CHAPTER 1

INTRODUCTION

1.1 GENERAL

In this world, most of the tropical countries like India use the solar energy as the source of electricity generation to meet the energy demand. In earlier days, seventy five percent of total global energy demand was supplied by the burning of fossil fuels. Due to the several disadvantages of fossil fuels such as increasing air pollution, global warming concerns, depletion of fossil fuels and their increasing cost, electrical utilities and end users of electrical power concentrate on the renewable energy sources for electricity generation. Among various renewable energy sources, Photovoltaic (PV) systems are being widely used to generate the electrical energy, because, they provide clean energy (pollution free) with less running and maintenance cost. This PV energy source can supply electricity in areas where there is no grid connection called stand-alone systems, or it can provide electricity to the grid connected systems.

In the PV fed grid connected system, as power electronics based devices and non-linear loads are connected at Point of Common Coupling (PCC), it can generate power quality issues such as harmonic currents and voltages, voltage sag, voltage swell, voltage flicker and power fluctuation etc., which may affect the quality of power. In grid connected systems, the power quality is one of the important factor to ensure the high transmission efficiency of the generated power from PV panel to grid. Therefore it is
necessary to analyse and solve the power quality issues with suitable type of custom power devices in the PV fed grid connected system.

Among various power quality issues, voltage sag is considered as the most severe power quality issue in the power system. The major reason for voltage sag is transmission system faults or distribution system faults at the feeder which is connected to the PCC. Another reason for Voltage sag is wide usage of voltage-sensitive loads such as Adjustable Speed Drives (ASD), process control equipment and computing devices. Short circuits, starting of large motors, sudden changes of load and energization of transformers are also the major causes of voltage sags. If the problem of voltage sag continues more than two or three cycles, it may cause voltage interruption or disruption and lead to heavy production and quality losses.

However, power electronics devices can be used to improve the quality of power in critical loads and to mitigate sags and swells. Among different types of compensation devices, use of Dynamic Voltage Restorer (DVR) is considered as effective solution since it can protect sensitive loads from the power quality issues such as sags or swells and also it can reduce the risk of load tripping during sag event. When voltage sag occurs at PCC, it injects appropriate three-phase AC voltages in series with the Supply voltage. By means of injecting the required amount of compensating voltage, quality of voltage can be improved effectively.

DVR also reduces the flow of high line fault current. The purpose of limiting the fault current is to restore the voltage at the point of common coupling and to protect the DVR system components during fault conditions in the electrical network.
1.2 LITERAURE REVIEW

Eteiba et al. (2013) implemented the photovoltaic model using basic circuit equations of the Photovoltaic (PV) cells with the effects of solar radiation and temperature changes. The mathematical modelling of PV module was done by Newton-Raphson algorithm. Characteristic curves such as current vs voltage (I-V) and power vs voltage (P-V) characteristics were obtained according to varying value of temperature and solar radiation. The design of PV array was also discussed.

Jena et al. (2014) discussed the combined circuit of the PV module with buck-boost converter. The curves were shown for varying temperature and irradiance. The results obtained from the model showed excellent correspondence to manufacturer’s curve. This paper provided a clear and concise understanding of the I-V and P-V characteristics of PV module.

Nasrudin et al. (2010) designed and presented the single-phase multistring five-level inverter for photovoltaic (PV) fed grid-connected system. To control the switches of inverter, multi reference single carrier Pulse Width Modulated (PWM) control scheme was used. To produce the required output voltage levels, three PV strings were cascaded together in parallel combination and it was connected to a five-level inverter. The inverter performance was compared with three level inverter and its output voltage waveform had lesser Total Harmonic Distortion (THD).

Mohamed Fasid et al. (2014) proposed a two inductor boost converter for the purpose of photovoltaic water pumping. The converter voltage was used to drive a three phase Induction motor directly from the PV energy. The remarkable feature of the proposed system was high lifespan since electrolytic capacitors were not used.
Vista Steny et al. (2015) described a Two Inductor Boost Converter integrated with cascade Cockcroft-Walton voltage multiplier. The multi-resonant tank employed in this converter was used to provide high voltage gain and to absorb the parasitic parameters of the transformer. With the use of snubber circuit, this type of converter could function as non-isolated converter. The voltage stress across the switch was also reduced. Advantages of this converter were low input current ripple, low cost and high step-up characteristics. To operate the PV cell at maximum power, converter switches were controlled by sine PWM control and MPPT control.

