CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

The focus of this chapter is to present a brief overview of diverse aspects of the control of grid-connected converters in micro-grid environment available from the extensive range of literature. The literature survey is classified into various topics starting from the general structure of grid-connected systems, the choice of converter and its switching schemes, output filter choice, control configurations in different Reference frames and their performances etc.

2.2 AC VOLTAGE GENERATION WITH VOLTAGE SOURCE CONVERTER

Line commutated converters were proposed for grid connection of VSC in the literature by the authors Shanthi & Ammasi Gounden (2007). A power electronic interface using boost converter and line commutated inverter is proposed with maximum power point tracking (MPPT) by them.

Blaabjerg et al. (2010) studied the trends of the most emerging renewable energy sources, wind energy and Solar photovoltaic (PV), and their impact on the power electronic converters and their control. In photovoltaic system transformer-less topologies are discussed with the perspective of reaching highest efficiencies. Line commutated as well as PWM converters were proposed by the authors.
Kadri et al. (2011) proposed a voltage-oriented control (VOC) to solve a fast-changing irradiation problem in solar PV converter systems. They used a two stage converter and control structure with an outer dc link voltage control loop and an inner current control loop. The reference currents are obtained from the dc-side voltage regulator by applying the energy-balancing control.

Haque et al. (2010) presented a novel control strategy for the operation of a direct drive permanent magnet synchronous generator (PMSG) based stand alone variable speed wind turbine. Here also a two stage converter scheme is used with a chopper and a grid side PWM converter with the dc link voltage maintained by chopper control.

Blaabjerg et al. (2006) conducted a review on the structures for the distributed power generation systems (DPGs) based on fuel cell, photovoltaic, and wind turbines. Here two stage as well as three stage converters are considered. The generic control structures of the grid-side converter are presented, and the possibility of compensation for low-order harmonics is also discussed.

Teodorescu et al. (2006) discussed the control of a two stage converter for interfacing renewable energy source to grid using proportional-resonant (PR) controllers and filters. They declare that the grid side converter reference tracking performance is enhanced with reduced steady state error, better dynamic response due to the elimination of synchronous reference frame transformations.

Noroozian et al. (2010) presented control of power flow in DC distribution system by network and storage converters. The converters for all renewable sources and storages are considered to be two stage converters with instantaneous power regulation scheme for the grid side converter.
Chomsuwan et al. (2002) described a two-stage photovoltaic grid-connected inverter. The first stage is a two-switch buck-boost circuit that performs various functions viz. tracking a maximum power point of the photovoltaic array and controlling current and the second stage is a H-bridge switch which shapes the current with low harmonic distortion and synchronize it to the utility.

Femia et al. (2009) proposed double-stage grid-connected photovoltaic (PV) inverters, the dynamic interactions among the DC/DC and DC/AC stages with maximum power point tracking (MPPT) controller. In this paper, the negative effects like system efficiency and MPPT performances, oscillations of the PV array voltage are minimized by a suitable compensation network acting on the error signal.

Multilevel converters are used for utility interface of renewable energy system in the literature (Tolbert 2000), in which, Multilevel inverter structures have been used for interconnection with high-voltage electrical systems. Renewable energy sources such as photovoltaic arrays or fuel cells are proposed to be connected through the 11–level cascaded H-bridges multilevel inverters.

Selvaraj et al. (2009) in their paper presented a single-phase five-level photovoltaic (PV) inverter topology for grid-connected PV systems with a novel pulsewidth-modulated (PWM) control scheme. The proposed inverter results less THD with unity power factor operation.

Alepuz et al. (2006) proposed a three-level, three-phase neutral-point-clamped voltage-source inverter for the connection of renewable energy sources to the utility grid interfacing system. D-q state-space averaged models of the system are used to calculate the reference quantities for simultaneously regulating the dc-link voltage and obtaining UPF current delivery.
Waleed Al-Saedi et al. (2013) studied the optimal power flow controller for a utility connected microgrid based on a real-time self-tuning method. Two stage IGBT inverters are considered and the control scheme consists of inner current loop and an outer power loop in dq frame with PI regulators. Particle Swarm Optimization (PSO) is used for self tuning the controllers.

