CHAPTER-2
OVERVIEW OF GRID CONNECTED PHOTOVOLTAIC SYSTEM

Now-A-Days, fossil fuels are the dominant source of energy for the global economy, but the knowledge of fossil fuels as a fundamental contributor to environmental concerns has prompted mankind to explore alternate energy sources. Additionally, the everyday growth in energy demand might cause challenges for power distributors, such as system instability and even blackouts. The need to create more energy, together with an interest in clean technologies, has resulted in an increase in the development of renewable energy-based power systems [1]. Renewable energy technologies such as photovoltaic (PV) are becoming more commonly accepted as a means of sustaining and enhancing living standards while minimizing environmental damage. The number of solar installations is expanding dramatically, thanks largely to government policies and utility company subsidies for grid-connected photovoltaic systems [3], [4]. Additionally, the standards for interfacing dispersed power generating equipment to the utility network emphasis to seamlessly inject power by overriding the grid disturbances. Both the grid synchronization mechanism and the current controller are crucial in the control system of distributed power generator. As a result, control strategies for dispersed power generating systems become highly intriguing. This chapter presents an overview of the various grid connected system structures, with interfacing photovoltaic (PV) panels as power generating source being covered first. This is followed by a study of grid-side converter control topologies in various reference frames. Moreover, the survey of various maximum power points tracking algorithm are also described in this chapter. This chapter also examines the major components of control mechanisms utilized in grid breakdown circumstances.

2.1 General control structure of grid tied PV system

The power controller unit (i.e. voltage source converter and/or DC –DC converter) configuration is directly interfaced to the input power source i.e. Photovoltaic panels, which converts solar energy into electrical energy. Depending on where the generation equipment is connected, the electricity produced can either be provided to local loads or injected to the utility network for distribution. The control structure of a grid tied PV system is a crucial component of the system i.e. brain of system. A general control structure of grid tied PV system is depicted in Figure 2-1. The duties associated with control can be classified into two major categories.

(i) A DC Power controller: The primary function of DC voltage control loop is to extract the maximum amount of power possible from the input source i.e. PV panels. In this controller, protection of the input-side converter is, of course, also taken into consideration.

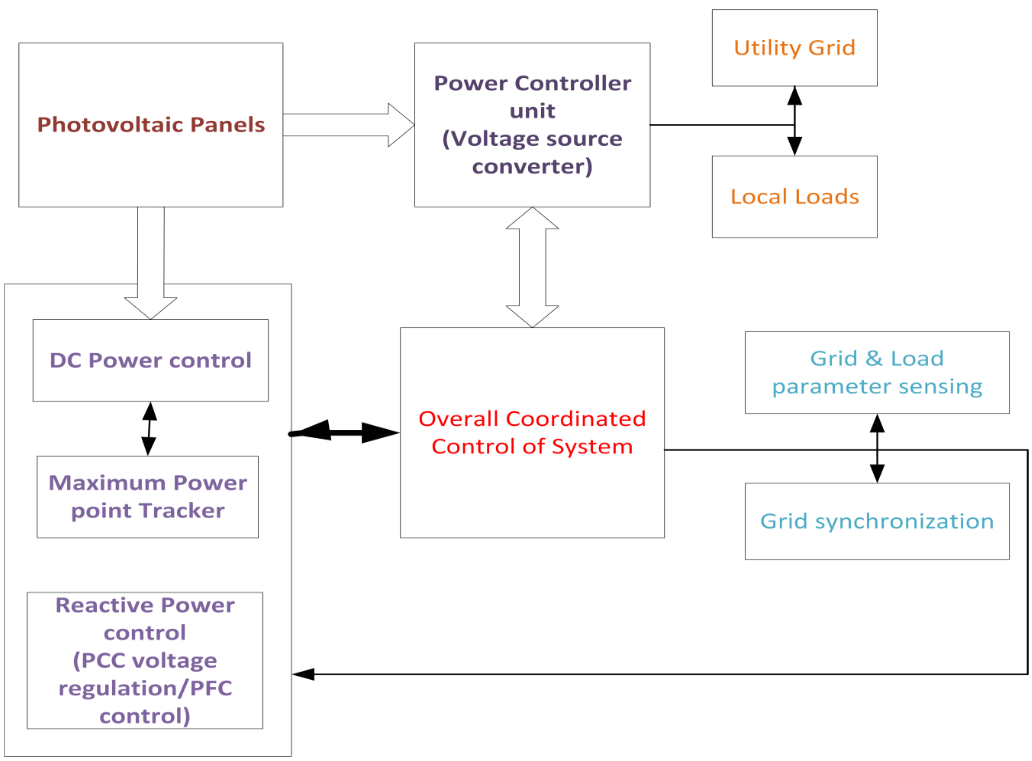

Figure 2-1: General control structure of grid tied PV system

(ii) Coordinated Grid controller: It may perform the following functions: control of active power injected into the grid; exchange of reactive power between the voltage source converter and the grid; control of dc-link voltage; and grid synchronization.

In addition, auxiliary services such as local voltage and frequency regulation, voltage harmonic compensation, and active filtering may be requested by the grid operator, depending on the situation. As previously stated, the power conversion unit has a variety of hardware structures, each of which is intimately tied to the type of the power being converted. A review of the technologies that are most commonly utilized nowadays in PV systems, as well as WT systems.

2.2 Topologies of Photovoltaic System

Despite the fact that the PV systems have a low-voltage input provided by the PV panels, a larger number of such units can be joined in the series or/and parallel configuration together to get the appropriate voltage, current and power. When it comes to providing typical customer load demand or dumping electricity into the grid, power conditioning systems, such as voltage source converter and DC-DC converters, are frequently employed in distributed power generating system.

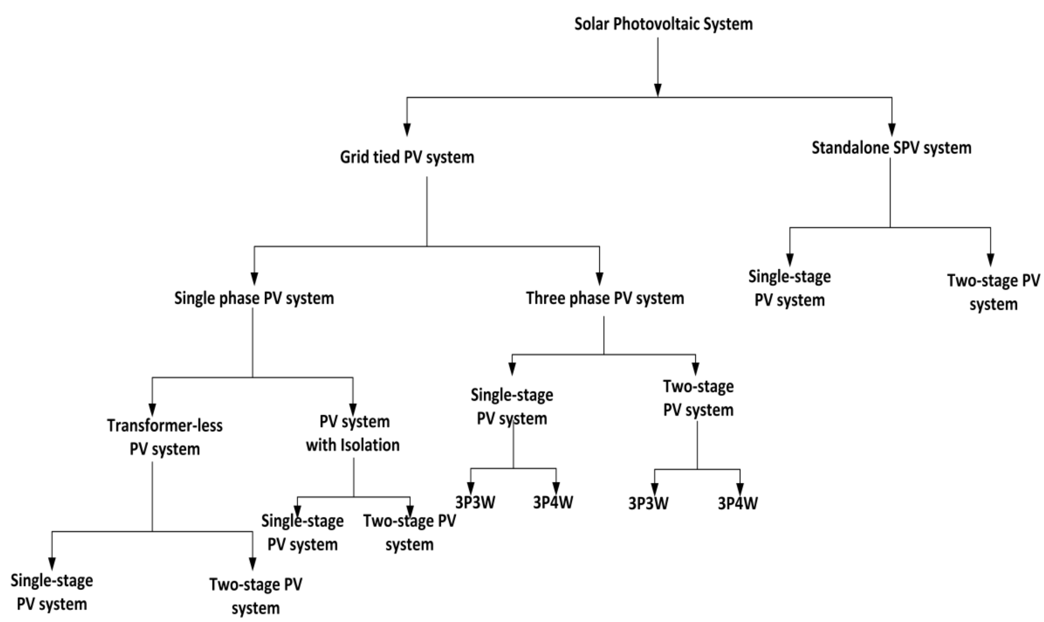

Figure 2-2: Classification of the grid tied PV system topology

The solar photovoltaic system based renewable power generating system is classified according to their structure as follow: (i) Grid interfaced solar photovoltaic system, and (ii) stand-alone solar photovoltaic system (i.e. without grid interconnection). The photovoltaic (PV) panels, in particular, have been designed to turn sunlight into electricity by using PV cells. The stand-alone solar photovoltaic system topologies consist of a DC-DC converter, an inverter (not connected to the grid), batteries, charge controller, and fuses. The electric energy infrastructure is either very expensive or non-existent to maintain in remote locations; thus, this is the only option. Small-scale stand-alone PV systems are employed in numerous scenarios to provide off-grid power in isolated or rural areas. Their adaptability makes them perfect for any location that receives sufficient sunlight. The benefits and drawbacks of a stand-alone PV system must be considered. Grid-connected photovoltaic (PV) systems are typically deployed using single-stage PV system topology or two-stage PV system topology power conversion. Typically, single-stage PV systems just consist of a grid-tied (DC-AC) converter, in which current control and maximum power point tracking (MPPT) algorithm are employed on the DC-AC converter. The DC bus of grid-tied inverter is directly interfaced to the PV array in this scenario. MPPT is performed by the grid-tied inverter for single-stage PV systems, which has the added benefit of greater efficiency than two-stage PV systems. Additionally, PV systems can control active power injection, and/or reactive power compensation, and active power filtering using either three phase three wire system (3P3W) topology or three phase four wire systems (3P4W). The single-stage 3P4W grid-connected PV system is capable to perform as shunt connected active power filter with a neutral current compensation.

