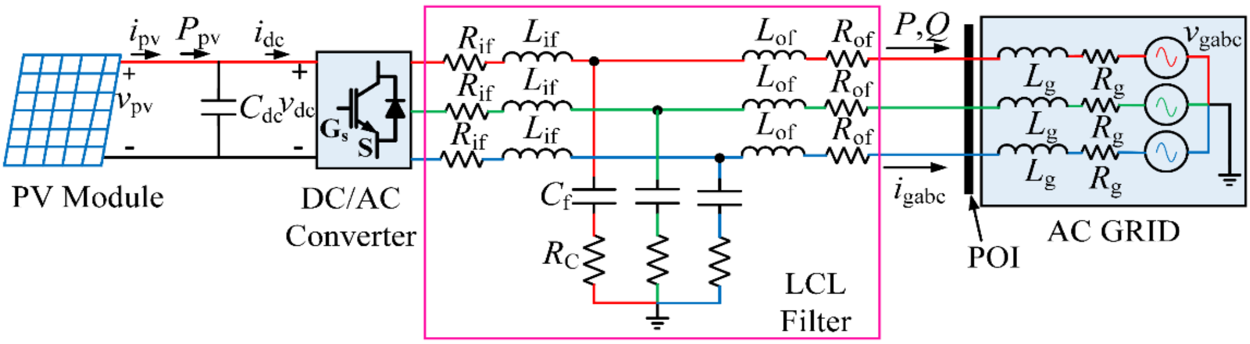


Fig. 1.1. Schematic diagram for the grid-tied PV system (P_{PV}: PV power generated, P_g: Active power delivered to the grid, Q_g: Reactive power exchanged with the grid)

The grid-tied inverter converts the DC power generated from the PV array into AC power and feed this power to the utility grid. Typically, the grid-tied PV system can be deployed by a single-stage grid-tied PV system and a double-stage grid-tied PV system [13]-[19]. Fig. 2 illustrates the general schematic of the single-stage and double-stage grid-tied PV systems. The double stage grid-tied PV system involves two power stages; the first stage is a DC-DC converter and the second stage is a DC-AC inverter. The DC-DC converter realizes the PV panel's maximum power point tracking (MPPT). The DC-AC inverter regulates the intermediate DC bus voltage and injects AC into the power grid. However, there are certain drawbacks in the double stage grid-tied PV systems; such as lower efficiency, larger size and higher cost due to the additional DC-DC stage. On the other hand, the single-stage grid-tied PV system achieves all the control functions; such as MPPT control and regulating the DC voltages and grid current through a single controller, which makes it a bit complex control design. However, the single-stage grid-tied PV systems have many advantages such as high efficiency, compact structure, low cost, small size, and low cooling requirements. These advantages become more prominent with the increase of power level of PV system. Due to these benefits, the single-stage grid-tied PV system is very popular in the case of large utility-scale PV power plants.



(a)



(b)

Fig. 1.2. System configuration of grid-tied PV system **(a)** double stage grid-tied PV system **(b)** single stage grid-tied PV system.

With the increase in grid integration of PV energy, the PV control scheme encounters greater challenges such as maintaining power quality due to the abnormal grid conditions, reliability in case fault condition and voltage fluctuations in weak grid condition, unintentional islanding, overloading of feeders etc. [20]-[23]. The power quality one of the important aspects of the grid-tied PV system. More and more attention has been paid to power quality issues of PV systems of the distribution grid such as: harmonics in grid injected currents, oscillations in grid injected active and reactive power, frequency fluctuations etc [24]-[34]. The poor power quality can cause series of problems; including increased line losses, reduced efficiency, increased production and maintenance costs, reduced product quality, decreased equipment lifespan, production interruptions and overall energy losses [35],[36]. There are many international standards for maintaining power quality in the grid-tied PV system as reported in [37]-[39]. Therefore, high-quality power has a tremendous impact in saving capital gain and thus has an economic advantage for a manufacturing company. Therefore, developing an intelligent novel control technique for the grid-tied PV system is necessary in the grid-tied PV system.

Harmonic distortion becomes a significant problem in grid-tied PV systems due to the increasing number of power electronic devices and non-linear loads in the distribution grid. Limiting the harmonic distortion is a commonly used power quality measure [41]. The wide application of power electronic devices is the main cause of harmonics in the distribution grid voltages due to their non-ideal switching behaviour [42]. The nonideal switching behaviour of power electronic converters in the grid-tied PV system impact the grid current. As a consequence, the grid injected current from the grid-tied PV system is highly affected with increased harmonics. This condition causes overloading and voltage flickering in the grid which are reported in [43]-[46]. Further, the harmonics may trigger the protection circuit and thus, the PV systems are unintentionally disconnected from the grid. Consequences of such events include considerable energy losses and challenges in the system stability in the case of large-scale grid-tied PV systems. Moreover, when the grid-tied inverter is connected to a weak grid at the point of common coupling, it may have an instability problem due to the wide variation of the grid impedance [47]-[49]. In such conditions, it becomes more difficult to maintain the harmonic components within the specified limit for grid injected current. Therefore, the grid-tied inverters should have reliable harmonic suppression capability to meet the stringent harmonics criteria.

Furthermore, grid voltage sag and swell are another critical power quality issue in the grid-tied PV system. The root causes of voltage sag are usually the faults and starting of large loads like synchronous motors. The switching of large capacitors and turning off the large loads are the leading causes of voltage swells. Thus, the utilities have developed new grid codes for the PV systems imposing on these systems to support the grid during grid voltage sag/swell [50]. In the past, the PV arrays was supposed to be isolated from the grid, when a fault occurs and the PV arrays was reconnected within several seconds, once the fault has been cleared. However, due to high PV power penetration in recent times, the same methods cannot be used because they will further deteriorate the power quality. Therefore, the PV systems are required to provide a low-voltage ride-through (LVRT) capability and remain connected to the grid-tied inverter under grid faults [51]-[56]. Consequently, the PV system must operate so that its control system efficiently maintains the power quality under the normal condition with MPPT and maintains the LVRT requirements in the grid fault mode. During LVRT conditions, the PV inverters must be capable of injecting reactive power to the grid as required.

Considering this, many grid codes are published by different international committees for transmission operators and distribution operators [57],[58]. These grid codes regulate the interaction between the utility and the PV system by monitoring the complex aspects, such as fault ride-through (FRT), active and reactive power control, islanding detection, anti-islanding de-energization and [59],[60]. Therefore, the grid-tied PV system should be capable of delivering active and power into the grid as per the requirement along with mitigating the power quality issues. The active and reactive power have some boundaries as per the rating of the system as a specification of the associated devices. The control schemes will get support by having some method for deciding the reactive power limits for PV system. The power quality issues such as; current harmonics, active and reactive power oscillations and feeding reactive power can be improved by introducing a better control strategy for the grid-tied PV system.