2.3 PULSE WIDTH MODULATION FOR VSC

The gate controlled converters will be operated using pulse width modulation techniques (PWM) to achieve the capabilities mentioned above. Many PWM techniques are available and utilized for grid connected converter control. Among the different choices of PWM controls, carrier based PWM such as Sine PWM (SPWM) and the recent Space Vector PWM (SVPWM) are the most extensively used techniques because of the stringent harmonic grid codes for grid interconnection. The SPWM falls under linear modulation techniques whereas SVPWM is a non-linear modulation technique. These modulation processes use a high frequency carrier for modulation, thus making the phase voltage lowest order harmonics (LOH) to be pushed to the high frequency side located around the switching frequency, consequentially reducing the size of the filter required. Harmonics can be minimized if the carrier is chosen as an odd multiple of three of the reference frequency. By and large the switching losses put a limitation on the increase of the switching frequency.

Blaabjerg et al. (2006) conducted a review on the structures for the distributed power generation systems (DPGSs) based on fuel cell, photovoltaic, and wind turbines. Here two stage as well as three stage converters are considered. The lower order harmonics are reduced by choosing the PWM technique and the switching frequency.
Ned Mohan et al. (2007) have written about different modulation techniques used for inverters in different applications. The influence of the switching frequency on the lower order harmonic and the switching losses were discussed. The influence of amplitude modulation index on the output voltage is also extensively covered.

Daniel W. Hart (2011) written about different modulation techniques used and their implementation with simulation tools for various applications. The selection of switching frequency and the selection of dc link voltage is dealt in detail.

Haque et al. (2010) discussed a direct drive permanent magnet synchronous generator (PMSG) based stand alone variable speed wind turbine with a two stage converter scheme with grid side converter controlled using sine PWM. Though the control strategy is implemented in dq reference frame the reference values are converter into abc and Sin PWM is used.

Holmes & Lipo (2003) have done an extensive analysis and discussions on various PWM techniques and their effectiveness on the specifications of the inverter output. Suggestions were given for selection of a particular PWM technique depending on the control variables and the output requirements.

Zmood & Holmes (2003) analysed a hybrid synchronous reference frame controller for PWM inverter, wherein the control is happening with the dc quantities after converting the reference abc quantities to dq, but the control signal is converted back to abc for switching a Sine PWM block, with proper selection of the switching frequency, the controller gain is calculated for a stable control loop.
Zhou et al. (2002) investigated a comprehensive comparison between the carrier-based PWM and space-vector. It is suggested that compared with three-phase Sine PWM, SVPWM can extend the linear modulation range for a required line-to-line voltages. Because of this reason, Sine PWM inverter requires large dc input voltage, i.e. it does not use the dc input voltage efficiently. Sometimes this may lead to the operation of converter in the over modulation region, resulting in square wave operation with high harmonic distortions at lower frequencies close to the fundamental frequency. Sine PWM does not suit advanced controls like vector control or grid synchronization where the grid frequency to be tracked by the converter.

Malinowsk et al. (2004) proposes a direct power controlled three-phase pulse width-modulated (PWM) rectifiers using space-vector modulation. In this paper the active and reactive powers are used as the pulse width modulated (PWM) control variables. Moreover, line voltage sensors are replaced by a virtual flux estimator. It is reported that spacevector PWM based control exhibits good dynamic response, constant switching frequency, and particularly it provides sinusoidal line current when supply voltage is not ideal and also simple algorithm.

Fang Yu et al. (2004) discussed an algorithm for space vector pulse width modulation in three phase power factor correction applications. They suggested that by their algorithm the running speed and precise control can be achieved. As a result the switching frequency and power density of the rectifier is increased considerably for applications like grid connected converters and vector control of industrial drives etc.