2.2.1 Control Structure of Photovoltaic system

It is indeed usual for photovoltaic system control concerns to be divided into two categories: fundamental and auxiliary. In order to cease solar power generation in the event of abnormal conditions, the fundamental control consists primarily of the maximum power extraction algorithm, grid synchronization harmonic elimination ability and unity power factor (which achieved through current controller). In order to comply with standards, PV system tied directly tied to residential power grid should be established to fulfil necessary requirements of grid codes. However, nowadays, it can also be implemented to improve the efficiency and enhance the performance of the electrical system by providing "ancillary services": unity power factor at grid side, frequency and voltage support could be offered to local loads [25], [26], or to the electricity grid [27].Now-a-days, photovoltaic converter can be implemented successfully to provide reactive power support as ancillary services for distribution grids [28–30]. It is possible to improve voltage profiles by injecting reactive power into the grid, which strengthens the utility grid and maintains the desired quality of supply without requiring further investments. This provides several evidence of how far the photovoltaic system perspective has shifted in recent decades, particularly when compared to surveys that have been compiled in the past that imply restrictions to the penetration of large number of renewable energy sources in order to prevent causing the false trips and voltage rise among other things. [31]. Ancillary service provided by Photovoltaic systems is not profit-free, as this fact must be taken into account. It is composed of two hardware units: the power circuit as heart of system and the control unit as brain of system. Taking into consideration the power circuit, the converter can be either a single-stage PV system (DC-AC converter) or a two-stage converter (DC-DC converter + DC-AC converter) with or without galvanic isolation [32]. A two-stage PV system is represented by the diagram in Figure 2-3. Once again, there are two methods for achieving isolation: (1) utilizing the DC-DC converter, and (2) employing an isolation transformer after the DC-AC stage, both of which are effective. Generally, the output voltage of the PV array is not high enough and varying with the changing environmental conditions.

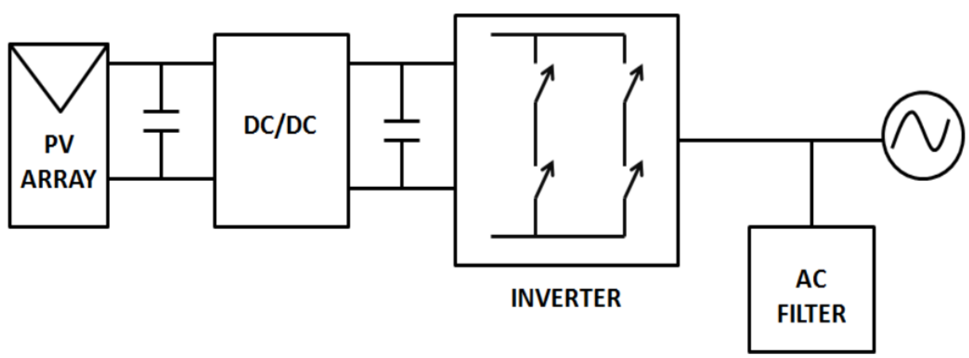

Figure 2-3: General structure of two –stage grid tied PV system

Figure 2-3 shows a typical configuration for this system. PV panel voltage fluctuates during the day due to temperature changes, so a step-up DC converter is needed to keep the DC-bus voltage constant. An additional boost converter stage is used to maintain a constant DC-bus voltage regardless of fluctuating input voltage to extract the maximum power from Photovoltaic panels. Two-stage topologies have some advantages in controller design, but it also has some drawbacks. The overall energy transfer efficiency decreases as the number of circuit stages increases and the system's complexity increases; as a result, making the system less reliable. Normally, an LCL filter is used between the voltage source converter and the utility grid.

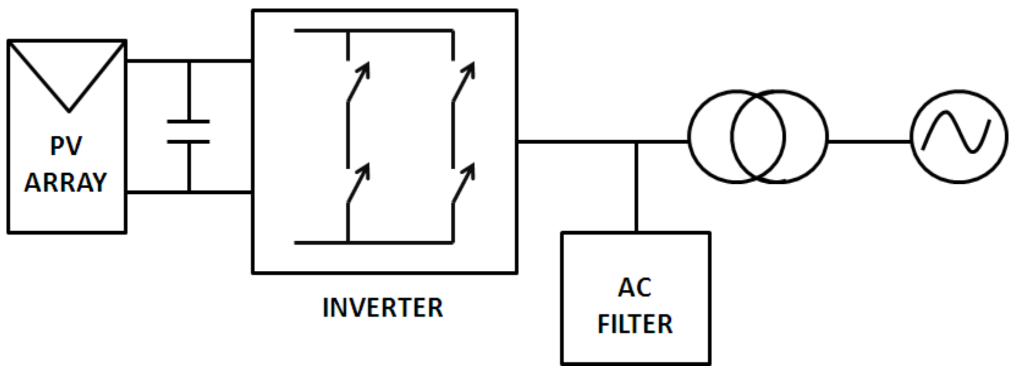

Figure 2-4: General structure of Single –Stage grid tied PV system

In addition to their high efficiency, single-stage converters have the advantages of being less expensive and being simpler to implement [33–35]. Figure 2-4 shows the basic block schematic of inverter topology without trans- former, which does not provide galvanic isolation with grid. The output filter is used to cut off the switching ripple that occurs during the switching process. The input power control, which is made of an MPPT algorithm and a DC voltage controller, provides the voltage/ current control reference signal for the outer voltage/ inner current control loop, respectively. In addition, in many countries, where such systems are built with the isolation between the input and output powers, which are essential to ensure proper operation and protection. Figure 2-5 shows the basic block schematic of grid connected PV inverter with transformer. The transformer shown here is low frequency transformer (LFT). It provides robust construction, galvanic isolation to grid, and protection to earth fault. It has drawback of high weight, decrease overall efficiency due to less efficiency of transformer, and increases size and cost of the structure due to DC-DC converter and transformer.

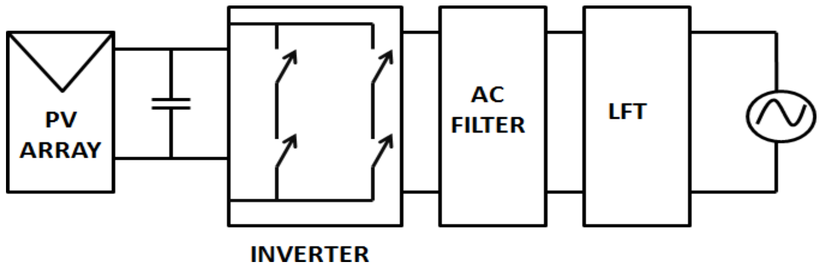

Figure 2-5: General structure of single-stage PV system with Galvanic Isolation

It has advantage of less weight and cost of system, improvement in efficiency, and reduces the overall system structure due to elimination of transformer. It also increases the reliability due to less number of components. The overall system can be developed on single printed circuit board(PCB) so the system become compact and easy to mount below the PV panels itself. It has drawback of no electrical separation to grid, may arise leakage current and issue of Common mode voltage with sinusoidal pulse width modulation switching scheme.

2.2.2 Survey on Maximum power point Tracking Methods

Temperature and solar radiation have a significant effect on the output of a PV module. As the temperature rises, output power from the solar panels is decreasing. As a result, the operating point must be constantly monitored using an MPPT algorithm [8]–[11] to extract maximum available power from the solar panels. The MPPT algorithm must immediately adjust the output power of the PV system to maximize performance for operating at MPP when the weather changes. Single-stage or Two-stage photovoltaic topologies necessitate various implementations of maximum power point tracking algorithms (MPPT). The maximum power point tracking algorithms is applied to the DC-DC converter for the extracting maximum power from the solar panels in a two-stage conversion system, while the MPPT is added to the control of the DC-AC converter in a single-stage conversion system. Direct control of AC current or DC voltage can be achieved by the MPPT; alternatively, a DC voltage controller can be used to regulate the AC current. The feed-forward power is used to improve the dynamic performance of the MPPT. The integration of each PV panel into the overall system is at the cutting edge of this technology since mismatching results in a decrease in MPPT efficiency. A DC-DC converter within the photovoltaic modules [21], [22], [24] or a DC-AC converter unit incorporated into each PV module can be used to run the MPPT algorithm in this instance [21], [22], [24]. MIC stands for "module integrated converter" when the entire unit is treated as a PV -AC system directly interfaced to the main grid [23]. The article [8] reviews the main aspects of the different MPPT approaches, whereas article [20] provides an estimate of the costs. MPPT techniques include the Constant Voltage (CV), Perturb and Observe (P&O), and Incremental Conductance (INC) approaches. They are referred to as "hill-climbing" methods because they rely on the power characteristic, which increases step- size in MPPT when the derivative of PV power with respect to PV voltage is greater than zero, a decrease step- size when this derivative is less than zero, and MPPT reach to maximum power point increase when this derivative is zero. For the constant voltage MPPT algorithm, it is implemented based on the observation that the ratio between the measured voltages at maximum power to the open-circuit voltage of PV module are about 0.77. The operative voltage is set to 76 percent of the open-circuit voltage of PV module, and this value is preserved for the specified period before the measurements are repeated, because the voltage varies slightly with shifting solar irradiance.

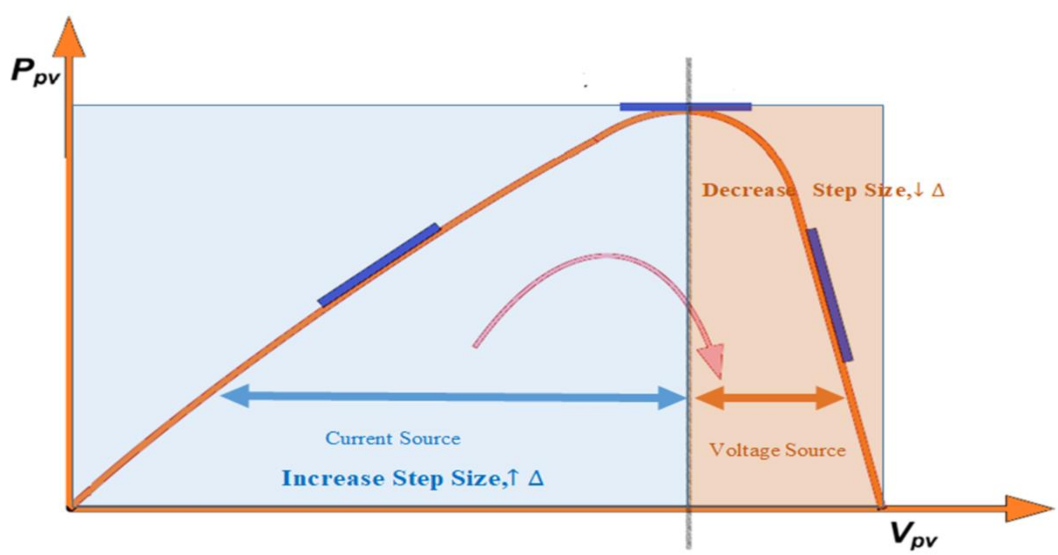

Figure 2-6: Power-voltage PV characteristic

The following are some standard MPPT algorithms: Perturb and Observe (P&O), Incremental Conductance (IC), Constant Open Voltage (CV), a combined approach using the Incremental Conductance and Constant Open Voltage, ripple correction, and short-circuit current. These techniques differ in terms of ease, hardware implementation, convergence speed, number of sensors involved, affordability, effectiveness range, and requirement for parameterization