1.2 Literature Review

The grid-tied inverter plays a crucial role in the grid-tied PV system. It needs to extract maximum available power from the PV energy source and transfers AC power to the utility grid. To improve the grid current performance, the total harmonic distortion (THD) of the grid current should be within the restricted value, as per IEEE 1547 standards [61]. Therefore, significant investigation for appropriate control strategies are required for the current harmonics reduction.

The current control strategy for the grid-tied PV system plays an important role and many different control strategies have been introduced such as proportional-integral (PI), hysteresis band control, deadbeat control and predictive control in the synchronous rotating *dq* reference frame [62]-[64]. A dead-beat control based on current predictive correction is discussed in [62] to control the grid current for a grid-connected converter. The conventional PI controller based on *dq* reference frame reported in [63] is discussed in this section to describe the general current control structure of the grid-tied PV system. The *dq* control structure uses the *abc* to *dq* transformation module to transform the control variables from their natural frame *abc* to a frame that synchronously rotates with the grid voltage frequency. Consequently, the control variables become DC signals. The PI controllers are associated with this control structure for regulating the grid-tied PV system's *d* and *q* axes current components. A typical transfer function of a PI controller is given by

$$G_{\mathrm{PI}}(s) = K_p + \frac{K_i}{s} \tag{1.1}$$

where K_p and K_i are the proportional and integral gains of the controller. The control structure of *dq* control involving cross-coupling and feedforward of the grid voltages is shown in Fig. 1.3. Since the grid voltage feedforward is used in this control structure, the control dynamics is good during grid voltage fluctuations. The phase-locked loop (PLL) is used to estimate the grid's phase and frequency. The synchronous reference frame PLL (SRF-PLL) is the most widely utilized solution. This technique provides excellent results under balanced grid conditions. However, the SRF-PLL cannot estimate the accurate phase and frequency under unbalanced and distorted grid voltage conditions.

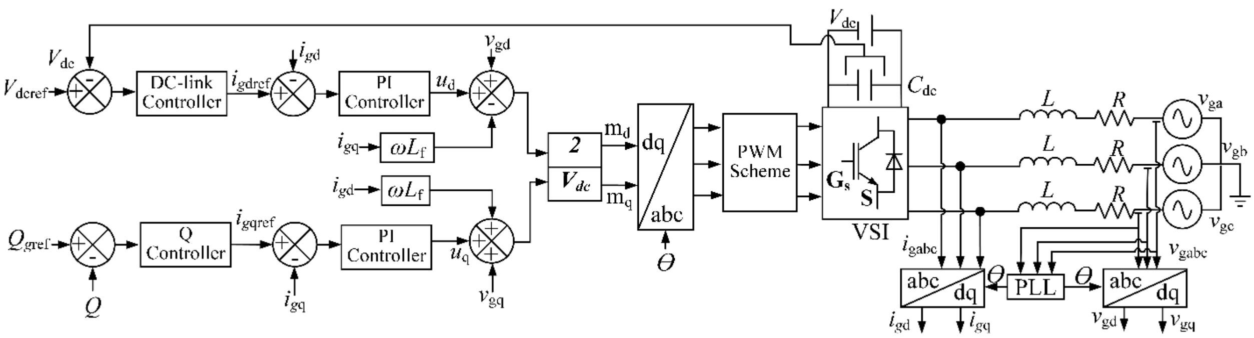


Fig. 1.3. A general structure for *dq* frame control using cross-coupling and voltage feedforward terms.

The PI controller works properly in normal grid conditions in the conventional control schemes. However, in distorted grid conditions, it has several drawbacks as follows. The PI current controller has a steady-state error in the *dq* reference frame, which cannot be eliminated.

The PI current controller used in the PV system cannot used where the lower order grid current harmonics are required to be suppressed as it cannot track the sinusoidal signals under distorted grid voltages.

- The PI controllers have poor performance due to cross-coupling between *d* and *q* coordinates, leading to instability issues, when multiple inverters are connected.
- Under unbalanced grid voltages, the dq reference frame current control becomes complex as it requires positive and negative sequence components to extract the grid current.

Four PI controllers are required for the positive and negative sequences based on the double synchronous reference frame, which increases the complexity and computational load.

A model-based current control (MBCC) strategy is discussed in [64] for a three-phase grid-connected inverter. This control strategy is based on controlling the inverter current in *dq* reference frame using current oriented PI controller rather than the voltage-oriented PI controller. The control structure diagram of the MBCC strategy presented in [64] is shown in Fig. 1.4. In this controller, the PI controllers used are current-oriented, where the input is the grid current error and the output is the reference inverter current. The grid current regulation is achieved by the PI controllers, and the inverter current regulation is performed by the MBCC loop. However, it is challenging to implement the MBCC in industrial applications, which require large sized passive filters. Moreover, the MBCC does not guarantee a constant and high switching frequency during the entire sampling period. Therefore, there are irregular switching frequencies or large current ripples. To take care of these, expensive digital signal microcontrollers or large-sized filter elements are required to achieve high performance. In [65], *P-Q* capability curves of the PV inverter have been presented for deciding the active and reactive power limit for the controller considering the variation of solar irradiance, temperature, DC voltage and modulation index. However, the capability curve of the PV inverter in ideal conditions has been considered in ideal conditions by neglecting the losses in the inverter, transformer and resistive part of the filter. The real power generated by the PV system has been considered to be equal to the grid injected real power. At the same time, the losses in grid-tied PV systems have a significant role in formulating the capability curve, which has not been considered.

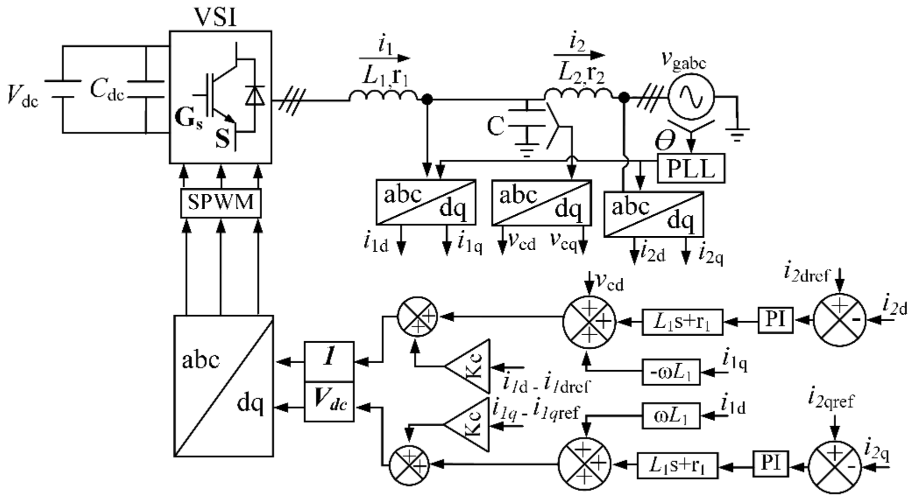


Fig. 1.4. Block diagram of the model-based current control (MBCC) strategy.