Rakesh Parekh (2005) in the application notes of Microchip Technologies has explained the implementation of Space vector PWM using 8-bit microcontroller for induction motor V/F control. He suggests the
advantages of SVPWM over Sine PWM as sophisticated, averaging, digital implementable algorithm, which gives 15% more output voltage for the same dc input voltage with the same $m_a$ compared to Sine PWM. This feature increases the utilization of the dc link voltage in case of the multi stage converters. It also has lower THD and switching losses compared to Sine PWM for the same switching frequency and $m_a$.

2.4 GRID SYNCHRONIZATION

The major hurdle in the injection of current into the grid through a voltage source converter (VSC) is the grid synchronization. i.e. the voltage, phase and frequency of the VSC need to be matched with the grid values continuously as it is a power electronic controlled asynchronous link.

Various techniques for detecting the phase angle of the grid voltage is presented in the literature. The commonly used synchronization techniques are: (i) Zero crossing detection, (ii) $\alpha\beta$ filtering algorithms, (iii) dq filtering algorithms, and recently, (iv) Synchronous Reference Frame Phase-Locked Loops (SRF-PLL).

Chung et al. (2000) proposed the analysis and design of a phase-locked loop (PLL) system for the grid synchronization of three phase inverters. The dynamic behaviour of the PLL system is analyzed under normal grid conditions as well as distorted grid conditions like phase unbalancing, harmonics, and offset. The proposed PLL is implemented digitally using a digital signal processor (DSP). The results are verified with the analytic results.

Kaura et al. (1997) studied the operation of a phase locked loop (PLL) system under distorted utility conditions like line notching, voltage
unbalance/loss, and frequency variations. The PLL is implemented in software and the analytical results are experimentally verified.

**Ghoshal Anirban & Vinod John (2007)** have developed a Phase tracking system for grid synchronization of a grid connected power converter. In this work a method to obtain accurate phase information when the grid voltages are unbalanced by adding a moving average filter to a SRF PLL has been proposed. A better fault ride through capability is obtained for the power converter with the proposed PLL.

**Venkatramanan & Vinod John (2010)** developed a control strategy for grid synchronisation and line current regulation. They have discussed a single phase PLL required for grid connection in dq frame of reference.

**Timbus et al. (2006)** have investigated the possibility of using the Phase Locked Loop (PLL) algorithms for grid monitoring. The main concern is on the ability of the PLL to extract other grid information like voltage, frequency, sequence components etc. besides the phase angle. The emphasis is on the voltage amplitude and frequency extraction, but the other attributes of the PLL systems such as the possibility to detect unbalance and to extract the positive and negative sequence from the grid voltages are also discussed. A detailed description of standards for wind turbine (WT) and photovoltaic (PV) systems regarding grid monitoring is also found in the literature.

**Agirman et al. (2003)** developed an observer which has a similar structure to a PLL which provides position or angle of line voltages for a grid connected three phase VSC control. For estimation of the magnitude of line voltage, they have used another observer in the q axis. Both the observers are implemented in synchronous frame of reference.
Chung & Se-Kyo (2000) have analysed and designed a phase-locked loop (PLL) for the power factor control of grid-connected three-phase power conversion systems. The performance of the developed PLL is also tested under distorted utility conditions such as the phase unbalancing harmonics, and offset caused by nonlinear loads and measurement errors. The system is tested both in simulation as well as in hardware.

Karimi-Ghartemani et al. (2004) proposed a new synchronization method using an enhanced phase-locked loop (EPLL). The EPLL-based synchronization method gives higher degree of immunity and insensitivity to noise, harmonics and other types of pollutions that exist in the utility. They recommended the use of their PLL for the distributed generation units, e.g., wind generation systems, which utilize power electronic converters as an integral part of their systems.