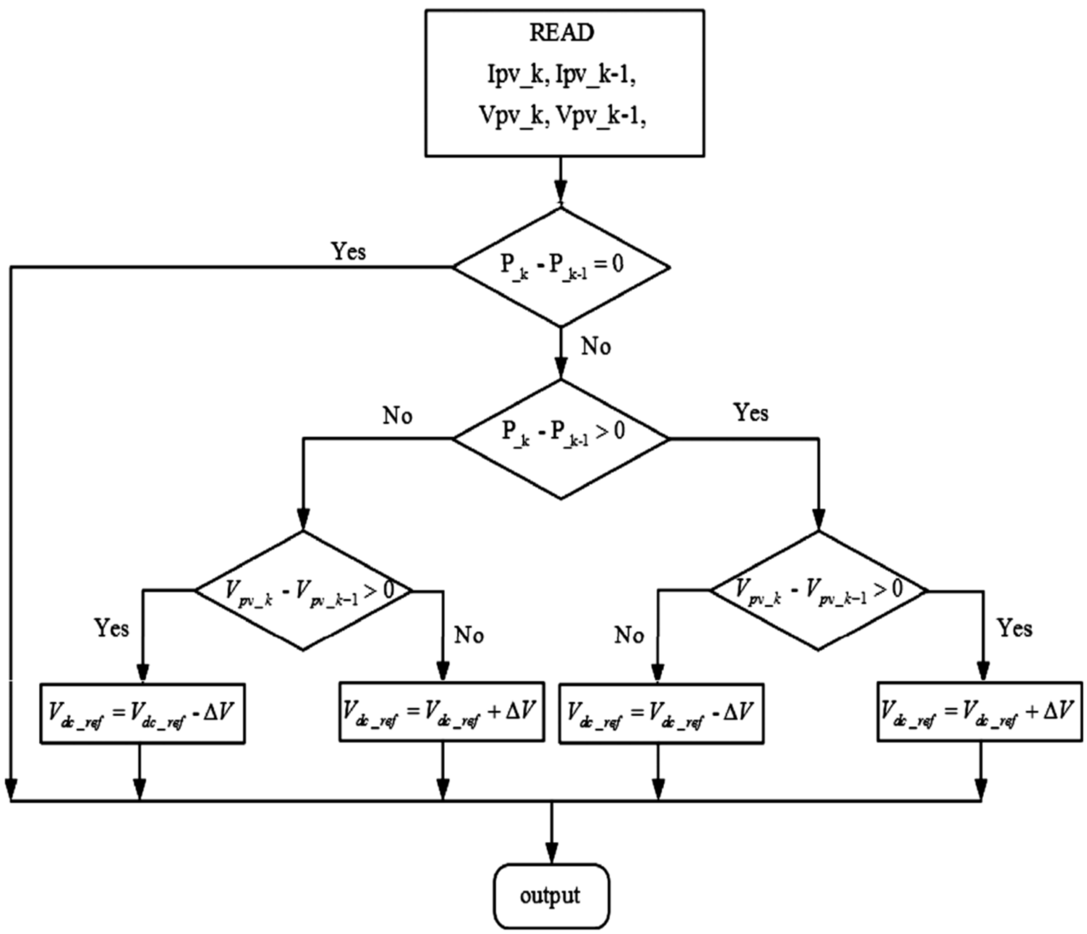

Figure 2-7: Flowchart of perturb and observe maximum power point algorithm

. Amongst the most popular MPPT methods is P&O, which is simple to implement on the microcontroller, digital signal processor, and an FPGA[13]. Figure 2-7 shows flowchart of perturb and observe(P&O) MPPT algorithm for the extraction of maximum power from PV panels in grid tied PV system. The P&O MPPT algorithm works as follow: when the voltage variation produces $\frac{dP_{PV}}{dV_{PV}} > 0$, the algorithm perturbs the PV voltage in the same direction, which implies it advances the set point toward the MPP. If $\frac{dP_{PV}}{dV_{PV}} < 0$, then its reverses the direction of perturb, since the set point is moving away from the MPP at this moment. This key benefit of P&O MPPT algorithm is its simplicity of implementation, which requires few sums, just one multiplication and comparisons. The drawbacks include swings in the vicinity of the MPP and a tendency to lose MPP tracking when the irradiance level changes rapidly.. The Incremental Conductance approach overcomes the limitation of the P&O MPPT algorithm in tracking peak power under varying air conditions. Incremental Conductance can be used to investigate whether the MPPT has achieved its Maximum PowerPoint and when it is wise to stop perturbing the operating point.

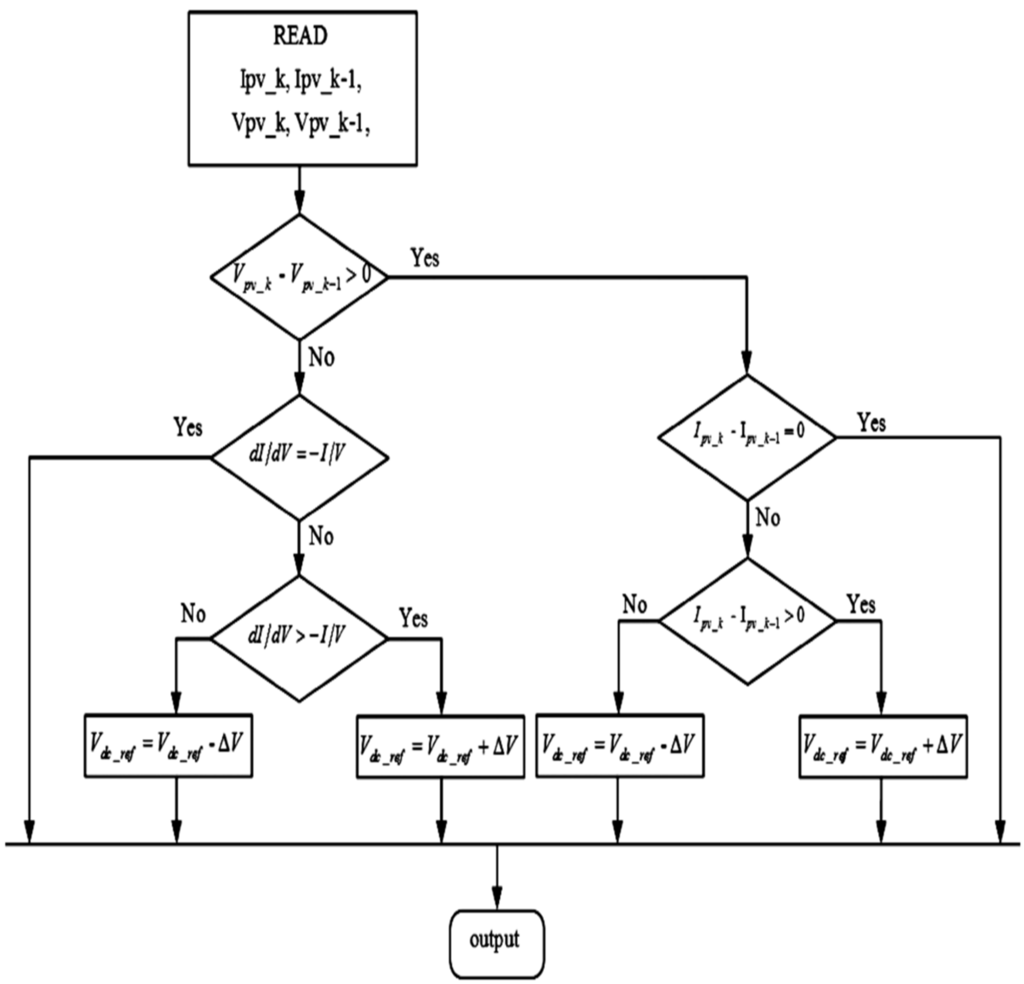

Figure 2-8: Flowchart of incremental conductance (INC) MPPT algorithm

The Incremental Conductance (IC) algorithm is based on the observation that the following equation holds at the MPP;

$$\frac{d\,P_{PV}}{d\,V_{PV}} = \frac{d\,(V_{PV}\ I_{PV})}{d\,V_{PV}} = I_{PV} + V_{PV}\frac{d\,I_{PV}}{d\,V_{PV}} \quad (2.1)$$

The equation (2.1) is simplified as:

$$\frac{1}{V_{PV}}\frac{d\,P}{d\,V_{PV}} = \frac{I_{PV}}{V_{PV}} + \frac{d\,I_{PV}}{d\,V_{PV}} = G + dG \quad (2.2)$$

Here, $dG = \frac{d\,I_{PV}}{d\,V_{PV}}$ is the incremental conductance and $\frac{I_{PV}}{V_{PV}}$ is the conductance.