Ammar et al. (2014) developed the three-phase five-level inverter with reduced the number of switches. To generate the switching gate pulses, staircase modulation method was employed. With this new topology of multi-level inverter, total installation area and cost of the system were considerably reduced. Performance of this proposed inverter was tested for various modulation indices. To analyse the performance of this inverter, power loss versus efficiency and output power versus efficiency were compared with the other types of inverter.

Ronald et al. (2013) presented the modes of operation of two-level boost converter. Based on the DC averaging technique, the proposed converter was analysed in steady state mode and an idle mode. With the features of this converter, such as simplicity, robustness, high power and high reliability this type of converter was proposed to operate Hybrid Electric Vehicle (HEV).

Mosazadeh et al. (2012) proposed a seven level inverter for three phase grid connected system. MLI switches were controlled by In Phase Disposition Switching Pattern (IPDSPWM). This method was used to solve various power sharing problem among various cells of MLI in IPDSPWM method. The main feature of this method was the requirement of reduced
number of DC link capacitors. With this feature, the total cost and volume of the system were decreased.

Ehsan Esfandiari et al. (2013) described the experimental verification of forty seven level prototype of the switch-ladder multilevel inverter. This type of inverter allowed only four switches to conduct in each interval to reduce the switching losses and to increase the efficiency. Performance of inverter was also discussed for various fault conditions.

Banaei et al. (2012) proposed a new type of cascaded twenty seven level inverter by connecting low-frequency single-phase transformers. Reduction of number of switches and DC sources were achieved with the use of the Cascaded Transformer Inverter with Two DC sources (CTITS) structure. Switching pulses were generated by Multi-Carrier Sub-Harmonic Pulse Width Modulation (MCSHPWM). By comparing a sinusoidal reference waveform, with shifted carrier triangular (or DC) waveform, gate pulses were generated. Due to the higher number of output voltage levels with MLI, it could synthesize more nearly a sinusoidal waveform. This circuit topology was used for higher rated converters in medium and high voltage distribution system.

Wenhao Cai et al. (2012) presented the Single-phase double-stage photovoltaic fed grid-connected system. To control the boost converter, two MPPT algorithms were compared. The parameters used in the perturbation and observation method were fewer and the control logic was very simple. As the perturbation step was fixed, it oscillated near the MPP and produced loss. Incremental conductance method could be applied to the environmental change in condition. But control logic of this method was more complicated and the tracking speed was less. To control boost converter, perturbation and observation method was used. To increase the efficiency of the system, it used the duty ratio of the DC/DC converter as the control object. This type of
MPPT automatically adjusted the duty ratio with respect to the changes of the output power generated by solar cells. In order to connect with the grid, a DC-AC inverter was used. Double closed loop control method was used to control the inverter in proper way. The output current could also track the grid quickly at that moment. PLL technique used in the inverter circuit ensured the tracking accuracy for the output current of the inverter.

Li Zhang et al. (2016) proposed the five-level Dual Buck Full-Bridge Inverter (DBFBI) for grid connected applications. In this type of inverter, lower power rating devices and smaller filter inductors were used. To improve the reliability of existing five-level DBFBI topologies, an extended circuit of five-level DBFBI topology was performed. The working principle, modulation methods, and control techniques of five-level DBFBI topology were analysed. Experimental verification of three level DBFBI was performed.

Venu sonti et al. (2015) presented a pulse width modulation (PWM) technique for Cascaded Multi-Level Inverter (CMLI) used in transformerless PV fed grid connected system. The switches of five level CMLI were controlled by PWM technique integrated with MPPT algorithm. The advantage of using the proposed PWM technique was that it would reduce the high frequency voltage transitions in the terminal and common mode voltage. Leakage current of the PV array was also minimized by this proposed PWM technique. In addition to that, terminal voltage across the PV array and common mode voltage of the inverter were analysed. With this PWM technique, less number of carrier waves was generated as in the case of the conventional sinusoidal pulse width modulation technique (SPWM) for the given CMLI.
Slamet Riyadi (2013) analysed single stage PV fed Grid connected system using single phase VSI. To maximize the power generated by PV and to effectively transfer the power to the grid, Inverter control scheme is very important. By implementing simple current control method, inverter control can be achieved. When the solar irradiance decreased, the maximum power delivered by PV also decreased. But with the help of the proposed MPPT and inverter current control method, inverter was capable of delivering all the power generated by PV to the grid.