1.2.1 Control Strategy of Harmonic Compensation for Grid Current

Over the last two decades, current harmonic compensation in the grid-tied PV system has become an important concern in various research groups. Many control strategies have been implemented to attenuate the grid current harmonics for grid-tied PV systems [66]- [78].

The control strategies can be mainly grouped into two categories: 1) control strategies based on the current controller to obtain high gains at harmonic frequencies and 2) control strategies using feed-forward terms in the control loop. The proportional feedforward output currents can compensate the current harmonics caused by non-linear loads [66], [67]. However, these methods cannot suppress the current harmonics under distorted grid voltages. To achieve a fixed-switching frequency and mitigate the steady-state error, the proportional resonant (PR) controller is generally utilized [68]-[71], which is capable of achieving zero steady-state error in AC reference by introducing an infinite gain at the resonant frequency. In [66], a repetitive controller (RPC) based on the internal model principle is discussed for grid-connected PV inverters to suppress the current harmonics. The control structure of the RPC presented in [66] is illustrated in Fig. 1.5. As shown in Fig. 1.5, the RPC is plugged into a PR-based current controller to mitigate the dead time harmonics and regulate the fundamental grid current component. The RPC can suppress all the frequencies below the resonant frequency. The transfer function of the entire current controller with an RPC harmonic compensator is expressed as

$$G_{\mathrm{op}}(s) = \underbrace{K_{\mathrm{p}} + \frac{K_{\mathrm{i}} s}{s^2 + \omega_0^{\,2}}}_{G_{\mathrm{PR}}(s)} + \underbrace{K_{\mathrm{rpc}} \frac{e^{-T_0 s} Q(s)}{1 - e^{-T_0 s} Q(s)}}_{G_{\mathrm{RPC}}(s)} \tag{1.2}$$

where K_{rpc} represents the control parameters of the RPC harmonic compensator, ω_0 is the fundamental grid frequency and T_0 is the grid fundamental period. Q(s) is a lowpass filter which is included in the RPC compensator to eliminate the high-frequency harmonics.

However, the major limitations of RPCs are that their dynamic response is much slower than that of a PI and PR controller. Since the RPCs are tuned to reject the unwanted harmonics, which are integral multiples of the fundamental frequency, it may lead to false operation of the grid-tied PV system under grid frequency variation. Moreover, the performance of the RCs rapidly deteriorates during the transient condition due to the changes in the grid frequency. In addition, designing a RPC is a challenging task as any numerical error or inaccurate modeling may lead to unstable controller operation. The RPC also increases the computational burden on the controller.

To avoid the above-mentioned drawbacks of the RPC, an alternative control scheme is required to reduce the grid current harmonics. The resonant controller (RC) has been widely applied in the grid-tied PV system to suppress multiple harmonics at resonant frequency because of its flexibility and computation efficiency. Moreover, the RCs can be used as harmonic compensators to improve the grid-connected PV system's power quality. A PR controller for a single-phase grid-tied inverter is reported in [72] to regulate the grid current by controlling either the DC-link voltage or the active/reactive power injected into the grid. Fig. 1.6 illustrates RC's general control structure block diagram [72]. When the grid voltage does not contain harmonic frequency components, the PR controller allows tracking of the fundamental reference current with zero steady-state error. The RC is connected in parallel with the PR controller to reduce selected lower-order harmonics. The open-loop transfer function of the entire current controller is obtained as

$$G_{\mathrm{op}}(s) = \underbrace{K_{\mathrm{p}} + \frac{K_{\mathrm{i}} s}{s^2 + \omega_0{}^2}}_{G_{\mathrm{PR}}(s)} + \underbrace{\sum_{h} \frac{K_{\mathrm{i}}^{\mathrm{h}} s}{s^2 + \omega_0{}^2}}_{G_{\mathrm{RC}}(s)} \tag{1.3}$$

where K_{p} and K_i are the controller coefficients of the PR controller. $k_{\mathrm{i}}^{\mathrm{h}}$ is the controller coefficients of the individual RC harmonic compensator and h is the harmonic order.

However, the RCs have the drawback that they are sensitive to the resonant frequency due to the infinite gain, which leads to system's instability. Also, under highly distorted grid voltage conditions, the RSCs are unable to suppress the grid current harmonics. Also, the bandwidth of the RCs are narrow due to the high gain frequency slope around the resonant frequency. Due to this narrow bandwidth, it becomes difficult to implement RCs using either analog or digital signal processors (DSP).

Some researchers have developed advanced control strategies to address the above issues in RSCs and RCs [68]-[71]. In [68], a quasi-proportional resonant (QPR) controller is discussed to eliminate the steady-state current tracking error of the capacitive coupling grid-connected inverter. An adaptive QPR (AQPR) controller is implemented for a single-phase grid-connected converter in [69]. However, the control strategies in [68] and [69] have been considered for a constant DC voltage source. Also, the compensation of grid current harmonics of the PV system has not been discussed in these works. A multifrequency PR controller is reported in [70] for reducing the current harmonics of a grid-connected inverter. However, the performance of PR controllers under grid voltage sag is not discussed in this work. Moreover, these control schemes necessitate PLL block, which increases the system complexity in practical implementation and leads to mal-operation under distorted grid voltages. In [71], an adaptive resonant controller based on a second-order generalized integrator frequency locked loop is presented to regulate the grid current of a grid-tied inverter. However, the PV array voltage is assumed to be constant, and the MPPT is not considered in this work. Also, the negative effect of the unbalanced voltage sags on active and reactive power injection into the grid is not discussed.

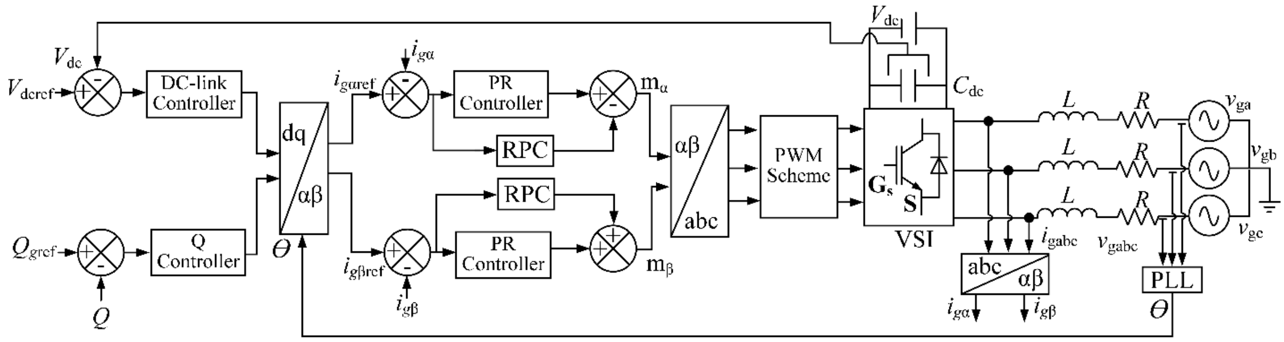


Fig.1.5. Control structure representation block diagram of the repetitive controller (RPC).