At the maximum power point, the derivative of PV power with respect to voltage becomes zero and it gives:

$$\frac{d\,I_{PV}}{d\,V_{PV}} = -\frac{I_{PV}}{V_{PV}} \quad (2.3)$$

If equation (2.3) is fulfilled, the algorithm halts its efforts to change the set-point of the algorithm. The algorithm determines which way to perturb the voltage depending on the sign of $\frac{d\,P}{d\,V_{PV}}$. Figure 2-8 illustrates the basic sequence of the incremental conductance algorithm. Using this approach, the maximum power point may be tracked quickly and accurately while avoiding abnormal fluctuations around the MPP, which would take additional computational time. Instead of adjusting the voltage of the PV panel, an alternative approach to INC focuses on modifying the current. From the PV curve shown in Figure 2-6, change of voltage between two consecutive sampling times can be ignored because it is so slow and steady on the right side of the maximum power point in P-Vcurve. A linear relationship between $\frac{d\,P}{d\,V_{PV}}$ versus I_{PV} and $\frac{d\,P}{d\,V_{PV}}$against V_{PV} has been hypothesized in this theory. As a result, the reference current is simple to calculate when $\frac{d\,P}{d\,V_{PV}}$changes linearly, while V_{ref} is more complex to calculate when $\frac{d\,P}{d\,V_{PV}}$ changes nonlinearly. In this scenario, the output of the INC method gives the current reference value instead of the voltage reference with minor modification

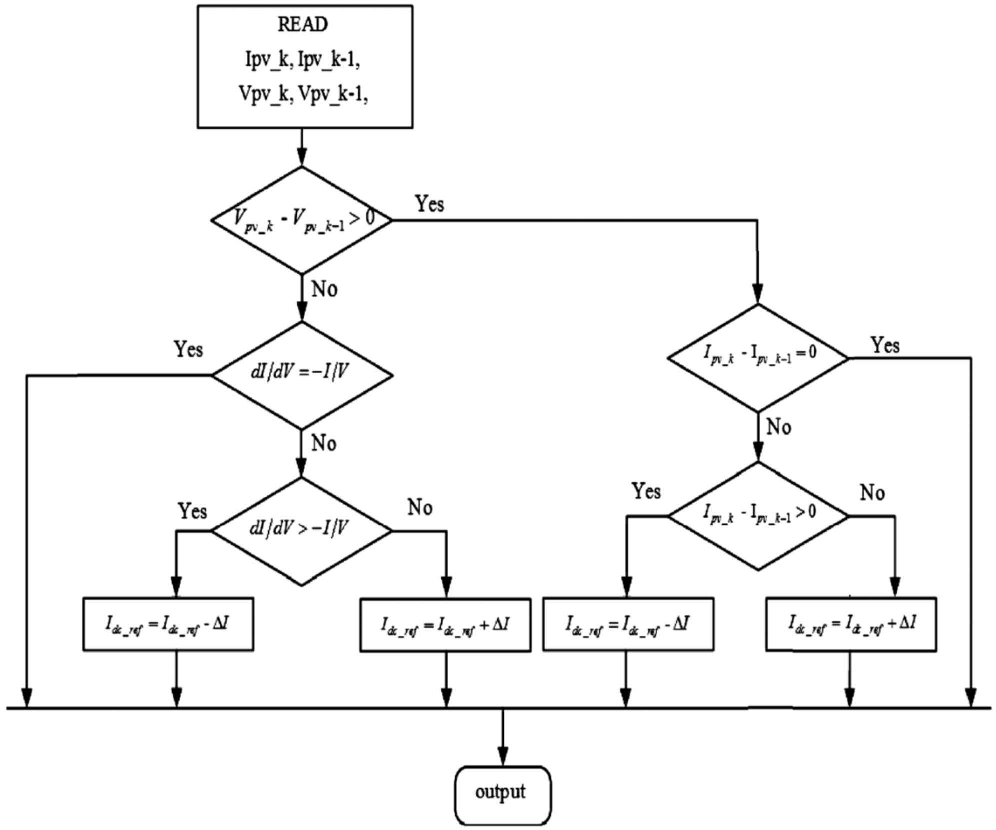

Figure 2-9: Flowchart of modified incremental conductance (INC) MPPT algorithm

Figure 2-9 shows the flowchart of modified INC MPPT algorithm to compute current reference value. The derivative of PV power (i.e.dP_{PV}) is not equal zero when the climatic situation has changed. As long as derivative of current (i.e. dI_{PV}) is below zero, the set-point will be moved away from the maximum power point by increasing $\frac{dP}{dV_{PV}}$and the current reference value. As soon as derivative of current (i.e. dI_{PV}) exceeds zero, the reversal is carried out. How quickly the maximum power point is maintained depends on the INC MPPT step-size. Following thumb rule should be observed when the value of step-size is chosen : with larger increments, faster tracking can be performed by the cost of poor performance of MPPT algorithm due to large oscillation around MPP, consequences, gives lower efficiency. When the MPPT has a smaller increment, the situation is reversed. For the fixed step-size MPPT, a trade-off must be made between dynamic and oscillatory dynamics. The single-stage grid tied PV systems gives grid side current control only, which means the MPPT controls the active component of grid current. As a result, the reference value of voltage is computed by MPPT algorithm for extracting maximum available solar power, which is further given to outer DC voltage control loop of PV system.

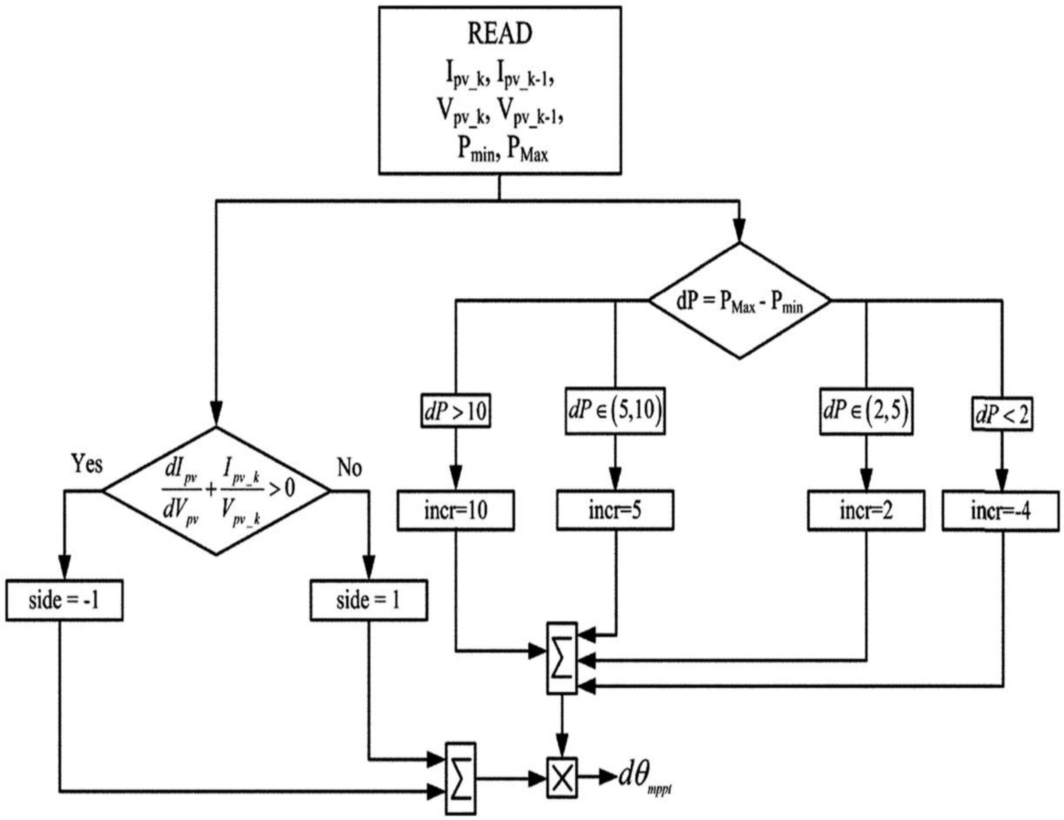

Figure 2-10 Flowchart of ripple correlation MPPT algorithm

As seen PV curve in Figure 2-6, the PV acts as a current source on the left and a voltage source on the right side of the MPP. Performing near the MPP reduces ripple power on the PV side [18]. The desired performance is carried by adopting a variable step-size MPPT algorithm, which gives reference voltage angle extracting maximum power from the PV [25], and this approach is known as ripple correlation algorithm and flowchart of this MPPT algorithm is shown in Figure 2-10. A power-voltage PV characteristic shows that if it runs on the left side of the MPP, the voltage angle derivative should be decreased , which is given by side = -1. However, the region on the right side of the MPP has to increase (side=+1). The PV side power oscillations are measured to set the increment (Figure 2-10). For comparison, the "ripple correlation control" approach has 99.7% efficiency in high irradiation environments [19], while P&O and INC have 98.7% and 99.1% efficiency [20]. However, due to concerns with consistency during MPP tracking studies, a consistent technique to examine MPPT algorithms is still lacking. In 2010, the BS EN 50530 European Standard [68] was published, which offers the sole process for measuring inverter MPPT efficiency. The impact of MPPT approaches on grid-side power quality is the final objective. The INC algorithm is much more appropriate for grid-tied PV systems with only single-conversion stage.

2.3 VSC Based Solar Energy Conversion System with Indirect Cost Reduction

The solar PV system remains unutilized for more then 2/3rd of the day. During day time, the power converters is employed to inject active power from PV panels along with other ancillary functions like harmonic compensation, grid current balancing, neutral current compensation, and reactive power compensation, which will also indirectly reduce the cost of operation. During night time, the voltage source converter of PV system can be employed to provide the reactive power compensation for the grid.

2.3.1 Operating Principle of STATCOM

Shunt-connected reactive compensation equipment like the Static Synchronous Compensator (STATCOM) can produce and/or absorb reactive power, and its output can be controlled to regulate certain electric power system variables. This type of compensator is similar to a rotating compensator without mechanical inertia because it uses solid-state power switching devices to alter the three-phase voltages quickly, both in magnitude and phase angle. The STATCOM consists of a three-phase voltage source converter, line filter, a step-down transformer ,and a DC-bus capacitor. The voltage source converter (VSC) is the core component of FACTS devices like a STATCOM. The leakage reactance enables reactive power transfer between the STATCOM and the grid so that the AC voltage at the bus bar can be controlled to improve the voltage profile of the grid, which is the prime objective of the STATCOM.