Xiaowei Wang et al. (2013) developed the mathematical modelling of three-phase PV fed grid-connected system. Boost converter switches were controlled by MPPT control and inverter was operated with current controlled mode. The developed model could accurately reflect the features and functions of PV system. Inverter control was performed by two control methods, namely inner-loop and outer-loop controls. The outer-loop control is voltage control loop method used to control DC/DC output voltage of boost converter. This particular loop was used to track the specified voltage by PI regulator. The inner-current control loop consisted of current-controlled voltage source inverter. This loop was used to control the grid-connected inverter based on the synchronous rotating reference frame theory. The purpose of d-axis current was to adjust the active power output of PV inverter, which helped to work the PV array at the maximum power operating point. The purpose of q-axis current was to adjust the reactive power output of PV inverter to control the power factor.

Lin Chen et al. (2014) designed and developed the two-stage three-phase four-wire grid-tie inverter system. LLC resonant converter was implemented with two stage ZVS. Different operating modes of ZVS were illustrated. To enhance the maximum power from PV, MPPT algorithm for the LLC resonant topology was implemented.
Sibasish Panda et al. (2013) analysed various faults in Maximum Power Point Tracking (MPPT) based grid connected system. To improve the solar energy conversion efficiency of PV array, perturb and observe (P&O) algorithm was used. Different types of AC faults were created on the grid side and its effects were analysed.

Ye Zhao et al. (2012) analysed line to line faults that occurred in solar photovoltaic (PV) arrays. The main purpose of fault analysis in PV array is to protect PV modules from damage and to minimize risks of safety hazards. Due to short-circuit faults or double ground faults this type of line-line fault occurs in PV array. The converter used in this method was controlled by maximum power point tracking (MPPT) method. Fault behaviour of PV arrays depends on fault location, fault impedance, irradiance level, and use of blocking diodes in PV array. Over Current Protection Devices (OCPD) were used in a PV array to prevent from high fault current. Effects of two types of fault conditions were analysed. One fault was considered under low irradiance condition and the other fault was considered during “night-to-day” transition. The effect of low irradiance fault condition and night-to-day transition condition was experimentally performed. Effectiveness of blocking diodes under line-line fault condition was also verified.

Kabir et al. (2014) introduced the coordinated use of PV inverters and battery energy storage to solve the voltage sag and swell problems. Furthermore, uncertainties in PV fed grid connected system were considered and discussed. Voltage profile of the grid system was improved greatly by employing larger battery energy storage system. Constant as well as variable droop-based battery energy storage system schemes were analysed.

Masoud et al. (2013) analysed the effects of various power quality issues such as voltage rise, voltage flicker, and power factor reduction
generated in grid-connected PV Systems. 16-bus test system was simulated to investigate the various effects of grid-connected PV systems on distribution systems. The mathematical model of PV panel was developed and Maximum Power Point Tracking (MPPT) algorithm was implemented in the boost converter to maximize the energy obtained from PV arrays. Furthermore, various parameters of PV panel were measured for varying solar irradiations. Effect of power fluctuation, voltage variation and harmonics were analysed in detail.

Reza Sedaghati et al. (2013) addressed the various power quality issues that occur in power system. Among different power quality issues, voltage sag and swell were considered as major concerns to the customers. Major causes and effects of sags and swells were discussed.

Mukthiar Singh et al. (2011) described the method of power quality improvement in grid interfacing inverter to at the Point of Common Coupling (PCC) for a 3-phase 4-wire Distributed Generation system. The proposed grid-interfacing inverter was used utilized as a multi-function device since it increased the real power transfer between PV, grid and improved the power quality. Various PQ issues such as current imbalance, current harmonics and voltage harmonics were compensated.

Yan Zhou et al. (2014) addressed the leakage current issue in PV fed grid connected system. In recent years, cascaded multi-level inverters were predominantly used in PV applications to maximize the energy harvested from solar PV panel. However, due to the parasitic capacitors and several grounding points, large amount of leakage current flowed through the cascaded multi-level inverter. To reduce the leakage current flow in the PV based system, suitable method of leakage current suppression was used. This method employed a resonant filter which consists of DC-side and AC-side
Common Mode (CM) chokes and capacitors. Filter parameters were designed by calculating leakage current value.