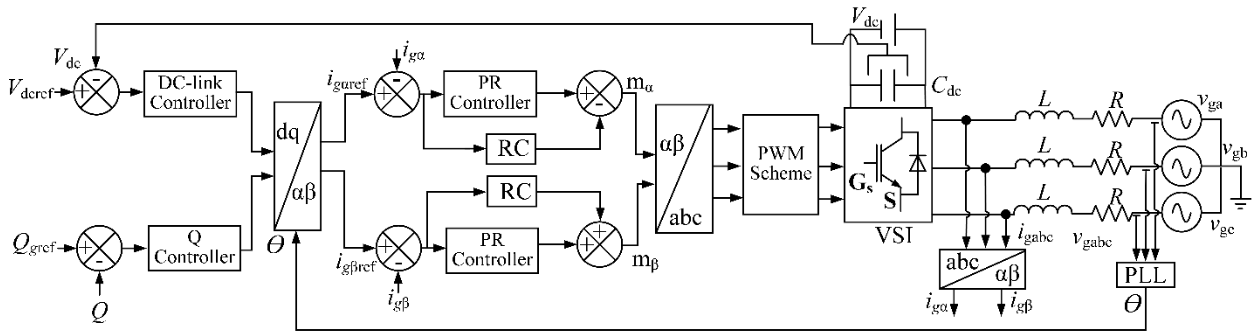


Fig. 1.6. Control structure block diagram of resonant controllers (RC).

Considering the aforementioned discussions, it is observed that all of the control strategies discussed in [65]-[78] require a PLL-block for grid voltage synchronization. Also, these techniques take more time to tune the PLL parameters for achieving satisfactory performance. Furthermore, the PLL dynamics negatively influence the grid current control with low-frequency oscillations, leading to instability in the system. Further, in practical implementations, these computationally complex techniques require a lot of memory, which becomes a cumbersome design challenge for implementation using a DSP. The effective harmonics mitigations, fast dynamics adaptability to grid frequency variations and low computational burden are difficult to achieve simultaneously.

1.2.2 Control Strategy for Reduction of Active and Reactive Power Oscillations

When the grid faults occur, the performance of the grid-tied PV system deteriorates. As a result, the negative sequence components appear in the grid voltages. The control strategy for the grid-tied PV system under balanced grid voltages lacks the control of negative sequence components. Due to the interaction between the negative sequence component grid voltages and currents, the active and reactive power injected into the grid oscillates at twice the grid frequency. Several control schemes have been reported in [79]-[88] to control the active and reactive power of the grid-connected voltage source inverter (VSI). These control schemes are based on current control, which can regulate active and reactive powers by exploring the direct relationship between the delivered power and the injected currents. The current references are calculated based on the active power; reactive power injected into the grid and the positive and negative sequence grid voltages. These current controllers are designed in the *dq* reference frame and may contain double fundamental frequency oscillations. In order to supply the grid with a constant active power under unbalanced voltages, it is required to inject three-phase currents with different amplitudes, which results in double fundamental frequency oscillations in the *dq* components of the grid current. However, these control schemes have not been examined under abnormal grid conditions. A direct power control (DPC) scheme to control the instantaneous active and reactive powers for a grid-connected voltage source converter is discussed in [79]. However, the steady-state performance of this control scheme deteriorates under highly distorted current conditions and in cases where significant oscillations are present in active and reactive power under the unbalanced grid voltage conditions. A direct active and reactive power control scheme for a three-phase grid-connected VSI using a port-controlled Hamiltonian system is reported in [80] to reduce the THD of the grid current. However, this scheme still has active and reactive power ripples under unbalanced grid voltage conditions. As the active power oscillations are reflected as a ripple in the DC-link voltage and can cause sudden disconnection of the VSI, the grid-tied PV performance can be enhanced by reducing the power oscillations. In [81], a current control scheme using a double sequence frame current controller is presented for a grid-connected distributed generation under unbalanced grid voltages. The grid-connected distribution generation system with the double sequence frame current controller is shown in Fig. 1.7. The double sequence frame current controller eliminates the active and reactive powers under the unbalanced grid voltage conditions.

The drawbacks of the double synchronous reference frame control scheme are as follows: i) there is a trade-off between the elimination of active and reactive power oscillations and grid currents; that is, the power oscillations are reduced with distorted grid current, ii) as both the positive sequence and negative sequence components of grid voltages are used in the controller, the implementation complexity and computational burden on the digital controller increase.

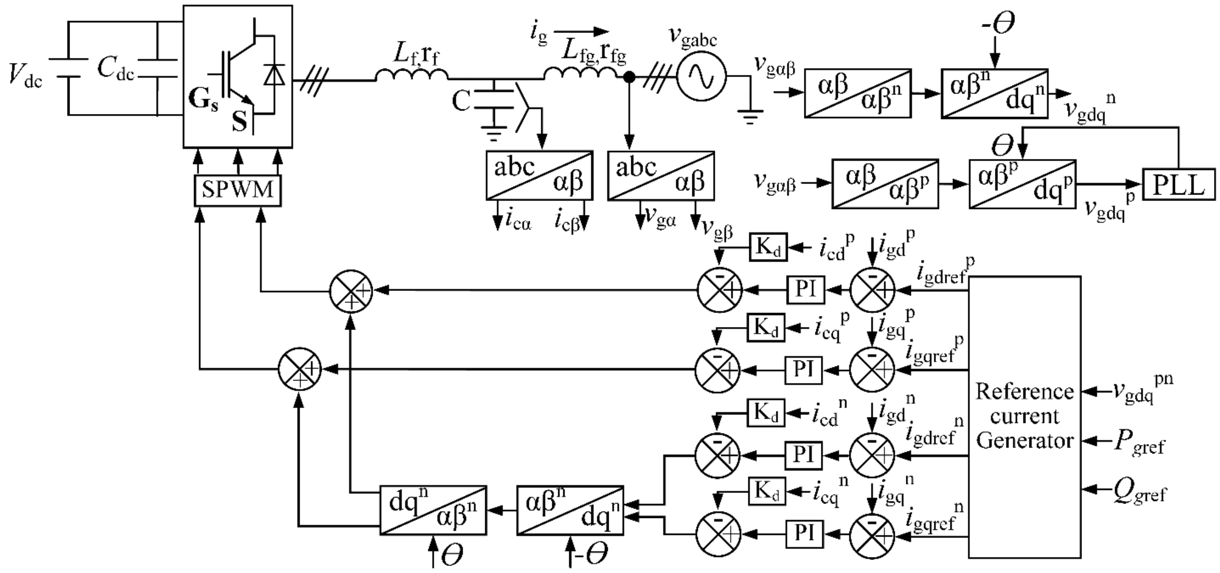


Fig. 1.7. Control structure block diagram of double synchronous frame current controller.