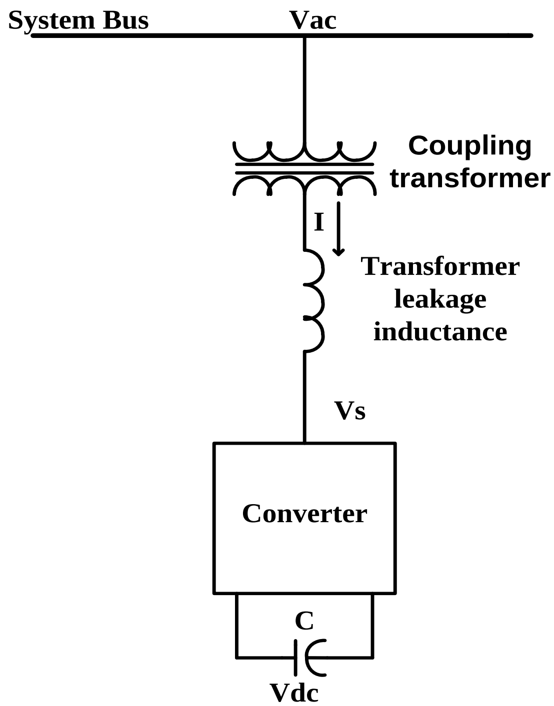

Figure 2-11: One-line diagram of a STATCOM

Figure 2-11 illustrates the underlying voltage-source inverter representation for reactive power compensation. The concept of STATCOM functionality is as follows. The VSC generates a controlled AC voltage behind the leaking reactance. The voltage of STATCOM is matched with the AC bus voltage of the grid if the magnitude of grid voltage is higher than the magnitude of the VSC; the STATCOM behaves as an inductor; otherwise, it acts as a capacitor. The net reactive power flow is zero if the magnitude of VSC and STATCOM are equal. The phase angle between STATCOM terminals and the grid can be used to control active power when STATCOM has a DC power or energy If the phase angle of the grid leads to the phase angle of STATCOM, then Active power is absorbed by the STATCOM; otherwise, it is supplied by the STATCOM. The distribution Static Compensator (DSTATCOM) device protects the distribution system against the impacts of voltage fluctuations, voltage sags, and voltage swells, as well as non-linear loads. It is also possible to use a dynamic voltage restorer (DVR) to shield a critical load from voltage fluctuations caused by the associated distribution system. A series and shunt controller called the Unified Power Quality Conditioner (UPQC) is used to correct supply voltage and load current faults in the distribution system. Reactive power compensation in Transmission networks can be provided via the DSTATCOM, a flexible device. Similar to a normal synchronous compensator, which is just a synchronous generator where the field current is utilized to alter the regulated voltage; this device uses the field current to control the voltage.

2.3.1.1 Concept of Reactive Power

The distribution Static Compensator (DSTATCOM) device protects the distribution system against the impacts of voltage fluctuations, voltage sags, and voltage swells, as well as non-linear loads. It is also possible to use a dynamic voltage restorer (DVR) to shield a critical load from voltage fluctuations caused by the associated distribution system. A series and shunt controller called the Unified Power Quality Conditioner (UPQC) is used to correct supply voltage and load current faults in the distribution system. Reactive power compensation in Transmission networks can be provided via the DSTATCOM, a flexible device. Like a normal synchronous compensator, which is just a synchronous generator where the field current is utilized to alter the regulated voltage, this device uses the field current to control the voltage. The DSTATCOM regulates the voltage using a voltage source converter (VSC). It is the ratio of real power to apparent power known as the power factor. Mathematically, this definition can be expressed as kW/kVA, where kW is the active (actual) power, and kVA is the active plus the reactive power. Even though reactive power has a straightforward definition, even those with a thorough understanding of technical concepts have trouble comprehending its complexities. Reactive power is explained as follows: in an AC power system, only actual power is transmitted when voltage and current rise and fall simultaneously (amplitude variation), while active and reactive power is transmitted when voltage and current shift in time(phase-angle variation). A net movement of power from one point to another can be seen when calculating the average active power over time; however, the average reactive power is zero regardless of network. Reactive power is when the energy pumped from one direction is precisely equal to the energy received in the other direction. As a result, no active energy is generated or used. Reactive power losses are measured and compensated for by introducing many reactive power compensating devices. An inductor stores reactive power since it stores energy in form of a magnetic field. Put another way, the magnetic field builds up over time, and the current reaches its full magnitude when voltage is supplied. This results in the current lagging behind the voltage. A capacitance generates reactive power since it stores energy in the form of an electric field.

In an inductive circuit, the instantaneous power is computed as:

$$p = V_{max} I_{max} \cos \omega t \cos(\omega t - \theta) \quad (2.4)$$

The simplification of equation (2.4) is described as:

$$p = \frac{V_{max} I_{max}}{2} \cos \theta \,(1 + \cos 2\omega t) + \frac{V_{max} I_{max}}{2} \sin \theta \sin 2\omega t \quad (2.5)$$

The instantaneous reactive power is given by:

$$Q = \frac{V_{max} I_{max}}{2} \sin \theta \sin 2\omega t \quad (2.6)$$

A number of parameters are used here, including the instantaneous power ‘p’, maximum voltage and maximum currentV_{max}, angular frequency ‘ ω’, and the angle ‘ θ’.

The average value of reactive power is null, and its instantaneous reactive power value pulsates at twice the system frequency. The instantaneous reactive power is given by:

$$Q = |V||I| \sin \theta \quad (2.7)$$

Although a zero average does not imply that no energy is moving, it does suggest that the actual quantity that flows in one direction for half a cycle and then returns in the next half-cycle means that no energy is moving. Variations in fundamental component voltages of the inverter are used to govern the reactive power transfer between the grid and compensators. By varying the switching angle of the semiconductor devices, the fundamental component of the inverter's voltage is driven to either lead or lag grid voltage by a few degrees. As a result, the inverter's output voltage and reactive power are affected by the amount of active energy flowing into or out of the inverter's DC capacitor. Active power is zero if the compensator solely provides reactive power; hence the DC capacitor has no effect. As a result, the capacitor's voltage remains constant. The capacitor, then, does not play a role in creating reactive power [2].

2.3.1.2 Need for Reactive Power Compensation

It is essential to use reactive power compensation to prevent voltage collapse and sag and improve the system's overall stability and better utilize the equipment connected to the system. System stability and transmission line impedance are both affected by the consumption of reactive power due to the impedance of transmission lines and the necessity for lagging VAR by most generators. Outages can occur due to excessive voltage dips because of the more significant losses that need to be provided by the source, resulting in additional stress on the system. As a result, it concludes that compensating reactive power alleviates these effects and aids in better transient reaction in the case of faults and disturbances. Since recently, there has been a rise in attention to approaches employed for compensation and the inclusion of more effective devices in technology. If the lines are to be freed from the burden of carrying reactive power, which is better delivered nearby the generators or the loads, it is imperative. A distribution substation or a transmission substation can use shunt compensation positioned close to the load. Increased transmission system losses, reduced power transmission capabilities, and significant amplitude voltage swings at the receiving end can be caused by reactive power. Voltage-amplitude oscillations caused by fast variations in the reactive power usage of loads can also be generated. As a result, power oscillations can be caused by voltage changes in the electric system

2.3.1.3 Analysis of STATCOM

Figure 2-12 [53] depicts the STATCOM system's per-phase entire equivalent circuit, which helps illustrate the system's basic working principles. Assume, the grid voltage is V_{pcc}, I_1 is the fundamental component of the current, and output voltage of the inverter is V_{inv} .The STATCOM is connected to the grid by a reactor L_s and a resistor R_s. As a result of reactive coupling, the line current that flows in/out of the VSC is always at an 90^oangle to the grid. Depending on the voltage of the DC side capacitor, the STATCOM absorbs or provides a certain amount of reactive power. This voltage can be controlled by adjusting the real power transmission between the grid and the STATCOM.

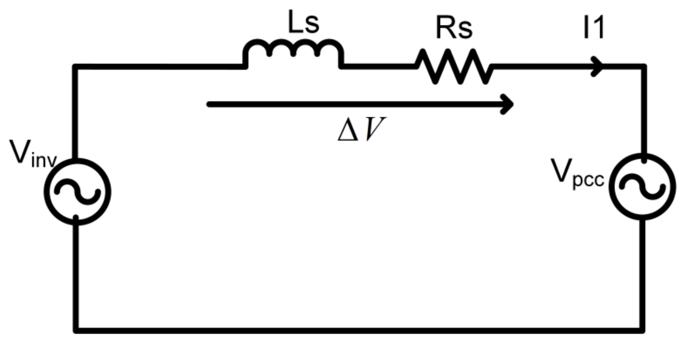

Figure 2-12: Per-phase fundamental equivalent circuit

The capacitor voltage drops when the inverter output voltage V_{inv} is ahead of the main voltage V_{pcc} by angleα , and it rises when the inverter output voltage V_{inv} is behind the main voltage V_{pcc} . Phase angle of inverter can vary the voltage levels of DC capacitors [102]. The phasor-diagram of voltage and current of VSC and grid is shown as in Figure 2-13, can be regulated in this way. The STATCOM is primarily responsible for controlling the power transmission voltage at the connection point. A regulated reactive current is drawn from the line to accomplish this. Statically controlled VAR generators do not have the capacity to interchange real power with a line, as the STATCOM does. For this reason, the converter and its DC-bus must be actively managed to maintain a value that is, on average, zero and only deviates from this value to account for system losses.