Quoc-Nam et al. (2014) described the advanced current control strategy to improve the power quality in the grid-connected Distributed Generation system. This control strategy was used to compensate for the effects of distorted grid voltage and to improve the grid current quality. By simultaneously eliminating the effect of non-linear local load and by compensating grid voltage distortions in the voltage output, grid current waveform could be produced like pure sinusoidal waveform. By using the d-q reference frame, new advanced current controller was designed and developed. It used Proportional – Integral (PI) controller and Repetitive Controller (RC). This single RC could compensate for a large number of harmonic components with the implementation of simple delay function. This method did not require the local load current measurement and the information about grid voltage harmonics. Without the installation of extra hardware, this method could be implemented for Distributed Generation (DG) control system.

Zamre Abdul Ghani (2013) investigated the performance of PV fed grid-connected three-phase inverter. Inverter switches were controlled by Proportional-Integral (PI) controllers, sinusoidal pulse-width modulation (SPWM) control technique and Park transformation. The main function of inverter was to convert generated PV power to AC power, stabilize the output voltage and current, and to supply the excess power to the utility grid. The inverter proposed in this method was operated under standalone and grid-connected mode. For standalone mode, two-loop control strategy structure was implemented. In this case, PI controller was used to regulate the inverter output voltage and the PV input voltage.
Jaume Miret et al. (2012) presented PWM current controller for a PV fed three-phase inverter. With the help of this controller, active power control and reactive power control were achieved even during the sag condition. The main objective of this type of controller was to assure minimum peak currents during the sag. The simulation and experimental results were compared with the conventional controller and by using this type of control scheme, the peak current values were highly reduced.

Shazly A. Mohammed et al. (2013) addressed the voltage sag and swell problem in grid connected system. Dynamic voltage restorer (DVR) was used for compensation of voltage sags and swells. DVR used in this method effectively handled both balanced and unbalanced sensitive loads. The controller for DVR action was designed in synchronous reference frame.

Zi Xuan Zheng et al. (2016) analysed the performance of Superconducting Magnetic Energy Storage (SMES) based VSC to compensate the voltage sags to protect sensitive load. The proposed system employed pre-sag compensation technique for mitigation of voltage sag. Voltage mitigation was performed under different voltage sag depths and different load capacities. The mathematical modelling of voltage sag angle was explained. The effects of the load capacity and voltage sag depth were analysed to protect short-time and long-time sensitive loads connected with the system.

Mollah Rezaul Alam et al. (2015) presented an algorithm for detection of voltage sags and swells due to balanced and unbalanced faults at different buses. To detect the presence of voltage sag, instantaneous magnitude of three phase voltage signals in three axes was used. In this method, three-phase voltage vector was used to trace an ellipse. From the parameters of ellipse, voltage sags and swells were classified and characterized. The proposed method was validated using simulation and experimental results.
Xiaoqing Han et al. (2013) developed and presented the Dynamic Voltage Restorer (DVR) for photovoltaic (PV) power generation system to improve the voltage quality in a micro grid. By developing the battery based Energy Management System (EMS), the proposed system could be operated under dynamic voltage restorer mode, uninterrupted power supply mode and micro-source mode, and it could be switched properly among any type of mode. In addition, voltage sag problem was addressed and it was compensated by DVR system. In this method, DVR was effectively designed to supply power to the load.

Dionisio Barros et al. (2010) presented optimal predictive controller for a Dynamic Voltage Restorer (DVR) to improve the voltage quality of sensitive loads. Voltage source inverter used in DVR was replaced by three-phase Neutral Point Clamped (NPC) multilevel converter to inject the compensation voltage vector in series with the line voltage, through series-connected transformer. Moreover, DVR switches were controlled by optimal predictive controller. To validate the performance of proposed predictive controller, its performance parameters were compared with proportional integral (PI) controller, synchronous frame and stationary frame controllers.