1.2.3 Control Strategy for Enhancement of LVRT

Research efforts on the LVRT capability of grid-tied PV inverters have grown in recent years to prevent the disconnection of grid-tied PV systems. LVRT requirement is the capability of the grid-tied PV inverters to stay connected to the grid and give reactive power support during the grid fault conditions with large voltage sag. There are different grid codes applicable for the required criteria of LVRT operation. One of the specific grid codes requires an immediate revamping of active and reactive powers to the pre-fault values once the voltage has recovered to its nominal value. Other LVRT grid codes require an increased reactive power injection by the PVs to provide voltage support to the grid. The operators demand this grid support due to the increasing PV penetration level in the distribution/transmission network. Many countries like Germany, China, UK, Italy, Denmark, etc., are continuously updating their LVRT grid codes based on their grid infrastructure to cope up with the rapidly expanding use of RESs [89]. The LVRT grid codes for Germany is demonstrated in Fig. 1.8. According to the German code, the PV inverter should ride through the fault for a maximum of 625 ms under the grid faults, i.e., when the grid voltage has dropped to 20% of the rated grid voltage. This code allows the PV units to remain connected without tripping if the voltage at the point of common coupling has recovered to 90% of its rated value within 1500 ms after a grid fault. If the grid voltage is between 50% to 90%, the PV unit should inject reactive current as a function of voltage sag. If the voltage sag is more than 50%, the DG unit should inject 100% reactive current. Several methods exist to enhance the LVRT capability of PV systems by using additional components like energy storage systems such as battery energy storage systems and capacitor energy storage systems, fault current limiters and static synchronous compensators [90]-[93]. However, the energy storage systems do not consider reactive current injection and flexible AC transmission system devices such as static compensators only inject reactive power to support the grid during fault. Moreover, the overall cost and complexity of the system also increase because of the addition of these hardware components. During the injection of reactive power under LVRT conditions, various challenges have been observed, such as inverter overcurrent, overvoltage in healthy phases, oscillations in active and reactive power, DC-link voltage and distortion in injected currents. Various control strategies have been discussed in the literature to overcome these issues associated with LVRT [94]-[102]. A control strategy that eliminates the double grid frequency oscillation in active power and dc-link voltage with the capability of injecting sinusoidal current is discussed in [94]. The block diagram of this control strategy is illustrated in Fig. 1.9. Under unbalanced grid faults, this control strategy formulates flexible active and reactive current references. Moreover, it involves a non MPPT operating mode under severe faults, when the maximum power from the PV array results in overcurrent in the inverter. However, in this control strategy, both the positive and negative sequence grid voltages are used, thus, the computational burden on the controller increases. A current reference strategy for asymmetrical fault control is discussed in [95] to calculate power references and controller gains while simultaneously complying with converter current limitation and fulfilling the recently developed grid codes requirements. This method is tested for asymmetrical grid faults considering the requirements for dynamic voltage support of the recently revised German grid code and the next-generation grid codes. The control strategies discussed above are used for the ride thorough operation of the grid-tied PV systems during balanced grid voltage sag by injecting reactive power into the grid without focusing on the improvement of power quality in the grid-tied PV system. However, during the unbalance grid voltage sag, the regulation of grid current and minimization of active power fluctuations becomes challenging. In [96], an LVRT control strategy based on positive/negative sequence droop control is discussed for the grid-interactive microgrid to ride-through voltage sags with not only inductive/resistive but also with complex line impedance. This control strategy consists of a voltage controller, current controller, a conventional droop control, a virtual impedance loop and a positive/negative sequence droop scheme to coordinate the power injection during voltage sags. However, the implementation complexity and the computational burden on the controller increase due to the multiple control loops. In [97], a feedback linearizing control strategy based on sliding mode compensation is discussed to operate a grid-connected photovoltaic system under grid faults to meet LVRT requirements. However, during the LVRT, the system's state can be significantly far away from the desired operating point with this control strategy. As a result, the dynamic response of the PV system is slow. Consequently, it may cause an LVRT failure, such as the abrupt current spike, which may exceed three times or more of the rated current and sudden surge of the DC-link voltage. This method provides active and reactive power support during the symmetrical grid faults.

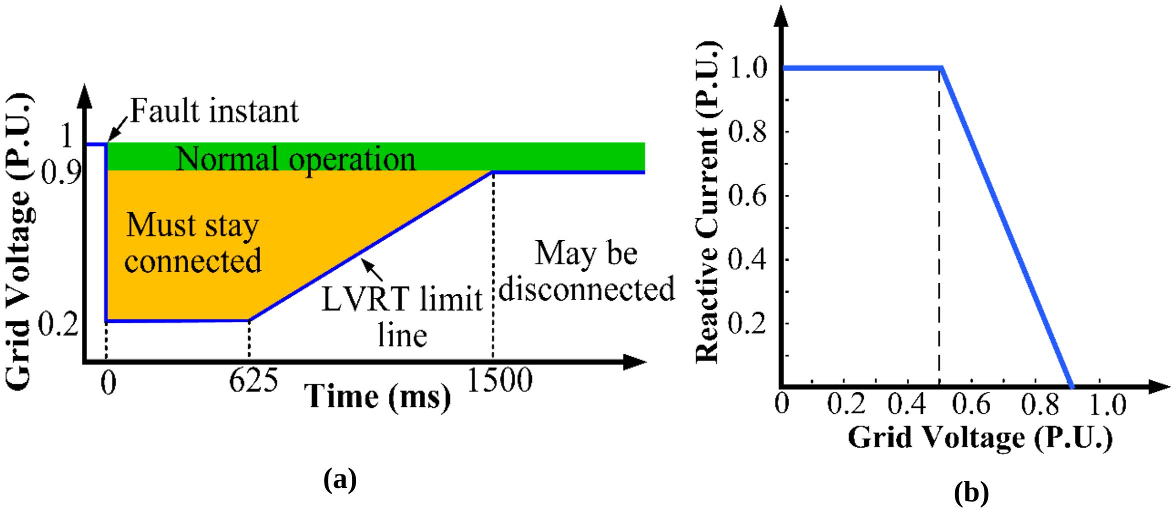


Fig. 1.8. LVRT requirement **(a)** LVRT grid codes, **(b)** grid codes for reactive power injection.