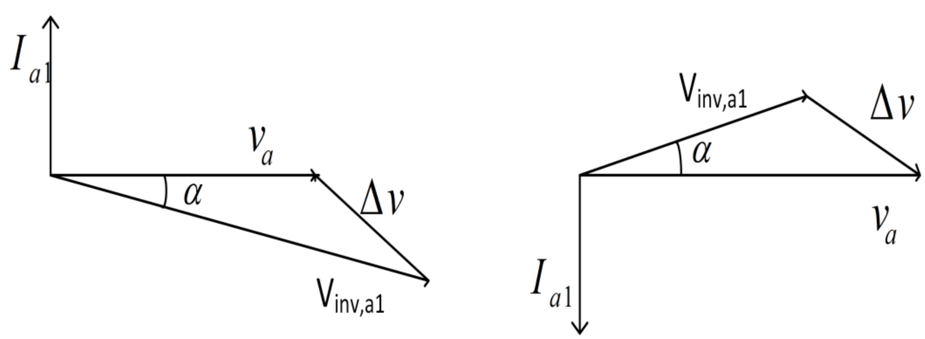

Figure 2-13: Phasor diagram for leading and lagging mode

To understand and control the behavior of the STATCOM , instantaneous real power is provided by:

$$p = v_a i_a + v_b i_b + v_c i_c \qquad (2.8)$$

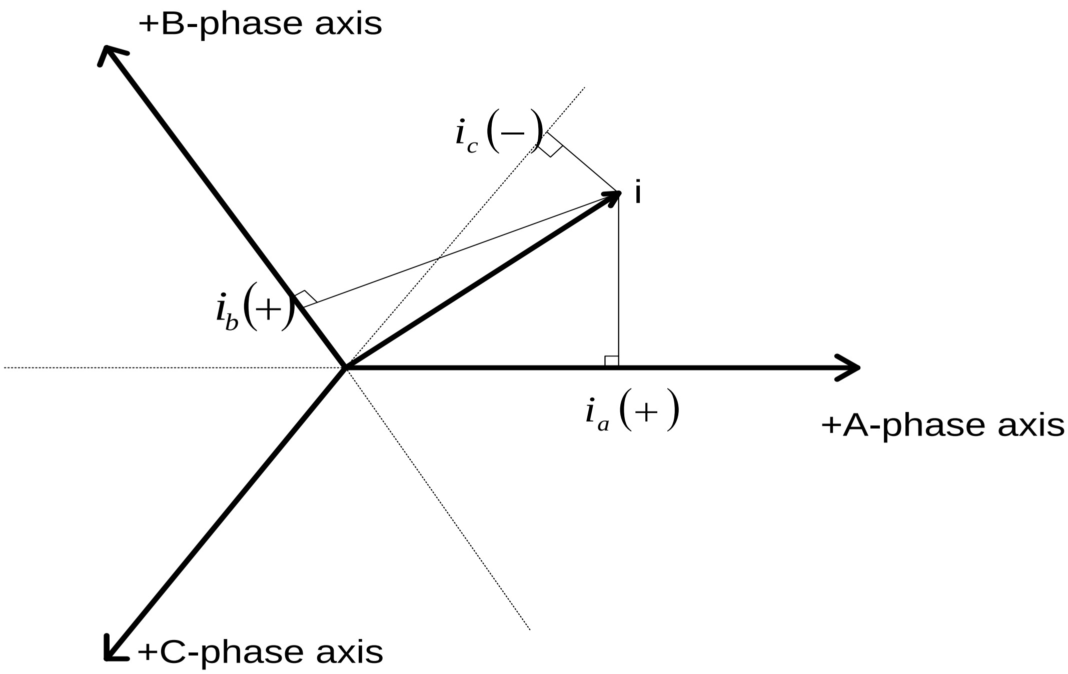

Figure 2-14: Vector representation of instantaneous three-phase variables

Instantaneous reactive current can be thought of conceptually as part of a three-phase current system that can be removed at any time without affecting P.

A vector interpretation of the instantaneous values of the circuit variables yields the algebraic definition of instantaneous reactive current. As shown in Figure 2-14, a vector diagram can represent a combination of three instantaneous phase variables that add up to zero. Each of the three symmetrically oriented phase axes corresponds to the instantaneous value of the corresponding phase variable when a vector drawn from the origin to this point is projected vertically onto it. As shown in Figure 2-15, an orthogonal coordinate system with DQ components is used to extend the vector representation further.

The current vectors transformation from abc →dq components are computed as:

$$\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} = \frac{3}{2}\begin{bmatrix} 1 & \frac{-1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.9}$$

Consequently, the constant 3/2 is selected so that the definition matches with the traditional phasor term in balanced steady-state conditions

In context of DQ reference frame, the instantaneous power can be computed as

$$P = \frac{3}{2}\,(v_d i_d + v_q i_q) \quad (2.10)$$

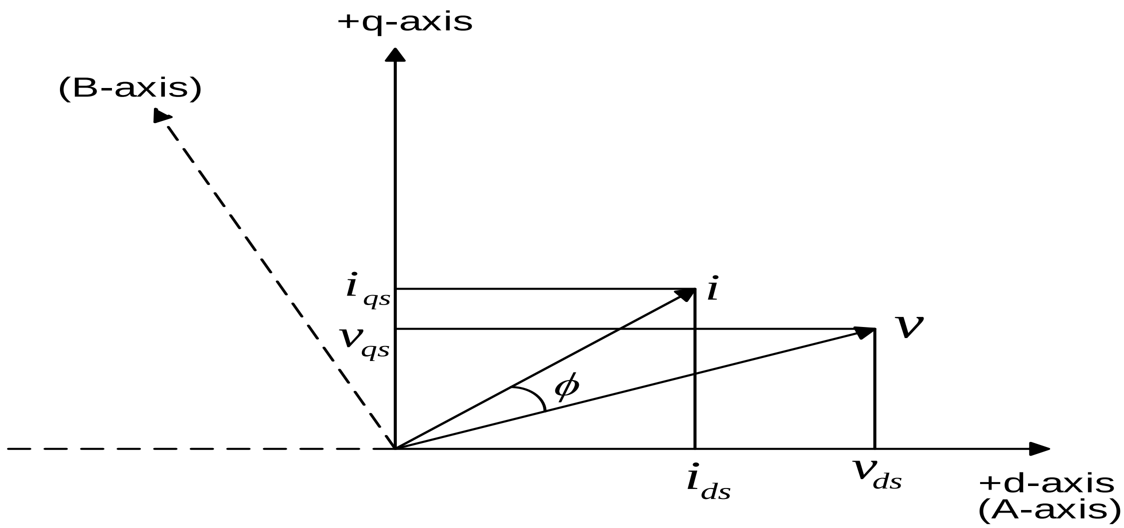

Figure 2-15: Definition of orthogonal coordinates

The phase angle between the voltage and current vectors can be seen in Figure 2-15. The current vector can only generate the instantaneous power in phase with the instantaneous voltage vector. The instantaneous reactive current is the remaining component of the current that can be withdrawn without affecting the power.

The definition for instantaneous reactive power can be derived from these findings:

$$Q = \frac{3}{2}\,(v_d i_q - v_q i_d) \quad (2\text{-}11)$$

They follow the trajectory of the voltage vector and the d and q coordinates within this synchronously rotating reference frame are given by the following time-varying transformation: Figure 2-16 illustrates how the vector coordinate frame can be manipulated further to separate variables, which is used to control the flow of real power in/out of grid. In the synchronous reference frame, the instantaneous active power and the instantaneous reactive power are computed as :

$$P = \frac{3}{2}\,|v| i_d\ ;\ Q = \frac{3}{2}\,|v| i_q\ ; \quad (2.12)$$

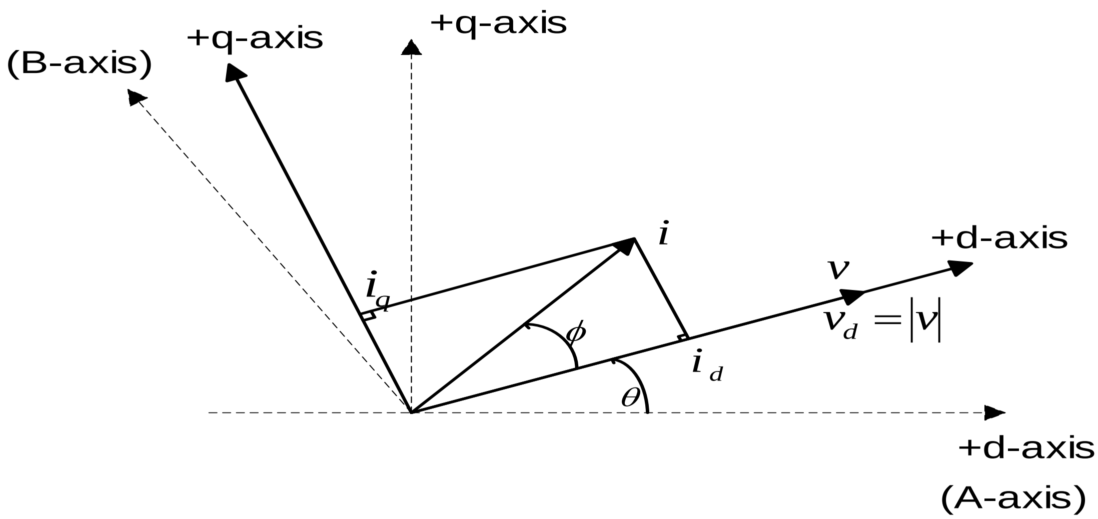

Figure 2-16: Definition of rotating reference frame

The vectors of current and voltage in the DQ reference frame have constant coordinates when the system is in balanced steady state.

2.4 Control system of grid connected system

The grid connected voltage source converter is controlled by two cascaded loops i.e. internal current control loop and outer voltage control loop. A quick internal current control loop governs grid current, whereas an outer voltage control loop regulates dc-link voltage [17–22]. Because the current control loop is responsible for ensuring power quality and ensuring current protection, the current controller must have harmonic correction and dynamic properties. Figure 2-17 shows the control structure of grid tied PV system in synchronous reference frame. System power flow can be balanced by using the dc-link voltage controller. The system stability with modest dynamics is often the goal of this controller design. A DC-bus voltage loop cascading with an inner power loop may be used to operate the grid-side controller in some works, rather than a current loop.