Deepak et al. (2014) dealt with the Ultra Capacitor (UCAP) based DVR to improve the power quality of the distribution grid. With this integration of UCAP into DVR, the power conditioner used in DVR would be able to compensate voltage sags and swells. To provide active/reactive power support Active Power Filter was developed. Ultra-Capacitor was integrated with the DVR through a bidirectional DC-DC converter at the dc-link of the DVR. The series inverter used in DVR was controlled by in phase compensation and the shunt inverter was implemented based on $i_d - i_q$ method.
Firouz Badrkhani Ajaei et al. (2011) proposed a novel control scheme for the dynamic voltage restorer (DVR). This type of control scheme was developed to mitigate voltage sag effectively. This method was able to control magnitude and phase angle of the injected voltage for each phase individually. For estimating magnitude and phase parameter of measured load voltage, Least Error Square (LES) filter was used. The filter used in this method had reduced the effects of noise, harmonics, and disturbances on the estimated phasor parameters. DVR was operated under both linear and nonlinear load conditions. DVR used in this method had restored the load voltages during balanced and unbalanced sags.

Jing Shi et al. (2010) presented a Superconducting Magnetic Energy Storage (SMES) based Dynamic Voltage Restorer (DVR) to protect electrical utilities from the grid voltage fluctuations. The operation principle of the SMES based DVR was analysed in detail. The control action of DVR was performed by voltage compensation control, PWM converter control and DC chopper control. To control the switches of PWM converter controller, Double-loop control strategy (inner current regulator and an outer voltage controller) was used. Performance comparison of DVR was done with all types of controller to show the effectiveness of DVR.

Suma et al. (2014) presented the storage less Dynamic Voltage Restorer to solve the voltage related PQ problem. This type of DVR was operating without the DC link by using a direct AC-AC converter. Since no storage device was used, these topologies required improved information on instantaneous load voltages at the point of common coupling and it required flexible control schemes depending on these voltages. Here type B sag was introduced and it was compensated by DVR. To achieve the voltage sag compensation, suitable compensation algorithm was performed and it took half a cycle to compensate. Since Fourier transform was applied to extract the
fundamental component, this same algorithm could be applied to compensate the harmonics and imbalance.

Sung-Hun Ko et al. (2012) presented a grid-connected photovoltaic (PV) system with direct coupled Power Quality Controller (PQC). This controller used two feedback control loops, inner current control loop and outer feedback control loop. By implementing inverter control by means of this control method, grid power quality and maximum power point tracking (MPPT) of PV arrays were improved. Inverter was operated under current control mode, so that it could maintain the THD level within permissible range without requiring any additional hardware or complex control. This single stage current controlled VSI reduced the complexity, cost and number of power conversions, which resulted in higher efficiency. The proposed system could be operated in both sunny mode and night mode. This system had increased the system utilization factor.

Adel M. Sharaf et al. (2014) presented a novel FACTS based Switched Power Filter Compensator (SPFC) scheme for smart grid application. This type of FACTS controller was used for efficient PV energy utilization. With this controller, bus voltage could be stabilized and fault inrush current could be limited to considerable value. Storage scheme used in this method consisted of PV-Li-Ion Battery. Based on the controller effectiveness, AC system stabilization, power factor improvement, voltage stabilization and power factor correction could be achieved.

Abdul et al. (2015) discussed the integration of DVR with grid-connected photovoltaic (PV) system. They modelled and simulated the six-port converter and used the same in DVR system. It consisted of nine semiconductor switches. With this concept, the number of switches was reduced from twelve to nine. The effectiveness of DVR system was investigated for various modes like grid healthy mode, grid fault mode and
voltage sag mode. To control the voltage source inverter of DVR, synchronous reference frame theory based control algorithm was developed and implemented.

César et al. (2013) designed and developed PV power generation systems based on a double power conversion structure. The control structures for PV micro inverter operation modes were described. The inverter was worked at both grid-connected mode and islanding mode. The designed inverter properly injected PV power to the grid during current control mode. Same type of current controller was used for the inverter during island mode. The reference signal for the inverter voltage loop was generated by means of droop scheme.

Qi Zhang et al. (2011) developed and presented the digital PLL (DPLL) method for single-phase grid connected inverter systems to detect the accurate phase information of the grid voltage. This information was very useful to achieve the unity power factor control. In grid connected systems, power quality is an important key factor. In this method, a digital butterworth filter was designed and implemented to extract the fundamental signal from the grid voltage and this signal was considered as unity sine reference signal. The sliding-window-based data sampling method was also presented to regulate the phase shift of the unity sine reference. But it did not use any stationary coordinate transformation or synchronously rotating coordinate transformation for grid synchronization.