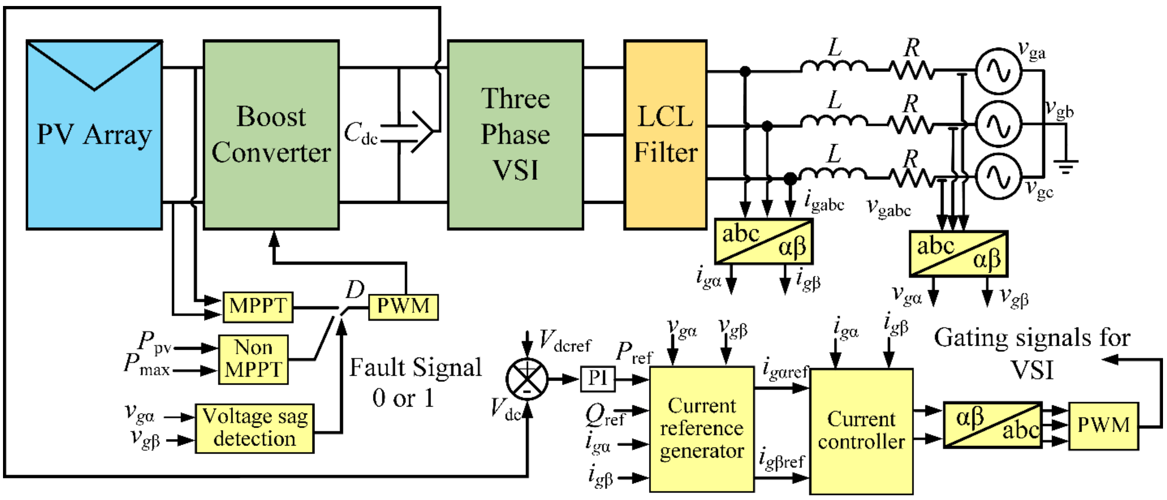


Fig. 1.9. Block diagram of control strategy for enhancement of LVRT capability.

The issues and limitations of these control strategies are as follows: i) the current limitation strategies proposed by most authors have considered active power injection only, ii) both positive and negative sequence current components are used in the controller, which increases the computational burden on the controller, iii) the power quality issues, like oscillations inactive, reactive powers and DC-link voltage and THD in currents, have not been discussed simultaneously. It is observed from the above discussions that the design complexity and implementation of adequate control schemes is a challenging task for the satisfactory operation of PV in abnormal grid conditions.

1.3 Challenges in the Grid-Tied PV System

The grid-tied PV system plays a vital role in the renewable power generation systems, which transfers the DC power generated from the PV panel into the DG. The grid-tied PV system presents challenges and issues that have to be considered to ensure PV system reliability with better power quality. Various power quality issues such as grid current harmonics, power oscillations, grid frequency variation and LVRT requirement occur due to unbalanced and distorted grid voltages in the grid-tied PV system. To obtain better power quality, researchers have developed some linear control schemes to address the power quality issues. However, these control schemes require PLLs, and thus increase the system complexity in practical implementation and lead to maloperation under distorted grid voltages. After carrying out a detailed literature study, the challenges of the existing grid-tied PV systems are summarized as follows:

- The existing control strategies are used to determine the operating point according to the *P-Q* capability curve of VSI under ideal conditions by neglecting the losses in the VSI. Also, the *P-Q* capability curves are evaluated under the non-MPP conditions.
- The existing control strategies do not explore the P-Q capability curves for the reactive power limits of the grid-tied PV system at MPP under variable atmospheric conditions.
- Conventionally, the PI-based current controllers are employed for the grid-tied PV system to regulate the grid current under balanced grid voltage conditions. However, it fails to follow a sinusoidal reference without the steady-state error under unbalanced or distorted grid voltage conditions.
- The conventional PI-based current controllers have poor performance due to cross-coupling between d and q coordinates.
- Under unbalanced grid voltage sags and swells, the implementation of the PI-based current controller is complex. It requires positive and negative sequence components to extract the grid current.

- The incapability of the PI-based current controller in handling the negative-sequence during asymmetrical grid faults may lead to over-current in some phases or harmonics in the delivered current due to lack of effective current limiters.
- The conventional RC has an infinite gain at the resonant frequency, thus, it is challenging to realize and difficult to implement it practically. Also, this controller is sensitive to the resonant frequency, which may lead to system instability.
- The bandwidth of the conventional RSC is narrow due to the high gain frequency slope around the resonant frequency. Due to this narrow bandwidth, the conventional RSC presents a challenge in digital implementation.
- The current loop gain of the existing control strategies decreases under weak grid conditions (large grid impedance); which reduces the system phase margin, bandwidth and stability.
- Most of the existing control strategies available in the literature are based on PLL, which is used for grid synchronization. However, these control strategies affect the grid-tied PV system's dynamic performance under weak grid conditions.
- Due to the presence of PLL, the computational burden and implementation complexity increase on the processor, which is not suitable for a low-cost microcontroller. Also, due to the non-linear behaviour of PLL, the tuning process is challenging and time-consuming.
- User-defined active and reactive powers references are considered in the existing control strategies. Therefore, selecting suitable active and reactive powers values during the voltage sag is challenging.
- With the existing control strategy, the active and reactive powers oscillate at twice the grid frequency under unbalanced grid voltages.
- These power oscillations contain a series of low-order frequency components, which are reflected in the frequency components of the amplitude of the inverter current and thus increase the THD of the grid current.
- The oscillations in active and reactive powers may lead to large fluctuations in the DC-link voltage, which may degrade the performance of the grid-tied PV system by deteriorating the power quality, increasing the power losses of the grid-tied PV system, shortening the life span and reducing the reliability of PV panels.
- During a grid voltage fault in the grid-tied PV system, the PV array operating point is required to move away from the MPP to a new equilibrium point above MPP

voltage and thus, the post-fault clearance PV active power decreases. This increases the probability of instability in the grid-tied PV system. Also, the determination of this operating point is always a challenge in the case of the grid-tied PV system.

- It is challenging to regulate the grid current for achieving LVRT operation by injecting reactive power into the grid during the unbalanced grid voltages.

1.4 Thesis Objectives

The objective of this thesis is to make a study about the power quality issues of single-stage three-phase grid-tied PV system. It is observed from the literature study that the grid-tied PV system with the existing control strategies have several power qualities issues. They are not capable of 1) reducing grid current harmonics under distorted and weak grid conditions; 2) minimizing active and reactive power oscillations and 3) enhancing LVRT capability during grid fault conditions. Further, the existing controllers do not implement any capability curve's reactive power limit under MPP condition. Many researchers have presented different control techniques for the grid-tied PV system over the past decade to address these issues. However, all these issues have not been taken care of in a single control strategy of the grid-tied PV system. Moreover, most of the existing control strategies have not considered the non-linear current-voltage characteristics of PV voltage sources. In addition, none of the existing control strategies have achieved the simultaneous suppression of grid current harmonics, enhancement of LVRT capability and elimination of power oscillations under distorted and weak grid conditions. Further, the above power quality issues have not been considered in the grid-tied PV without a PLL unit. Hence, there is a need for an advanced control strategy for the grid-tied PV system to take care of the above-said issues.