2.4.1 Synchronous Reference Frame Current Control

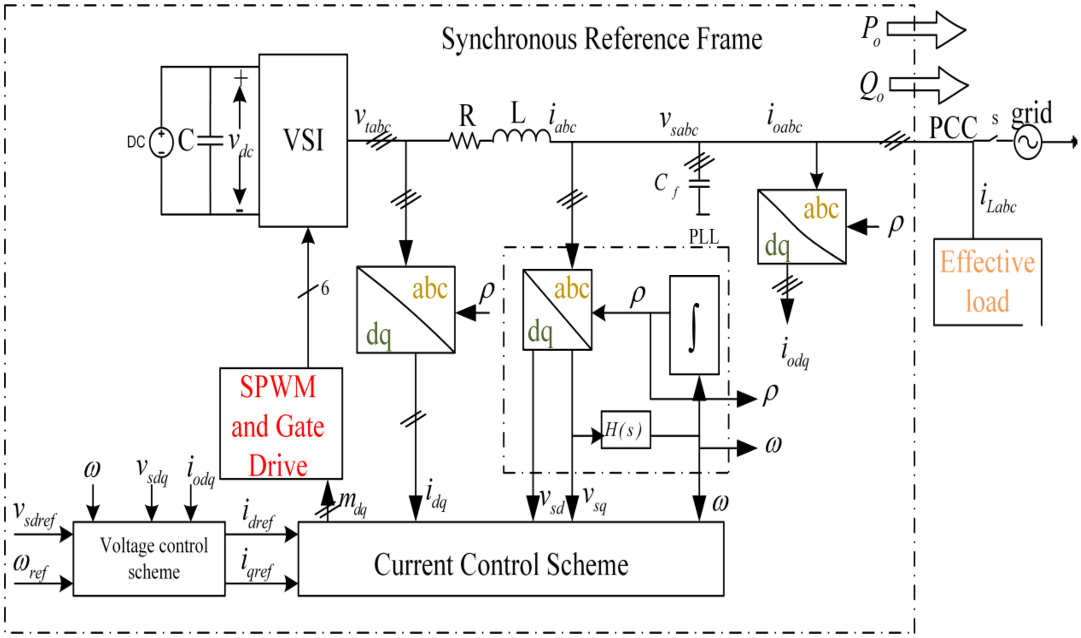

Figure 2-17: Control structure of grid tied PV system in synchronous reference frame

A reference frame transformation module, such as abc→dq, is used in synchronous reference frame control, also known as dq control, to transform grid current and voltage waveforms into a reference frame that rotates in synchronous with the grid voltage. It is possible to filter and control more easily [25] by converting the control variables to DC values. In this design, the DC bus voltage is regulated to meet the output power requirements. Active current controllers use this as their output, but the reactive current controllers often use zero as a reference if reactive power controls are not allowed. A reactive power reference must be imposed on the system in order to manage the reactive power. Proportional–integral (PI) controllers are commonly connected with the dq control structure due to their ability to regulate DC variables. Because the controlled current must be in phase with the grid voltage, the abc→dq transformation module must extract the phase- angle from the grid voltages. Filtering the grid voltages and extracting the phase angle using the arc-tangent function may be a solution. [26]–[28]. For grid connected system, the phase-locked loop (PLL) technique [29–33] has become standard for obtaining the phase angle of grid voltages. Cross-coupling terms and voltage feedforward are commonly employed to improve PI controller performance in Figure 2-17 [17], [19], [25], [34],

[35]. Despite these advancements, low-order harmonic correction in PI controllers is still weak, posing a severe problem in grid-connected systems.

2.4.2 abc Frame Control

Natural (abc) frame control is based on the principle that each grid current should have its own controller, but still the alternative approaches to integrate three-phase systems, such as star or delta connection, without or with an neutral wire, must be taken into account when developing the control system.

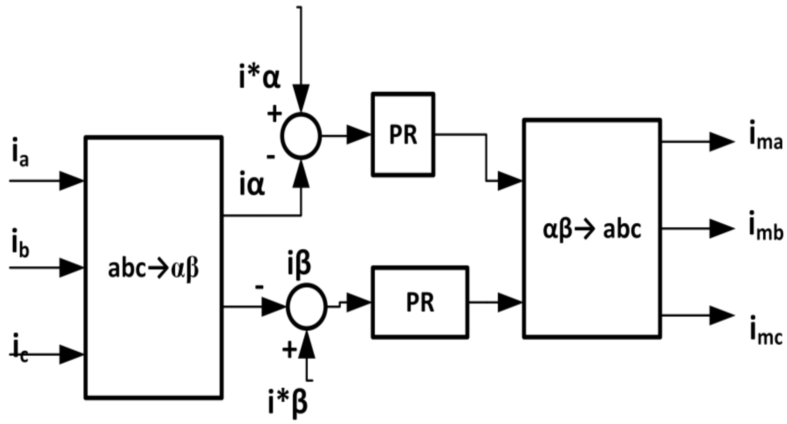

Figure 2-18 : Current Control loop of grid tied PV system for stationary reference frame(PR controller)

Additionally, it is viable to have three distinct controllers, which includes additional considerations for the dead- band technique or hysteresis technique. The dead- band technique or hysteresis technique are frequently used in natural (abc) frame control systems during non-linear loads because of the high dynamics they provide. Digital systems like high-speed microcontroller, field-programmable gate arrays (FPGA), and digital signal processors(DSP) are efficient since the efficiency and capability of these controllers is directly related to the sampling frequency. The three reference currents aregeneratedwithout PLLsystem.These reference currents are compared to th e matching sensed currents, and theerrors are logged in the controller for the gating signal generation. The modulator is no longer required if dead beat controllers or hys teresis are used in the current loop. The PWM modulator is required to generate gating signals when the PI or PR controllers are employed. It is possible to implement the PR controller in the abc frame as shown in Figure 2-18[35]. PI controller is often used in the synchronous reference frame, as shown in Figure 2-17. Because the control system is already in a stationary frame, the implementation of a PR controller is simple in abc. Hysteresis control requires an adaptive band to be developed for a fixed switching frequency in the case of an adaptive controller. Various approaches and strategies to achieve fixed switching frequencies are discussed in [67].

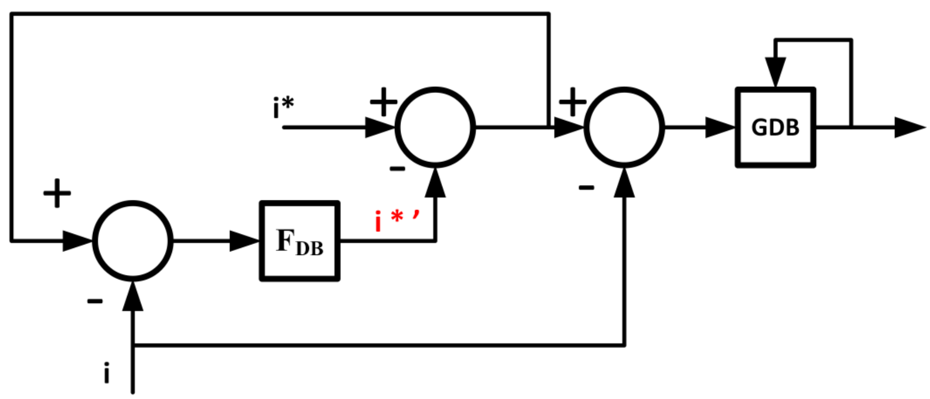

Figure 2-19: Current Control loop of grid tied PV system for dead-beat controller

Using a dead-beat controller, the control system adds unit sample delay. An observer can be added to the controller to mitigate for the unit sample delay [46], as shown in Figure 2-19, to adjust the current reference.

The discrete transfer function of controller is describe as :

$$G_{DB} = \frac{1}{A}\,\frac{1-e^{-\frac{R_f}{L_f}T_s}z^{-1}}{1-z^{-1}} \;;\quad A = \frac{1}{R_f}\,\left(e^{-\frac{R_f}{L_f}T_s} - 1\right) \tag{2.13}$$

The observer of dead-beat controller is given as:

$$F_{DB} = \frac{1}{1-z^{-1}} \tag{2.14}$$

Hence, reference current is computed as:

$$i^{*\prime} = F_{DB}\,(i^{*} - i) \tag{2.15}$$

An effort was made by the controller to eliminate the anomaly by adding one sample delay. As a result, a controller with a very fast response time and no delay has been created. Another benefit of using a microprocessor is that the dead-beat controller and observer algorithms are simple.

2.4.2.1 Survey of Control Structures for reference current generation

One of the key limitations of the synchronous reference frame based control system is the requirement for cross-coupling terms and voltage feedforward. In addition, the grid voltage phase angle is crucial in this approach. Figure 2-20 and Figure 2-21 show hypothetical application of abc frame control in which reference current for active power is determined by the output DC-bus voltage controller. The gating pulses for the voltage source converter are generated using either hysteresis current controller or sinusoidal pulse width modulation , as shown in Figure 2-20 and Figure 2-21.

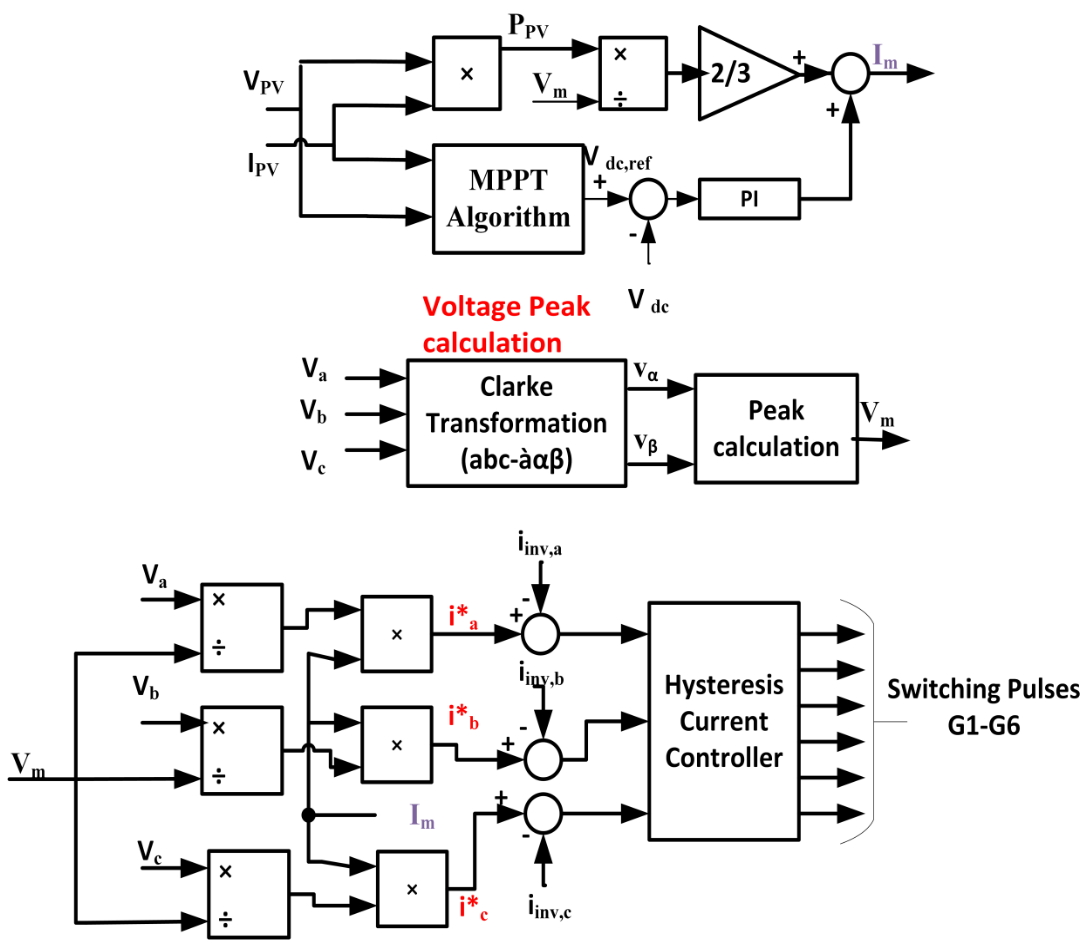

Figure 2-20: Control structure of grid tied PV system using hysteresis current controller

While complexity of the control of reference current generation using PR controllers in a stationary reference frame becomes lower than when using synchronous reference frame based control system. Moreover, the inclusion of the grid voltages template for reference current generation eliminates the necessity of PLL or phase angle information. Due to the sheer nature of the abc or stationary reference frame, a great degree of complexity can be achieved using a hysteresis controller with an adaptive band . Implementing a dead-beat controller, on the other hand, results in a more straightforward control strategy. Just as with stationary frame control, it is not necessary to know the phase angle or need of PLL. If grid voltages are employed to create the current reference, this control structure allows for individual control of each phase.