Dineshbabu et al. (2014) compared and analysed the performance of various types of grid synchronization techniques such as zero crossing detection technique, charge pump phase locked loop and synchronized reference frame phase locked loop. In addition, harmonic issues in grid synchronization techniques had been addressed and compared with power quality standards.
Yongheng et al. (2013) experimentally analysed and tested the performance of single phase grid connected system at grid faults and abnormal grid conditions. The second-order-general integral-based phase-locked-loop technique was implemented and grid synchronization was achieved. Different control strategies used in single-phase PV systems under grid faults were explained and comparison had been done to select the best choice of control technique.

Pedro Rodríguez et al. (2011) presented the multi resonant frequency adaptive synchronization method for grid-connected power conversion system. This type of frequency locked loop was used to estimate the positive- and negative-sequence components of the power signal at the fundamental frequency and it could estimate other sequence components at other harmonic frequencies. This type of system was named as MSOGI-FLL since it was based on both a harmonic decoupling network consisting of Multiple Second-Order Generalized Integrators (MSOGIs) and a Frequency-Locked Loop (FLL). This type of FLL makes the system frequency adaptive.

Gerardo Escobar et al. (2011) presented the method of achieving grid synchronization in three phase grid connected system. Fixed Reference Frame (FRF)-PLL was implemented to achieve grid synchronization. Various steps involved in estimation of the angular frequency and both the positive and negative sequences of the fundamental component of an unbalanced three-phase signal were explained in detail. FRF-PLL did not require transformation of variables into the synchronous frame coordinates. Simulation results confirmed the effectiveness of FRF-PLL for unbalanced conditions, angular frequency variations, sags, and swells.

Fengjiang et al. (2015) proposed the new Two-Phase Stationary-Frame Based Enhanced Phase-Locked Loop (TPSF-EPLL) for the purpose of detecting the amplitude, phase angle, and frequency of a three phase grid.
TPSF-EPLL required lesser calculation since transformation into a rotating reference frame was not involved. In this method, all the calculation was performed in a two-phase stationary frame. Based on equations of linear control theory, stability of the TPSF-EPLL was analysed. The performance comparison of TPSF-EPLL with other types of PLLs was presented. This type of TPSF-EPLL was used to calculate the amplitude, frequency, and phase angle of a three-phase grid voltage accurately without transformation into a rotating reference frame.

Sergio Martín et al. (2013) developed a three-phase Digital Phase Locked Loop (DPLL) for grid synchronization. To estimate the instantaneous grid frequency new Phase Detector (PD) structures based on single-phase voltage values were proposed and analysed. To accurately measure the phase angle and magnitude of grid voltage, Estimated phase angle and Amplitude method (EphA) was used in this scheme. This method was effectively working even under the presence of these imbalance disturbances.

Lenos Hadjidemetriou et al. (2016) employed a Multi Harmonic Decoupling Cell (MHDC) based phase locked loop for single-phase grid-tied inverter. Due to lower order harmonics, synchronization signals contained oscillations and to minimize those oscillations MHDC-PLL was designed and developed. The performance of this proposed PLL was analysed for highly distorted grid voltage condition and different grid disturbances such as voltage sag and phase jump. But this method did not effectively work to eliminate the small oscillations under non-nominal frequency.

Yi Fei Wang et al. (2011) described the concept of Delayed Signal Cancellation (DSC) to achieve grid synchronization. In grid connected system, DSC was mainly used to eliminate any specified harmonics. To eliminate a particular range of undesired harmonics in the grid voltage,
number of DSC operators was combined into a Cascaded DSC (CDSC) operator. By proper selection of PLL control loop, accurate bandwidth and fast detection of grid phase angle could be obtained. By means of various configurations of the CDSC block, two types of PLL were designed. All symmetrical (odd and even) harmonics were eliminated by the first type of PLL. Both symmetrical and asymmetrical harmonics were eliminated by the second type of PLL. The performance of PLLs was analysed in terms of transient and steady-state conditions. During grid frequency variations, frequency feedback loop was added to both types of PLL. These types of PLL were working effectively at grid voltage distortion and grid voltage phase jump.

Evgenije Adzic et al. (2013) discussed the PLL design methods for grid-connected system. The designed PLL was used to achieve grid synchronization for highly unbalanced and distorted grid voltage conditions. To eliminate harmonic components in estimated grid frequency and angle information, PLL filter was properly designed. This type of PLL was used to achieve fast dynamic response in the case of voltage phase jumps during grid voltage sags.