In order to include the aforementioned control features in the grid-tied PV system’s control strategies, three advanced control strategies and an improved mathematical methodology is developed in this work. The proposed mathematical methodology is utilized to derive the *P-Q* capability curve of the grid-tied PV system for managing the reactive power injection into the grid at MPP conditions under various environmental conditions. This methodology is used to obtain the reactive power limits of the grid-tied PV system by evaluating all the possible sets of operating points within the stable region of the *P-Q* capability curve. An interlinked control strategy for a grid-tied PV system has been presented to regulate the active and reactive powers injected into the distribution grid. However, the developed control strategy and the improved methodology operate during the balanced grid voltage conditions. Also, the developed control strategy is based on PI controller, which faces issues to regulate the grid current harmonics under distorted grid voltages.

The first advanced control strategy is based on PLL, which simultaneously reduces the grid current harmonics and power oscillations under distorted grid voltage conditions. The proposed control strategy consists of an advanced proportional multi-resonant (APMR) controller and compensator for grid voltage sag (CGVS). The APMR controller has two compensators; proportional resonant compensator (PRC) and multiple resonant harmonic compensator (RHC). The PRC is used to track the fundamental component of grid current with zero steady-state error and the RHC is used to attenuate the selected grid current harmonics. To overcome the issues of conventional PMR (CPMR) controller such as infinite gain at resonant frequency, narrower bandwidth, difficulty in digital implementation and sensitivity to grid frequency deviation, the proposed APMR controller is designed by modifying the control structure of the CPMR controller. The modification is done by including a damping factor (ξ) to the transfer function of the CPMR controller. With the above modifications, the advantages of the proposed APMR current controller are:1) it can reduce the grid current harmonics under highly distorted grid voltages, 2) it has finite gain at the fundamental resonant frequency and 3) it can achieve wider bandwidth, which makes easier for digital implementation. These improvements in the proposed APMR controller characteristics are suitable for reducing grid current harmonics under distorted grid voltages. Further, the active and reactive power oscillations due to unbalanced grid voltages are eliminated by integrating a CGVS with the APMR controller. The CGVS is designed by including a band-reject filter in the PLL loop to eliminate the oscillations in the active and reactive powers. In order to achieve faster-tracking speed and better MPP tracking accuracy under variable environmental conditions, an adaptive step size INC (ASINC) MPPT algorithm is implemented with the proposed control strategy.

Furthermore, to consider other points associated to PLL such as more significant computational burden, implementation complexity and more extensive tuning of control parameters, the second advanced control strategy based on PLL-less technique is proposed in this work. The proposed PLL-less control strategy is used to mitigate grid current harmonics and power oscillations simultaneously for the grid-tied PV system under distorted grid voltage conditions. The proposed APMR controller is integrated with a phase compensated reference current generator (PCRCG) to reduce the grid current harmonics and power oscillations. The proposed PLL-less control strategy is achieved after some control structure modifications in the APMR controller. The PCRCG generates the reference grid current for the APMR controller with grid voltages ($v_{g\alpha}$ and $v_{g\beta}$), active power and reactive power as inputs. The PCRCG consists of a bandpass filter that compensates the phase angle of the grid voltages (vgα and vgβ) to eliminate active and reactive power oscillations under unbalanced grid voltages. The synchronization task is embedded in the PCRCG, making the grid-tied PV system PLL-less or self-synchronizing. Thus, the computational burden on the digital controller reduces.

During grid faults, the control structure of the aforementioned PLL-less control strategy is modified to develop the third advanced control strategy which successfully achieves enhanced LVRT operation, reduced grid current harmonics and negligible power oscillations simultaneously under weak and distorted grid voltages. The proposed PLL-less control strategy consists of an active power regulator (APR) with dynamic reactive power support (DRPS) controller, which enhances the LVRT capability of the grid-tied PV system during unbalanced grid faults. Further, an advanced phase compensated multi-resonant (APCMR) controller integrated with the APR and DRPS controllers reduce the grid current harmonics under distorted and weak grid conditions. The proposed APCMR controller is designed by adding a phase leading angle to the transfer functions of the APMR controller, which is used to reduce grid current harmonics under distorted and weak grid conditions.

This thesis's major novelty is enhancing the power quality of a grid-tied PV system under different abnormal conditions. The objectives of the thesis can be summarized as follows

- **Development of an improved methodology to derive the P-Q capability curve of the grid-tied PV system at MPP condition.**

An improved mathematical methodology is proposed to derive the P-Q capability curve of the grid-tied PV system for managing the reactive power injection at MPP conditions. The proposed methodology is used to obtain the reactive power limits of the grid-tied PV system.

- **Development and implementation of a PLL-based control strategy for simultaneous reduction of current harmonics and power oscillations.**

The first control strategy based on PLL reduces the current harmonics and power oscillations simultaneously under distorted grid voltage conditions. In this control strategy, the APMR controller with CGVS co-ordinately operates to reduce the grid current harmonics and power oscillations simultaneously.

- **Development and implementation of an advanced PLL-less control strategy for simultaneous reduction of current harmonics and power oscillations.**

The second control strategy based on the PLL-less technique is proposed to simultaneously reduce grid current harmonics and eliminate power oscillations under distorted grid voltage conditions. This control strategy has an APMR current controller integrated with the PCRCG and operated in a coordinated way to reduce the current harmonics and power oscillations simultaneously.

- **Development and implementation of an advanced PLL-less control strategy for simultaneous reduction of current harmonics, power oscillations and enhancement of LVRT operation.**

Some control structure modification develops the third control strategy from the second control strategy. The third control strategy is proposed to simultaneously reduce grid current harmonics, eliminate power oscillation, and enhance LVRT operation under distorted and weak grid conditions.