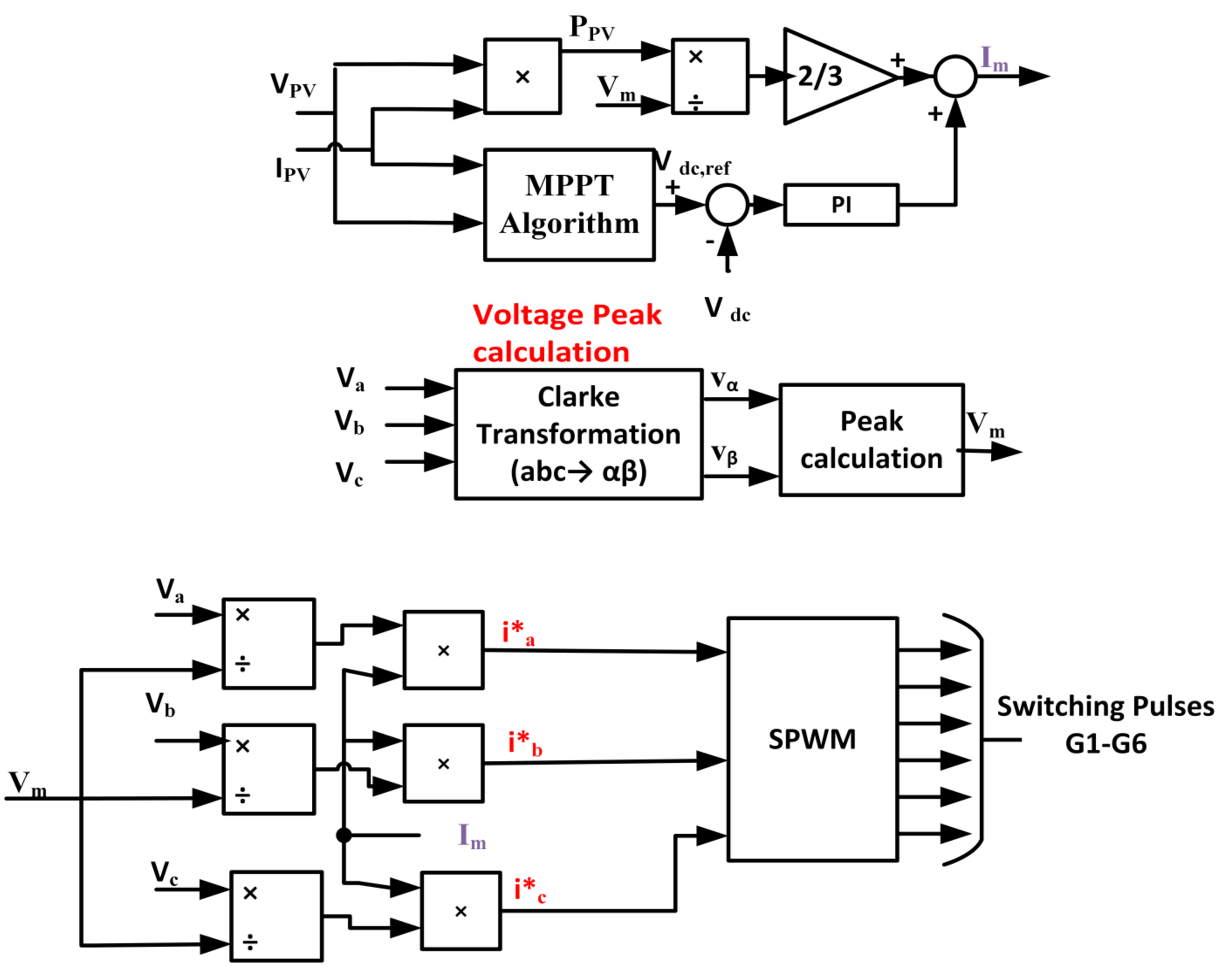

Figure 2-21: Control structure of grid tied PV system using sinusoidal pulse width modulation

2.5 Survey of Control Strategy during the abnormality in grid

Power grid instability may occur in some countries when large amounts of distributed power generation are interconnected. Because of this, dispersed power generation requires more stringent grid connecting regulations. Distributed power generation is becoming increasingly popular as a means of addressing with grid disturbances including sudden changes in voltage and frequency. Grid faults can be divided into two categories. [55]:

(i) Balanced voltage sag: It arises when all three grid voltages drop equally, but the system as a whole remains stable. This type of failure is extremely rare in power systems.

(ii) Unbalanced voltage sag: This occurs when the phases have unequal amplitude drops and phase shifts between them. Shorting one or two phases to ground or to each other causes this issue.

Second harmonic oscillations migrate across the system and cause ripples in the DC-link voltage. The control variables of the system are also affected. It is possible to tune the PLL system to obtain the precise phase angle of the grid voltage and to filter out the negative sequences. ([57–59]).

If the PLL system is not designed to be immune to imbalance, second-harmonic oscillations can affect the phase angle of grid voltages. The generation of current reference is also affected by second harmonic oscillations in the DC-bus voltage. Ride-through ability for distributed power generating system requires that the consequence of the unbalance be mitigated when performing in abnormal conditions.

Under faults, a control strategy can be implemented in one of four ways.

2.5.1 Unity Power Factor control approach

While grid faults occur, grid tied system has the ability to maintain unity power factor by employing various control strategies. Distributed power generation systems are stable during balanced grid voltages, but the negative sequence component of a grid fault causes oscillations at double the fundamental frequency of grid voltage phase angle oscillations. Because the injected currents will no longer have a sine-like waveform, they will instead have high-order components in their waveforms. There is no reactive power being injected into the grid since the current vector is directly proportional to the voltage vector at all times. Thus, during the fault duration, both active and reactive instantaneous powers remain constant.

2.5.2 Control approach of the Positive sequences detection (PSC)

Another control strategy that can be employed in a fault event is the positive sequence of grid voltages. In contrast to unity power factor management, a precise phase-angle extraction from grid voltages is necessary during unbalance grid voltage situation. Decouple double synchronous reference frame -PLL (DDSRF-PLL) are desirable for the detection of Positive voltage sequences of grid voltage and elimination of and negative voltage from the grid voltages. However, it gives precise phase-angle of grid voltages to the control system of grid tied system by the cost of complexity in implementation as well as slower down the performance of PLL . To encounter above issue , the dual-second ordered generalized integrator -frequency lock loop(DSOGI-FLL) is employed to extract precise phase-angle of grid voltage without compromising the reduction in bandwidth of PLL. There are identical reference currents generation for the distributed power generating system using a control structure like a dq-SRF using either DDSRF-PLL or DSOGI-FLL, and natural frame control using either DDSRF-PLL or DSOGI-FLL . Here, the only problem is the DC-bus voltage ripple, which has an impact on the current flowing. Using a digital filter such as delay signal cancellation [17], this can be eliminated without causing any delay to the system. Second-harmonic ripple can cause device failure if the DC-bus capacitor is not large enough. The amplitude of grid currents will increase, but they will stay sinusoidal and balanced if there is a defect in the grid. Double-frequency oscillations will appear in all power during the fault.

2.5.3 Control approach for constant Active Power Management

Under abnormal grid conditions, a third control method may be to preserve constant active power injection to the grid by distributed power generating system. In the event of an imbalance in the grid voltages, both positive as well as negative sequences will be present. In the same manner, the grid current will become unbalanced, resulting in double-harmonic oscillations for both active and reactive powers. PI controllers are used to regulate the current in the control structure, however extra controllers are required for the elimination of negative sequence from the current of distributed power generating system[17], [61]. This controller has the ability to regulate both $+\omega$ and $-\omega$ currents, making it a clear benefit from an implementation perspective in the event of a system of control based on the PR controller. While a disturbance is occurring, the grid currents really aren't balanced when using a constant power regulation technique. Furthermore, the reactive power oscillates at a significant rate.

2.5.4 Control approach for constant reactive Power Management

An analogous expression can be found for reactive power to eliminate the double-frequency oscillations, much like for constant active power management. It is also possible to find a current vector that is orthogonal to the grid voltage vector, giving the distributed power generating system the ability to independently manage its reactive power output. It is necessary to alter the reference for reactive power from zero to the corresponding value when a grid fault is recognized in this situation. By utilizing one of these control strategies, it is possible to comply with the impending grid rules regardless of what demands are placed on it by the power system controller when the distributed power generating system is interfaced to the grid

2.6 Conclusion

There is an overview of control structures that can be employed in a grid-connected system. The main aspects of various implementation structures, such as natural frame, stationary frame, and synchronous frame control structures, were highlighted. A control techniques for the grid-tied distributive generating system during the imbalanced grid disturbances were also categorized. Single-stage

PV systems often use an INC-based MPPT method, while power derivative (dP)-INC MPPT, which monitors the power oscillations, has shown the superior efficiency as compared to the other techniques.