Guerrero et al. (2014) investigated various synchronization algorithms used in grid-connected system. The effectiveness of various synchronization algorithms at frequency variation and harmonic injection in the three phase grid connected system was analysed. The behaviour of Multiple Second order Generalised Integrator – Frequency Locked Loop was better as compared with the other types of PLL method since accurate phase detection was achieved.
In the above cited literature, three phase PV fed grid connected system was implemented with voltage source inverter. Multi-level inverters were not reported to improve the quality of PV fed grid connected system. In the works cited in the literature, Synchronous Reference Frame theory based Phase Locked Loop (SRF-PLL or dq-PLL) was implemented to achieve grid synchronization at varying frequency conditions. Thus the literature does not deal with the SRF-PLL control during voltage sag and swell conditions.

1.3 OBJECTIVES OF THE THESIS

The objectives of the investigations carried out can be summarized as follows:

To design and develop the MATLAB/ SIMULINK model for three phase PV fed grid connected system with multi-level inverter.

To perform the multi carrier based modulation technique for three phase multi-level inverter and to perform the harmonic analysis to select the suitable choice of modulation strategy.

To design and develop the Dynamic voltage Restorer to mitigate voltage sags and swells.

To design and develop synchronous reference frame theory based PLL to achieve grid synchronization during frequency variations, sag and swell conditions.

To implement the hardware of DVR system to compensate for the voltage sag.
In order to validate the analysis and design of the above PV fed grid connected system with multi-level inverter and to verify the effectiveness of the SRF-PLL technique, MATLAB/ SIMULINK software is used. PIC16F87C microcontroller is used to ascertain the effectiveness of the control techniques in real time.

1.4 BLOCK DIAGRAM

![Block Diagram of PV Fed Grid Connected System](image)

**Figure 1.1 Block diagram of PV fed grid connected system**

The block diagram of three phase PV fed grid connected system is shown in Figure 1.1. It consists of PV array as a source, DC/DC converter, MLI, Dynamic Voltage Restorer (DVR) system, three phase transformer, grid synchronization block. Here energy obtained from PV module is used as source. Two inductor boost converter is used to boost the voltage generated by PV module. Since power obtained by a PV source is DC, it requires DC to AC inversion stage. To convert DC to AC, multi-level inverter is connected.
with the grid. Its important function is to enhance the active power injected by PV array and to interconnect the PV module with grid. The switches of MLI are controlled by multi carrier PWM switching pattern. DVR is connected to mitigate sag and swell during fall and rise of the voltage. Here DVR can compensate voltage sags by means of injecting the three phase inverter voltage through the series connected transformer. Grid synchronization block is used to achieve the grid synchronization with the help of SRF-PLL.

1.5 ORGANISATION OF THE THESIS

The thesis is divided into seven chapters. Organization of the thesis is as follows:

The Chapter 1 presents the general introduction to the problem and the review of previous investigations reported in the literature. It concludes with the statement of the main objectives of the work presented in the thesis.

The Chapter 2 describes modelling and simulation of PV module. Various modes of operation and Simulink model of Two Inductor Boost Converter (TIBC) used in the PV fed grid connected system are explained in this chapter.

The Chapter 3 analyses the performance of multi reference PWM based and multi carrier PWM based MLI used in grid connected system. The details of hardware implementation of MLI are also presented in this chapter.

Chapter 4 describes the various faults that may occur in the grid connected system. It describes the effect of both symmetrical and asymmetrical faults on grid system. The working principles of DVR and fault compensation using DVR are explained in detail. Simulation results using MATLAB/SIMULINK package are also presented.
Chapter 5 presents the various power quality issues involved in the grid connected system. The effect of grid connected system during sags and swells is presented. This chapter gives the concept of sag and swell mitigation using DVR. Experimental verification of DVR to compensate the voltage sag is also presented in this chapter.

The concept of synchronous reference frame theory is explained in the Chapter 6. The design and Simulink model of SRF based PLL to control the DVR-VSI are presented in this chapter. This chapter also presents the grid synchronization using SRF-PLL under frequency variations, sags and swell conditions.

Chapter 7 concludes the thesis indicating the scope for further research.

1.6 CONCLUSION

The literature review, objectives and organization of the thesis are presented in this chapter.