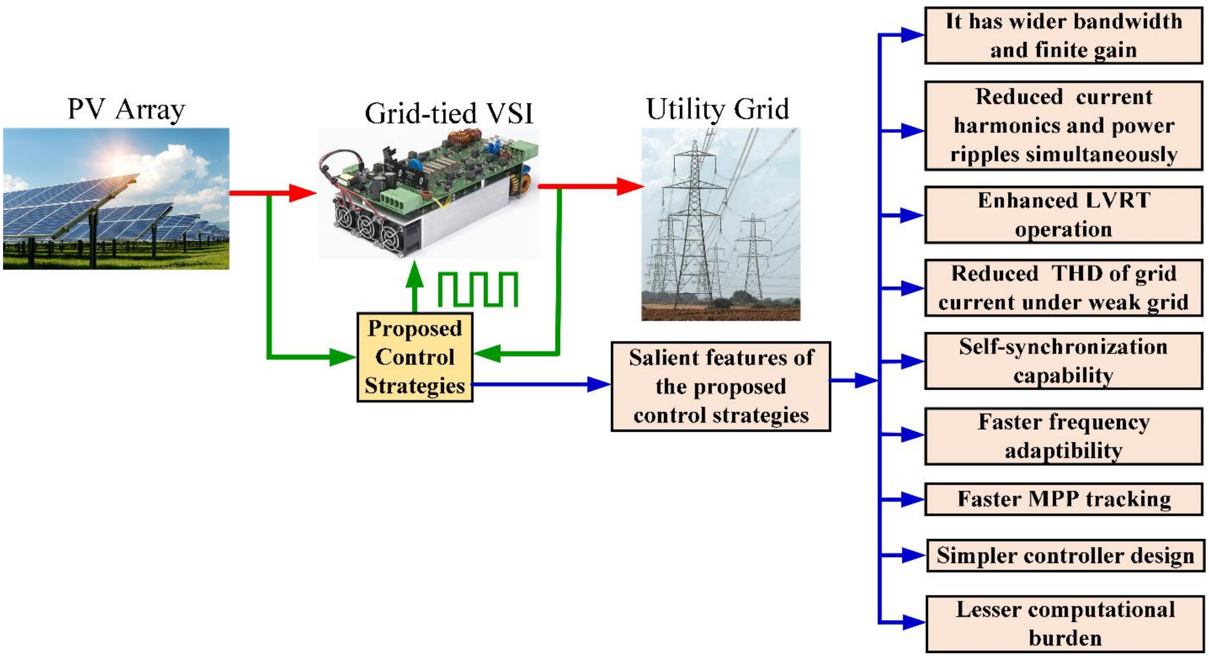


Fig. 1.10. Block diagram representation of the proposed control strategies for grid-tied PV system.

The block diagram representation of the proposed advanced control strategies and its salient features is demonstrated in Fig. 1.10. In brief the salient features and advantages of the control strategies presented in this thesis are;1) it can reduce grid current harmonics and power ripples simultaneously, 2) it enhances the LVRT operation under weak grid conditions, 3) it can achieve wider bandwidth and achieve finite gain, 4) it has reduced the computational burden due to the elimination of PLL, 5) it has better frequency adaptability under grid frequency variations and 6) it can achieve enhanced LVRT operation of grid-tied PV system under unbalanced grid faults.

The various issues discussed in the literature study have been taken care of in this work using advanced control strategies. The laboratory prototypes are developed to verify the effectiveness of the proposed control strategies are evaluated under adverse grid conditions, such during harmonically distorted grid voltages, variable grid impedances (weak grids), various grid faults and grid frequency variations.

1.5 Thesis Organization

Apart from this chapter, the thesis contains five more chapters. A brief discussion of the remaining chapters are outlined as follows.

Chapter 2 presents an improved methodology to derive the *P-Q* capability curve of the grid-tied PV system, which is used to find the reactive power limits at MPP under different atmospheric conditions. A detailed mathematical formulation is derived to obtain the *P-Q* capability curve and determine the reactive power limits at MPP conditions. A coordinated PI-based control strategy for the grid-tied PV system has been implemented to regulate active and reactive powers injected into the distribution grids. The improved methodology provides the basis for selecting the reference to the controllers and accordingly managing the active and reactive power injection into the grid. A laboratory prototype is developed and implemented using an OPAL-RT digital simulator to verify the effectiveness of the proposed methodology.

Chapter 3 presents the first advanced control strategy to reduce grid current harmonics and minimize active and reactive power oscillations simultaneously for a grid-tied PV system under distorted grid voltage conditions. The proposed control strategy consists of an APMR current controller based on resonant control approach and a CGVS, which is implemented using a PLL block for grid synchronization. A detailed discussion on the mathematical modeling of the APMR controller and CGVS is also presented. Due to the wider bandwidth and finite gain at the resonant frequency of the proposed APMR controller, it achieves superior harmonic suppression, power ripples reduction and faster frequency tracking capability as compared to the conventional PMR controller. Furthermore, the frequency response analysis of the proposed APMR controller with variable control parameters is discussed to evaluate the optimal values of the control parameters. An ASINC MPPT controller is incorporated with the proposed control strategy for faster tracking of MPP under different environmental conditions. A 3.8 kW laboratory prototype is developed and implemented using OPAL-RT OP-4510 digital simulator to verify the effectiveness of the proposed control strategy.

Chapter 4 presents the second advanced control strategy to mitigate grid current harmonics and power ripples of the grid-tied PV system under distorted grid voltages without PLL. The coordinated operation of the proposed APMR controller and PCRCG is used to reduce the grid current and eliminate the active and reactive power oscillations under distorted grid voltage conditions. A detailed discussion of the mathematical modelling of the proposed control strategy is also presented. A synchronization unit is also included in the proposed control strategy. Due to the elimination of the PLL block, the proposed PLL-less control strategy reduces the computational burden and implementation complexities on the digital controller. A step-by-step design procedure is discussed to determine the optimal values of the control parameters of the proposed APMR controller. The experiments are carried out to verify the feasibility and validity of the proposed control strategy on a laboratory prototype of 3.65 kW and implemented using OPAL-RT OP-4510 digital simulator. A comparison is made among the existing control strategies and the proposed PLL-less control strategy. It is observed that the performance of the proposed PLL-less control strategy is superior in terms of harmonics reduction, power ripple elimination, faster frequency adaptability and lesser computational burden.

Chapter 5 presents the third advanced control strategy to reduce the grid current harmonics, eliminate the power ripples and enhance LVRT capability of the grid-tied PV system under distorted and weak grid conditions. To develop the APCMR controller, some control structure modifications are done in the APMR controller to reduce the grid current harmonics under weak grid conditions. Due to the wider bandwidth, increased phase margin and finite gain features, the proposed APCMR controller gives better harmonic attenuation capability than the conventional PMR controller. The proposed control strategy achieves enhanced LVRT operation of the grid-tied PV system by incorporating an APR with DRPS controller. As the synchronization mechanism of the grid-tied PV system is included in PCRCG, the requirement of PLL can be avoided in this control strategy. Further, the frequency response analysis of the proposed APCMR controller is discussed under variable grid impedances. The proposed PLL-less control strategy has been validated experimentally through a 4.3 kW PV power laboratory setup implemented using OPAL-RT digital simulator. The experimental results obtained through the proposed PLL-less control strategy demonstrate significant improvement in LVRT capability, grid current harmonics reduction and power oscillations reduction as compared to the conventional PLL-based control strategy.

Chapter 6 summarizes the main findings and conclusion of the thesis, which also outlines the directions for future work.