Timbus et al. (2005, 2006) reviewed the grid synchronization methods for three phase utility interface of three phase voltage source converters. He discussed the dq frame PLL both for single and for three phase systems. Also the use of two linear controllers is discussed for independent control. In another paper of the same author different synchronization techniques like ZCD, dq filtering and SRF PLL were compared for their dynamic performance under various grid conditions for a grid connected VSC.

Nicastri & Naglieri (2010) presented the basic features of the PLL techniques and in particular Synchronous Reference Frame-PLL scheme. For filtering the grid voltage Low Pass Filter, Resonant Filter, Moving Average Filter, Repetitive Controller were considered for internal filtering and dual SOGI-PLL and Enhanced-PLL were adapted for external filtering.
These filters make the PLL to work even under abnormal conditions like unbalance, harmonics etc.

**Rodriguez et al. (2008)** employed a double synchronous reference frame PLL (DSRF-PLL) for grid synchronization of VSC wind energy system when a transient fault occurs in the grid. It uses a dual synchronous reference frame to separate the positive and negative-sequence voltage components. Experimental evaluation with DSRF-PLL in the grid synchronization of WT's power converters were presented for unfavourable grid conditions.

**Svensson (2001)** investigated four different synchronisation methods for a voltage source converter connected to a three-phase grid. The results are compared by response characteristics of phase-shift steps, frequency steps and low-frequency grid voltage harmonics. A new method called extended space vector filtering is adopted to account frequency variations, and claimed that it is better compared to Kalman filter algorithm.

**Kim et al. (2004)** in their paper presented a novel method to generate reference waves synchronized with the grid even under fault conditions of the grid. The algorithm proposed by them synthesizes the expected positive sequence reference waves from the measured line voltages with or without distortion. The dynamic performance is reported to be good for grid connected applications.

**Hsieh Guan-Chyun & James Hung (1996)** discussed the fundamental phase-locked loop (PLL) techniques of the past 30 years. Recommendations of the basic PLL structures suitable for communication and servo control systems were reported with the popularly available PLL chips in the market.
As seen above the SRF PLL discussed has a reference frame transformation, which serves as the basic building block in obtaining the actual grid information. This implies that the accuracy of the phase detection is highly related to the accuracy of this transformation. When the grid conditions are distorted, the accuracy of transformation will be lost and so the accuracy of the SRF-PLL will also be compromised.

2.5 CHOICE OF OUTPUT FILTER TOPOLOGIES

The choice of the output filters are dictated by stringent tolerances set by standards such as IEEE 519-1992 and IEEE P1547.2-2003, the grid codes for harmonic standards for grid interconnection of renewable sources. Higher order filters is a better choice to achieve these standards. However, the increase in size, weight and cost, the decrease in system stability due to increased order, and the complicated controls for higher order systems are the bottle-necks with such topologies.

The three topologies commonly found in literature as the output filter for grid connected converter schemes are L filter, LC filter and LCL filter. The transfer function of the current delivered to the grid to the inverter voltage with V_g short circuited is \( H(s) = \frac{1}{Ls} \) with L filter at the output. But the transfer function will remain the same even with LC filter. Therefore, size of inductor does not change with L or LC filters. But LCL filters are better choices with an attenuation of 60 dB/decade for frequencies above resonant frequency; therefore converters could be switched at lower switching frequencies. But the LCL filter will be vulnerable to oscillations and it will amplify frequencies around its cut-off frequency due to series and parallel resonance. Therefore the filter is provided with damping, which constitutes losses and requires a complicated control if active damping is to be done.
Channegowda et al. (2010) discussed the use of higher order LCL filters for meeting the interconnection standard requirement for grid-connected voltage source converters. A comparison between L, LC and LCL filters with respect to harmonic attenuation, efficiency and size is discussed in detail. The focus of the paper was to analyze the LCL filter design procedure from the point of view of power loss and efficiency. The power loss and harmonic output spectrum of the grid-connected LCL filter was found through experimental studies.

Parikshith & Vinod John (2008) presented the design of higher order LCL filters for grid-connected inverters with multiple constraints like size reduction, minimum power loss etc. The standards such as IEEE 519-1992 and IEEE P1547.2-2003 were considered for fixing the filtering tolerances. They discussed the design procedure for higher order LCL filters in per unit. Experimental verification of results for the designed filters was also presented.

Timbus, Adrian et al. (2006) in their paper discussed different current controllers for grid-connected distributed power generation systems. An improved DB controller robust against grid impedance variation is presented. Under steady-state, the total harmonic distortion of the grid current is maintained to meet the standard. The analysis is based on different types of filters.

He Jinwei & Yun Wei Li (2012) proposed a closed-loop control scheme for voltage source converters with LC or LCL output filters. The proposed scheme has virtual impedance terms and the control is upgraded with this. The experimental verifications of the control scheme with the virtual impedance with LC and LCL filter were presented.
Twining & Holmes (2003) presented a comparative study of series inductance filter and an LCL network to reduce the harmonics in the distribution network. It is found by the author that the systems with LCL filters need complex control strategies and are not commonly available in literature. Expressions for harmonic impedance of the system are derived in order to study the effects of supply voltage distortion on the harmonic performance of the system.

Liserre et al. (2004) proposed an active rectifier for grid connection. They suggested that the overall system behaviour is the key factor for control. The sub topics covered are selection of passive elements, sensor’s position, analog/digital filters and ac current/dc voltage controllers etc. The authors also observed how these parameters change the dynamics of the systems.

Prodanovic, Milan et al. (2003) presented a control scheme that utilize the controllability of inverters to operate a micro-grid and provide good power quality. They examined the system for various filter choices. The limitations of communication and control bandwidth were also discussed.

Prodanovic, Milan et al. (2003) presented in another paper the effect of switching frequency and pre-existing grid voltage distortion on delivered power quality. They have emphasized the requirement of a well designed filter for elimination of switching frequency harmonics. The effect of the filter size on the control bandwidth and the impedance presented to grid distortion are also discussed in detail. The paper describes a filter designed to with an isolating transformer, a controller design which rejects grid disturbance, at the same time achieves real and reactive power control.

Enslin et al. (2004) analysed the harmonic interference of large PV inverters and compared the network interaction of different inverter
topologies and control combinations. The PV penetration with the controllers and the filters and high switching frequencies were discussed in detail.

Wang et al. (2003) presented the comparison of conventional LC filter with third order LCL filter for grid-interconnected inverter. The design considerations of the output filter for the grid-interconnected inverter were discussed in detail. Different passive damping filters and the optimized design guidelines were also proposed by the authors.

2.6 CURRENT CONTROLLERS FOR ACTIVE-REACTIVE POWER CONTROL

The control capabilities for the grid connected power converters listed in the beginning of this chapter are achieved through feedback controllers with various controlled and controlling parameters. The performance of such converters solely depends on the stability, the reference tracking, and the dynamic response of the controller, which delivers a predefined amount of current for a given reference power value. Hence, the design and structure of possible current controllers are important issues to be considered in power electronic converter control. The conflict in this problem is that, the controlled parameters are the phase currents which are ac quantities and the legacy control techniques like P, PI and PID regulators can handle only dc quantities. The control problems would be (i) is it possible to have dc control loops rather than ac? (ii) If only ac control loops are to be used then what will be structure of the new regulator? (iii) Will the new regulator be as effective as the time tested dc regulators? (iv) If only dc regulators are to be used, then how to achieve an equivalent dc from the ac quantities? This subsection analyses and discusses the possible answers available in the literature for the identified control problems for the grid connected power converters.
Kazmierkowski et al. (1998) proposed a review of current control techniques for three-phase voltage-source pulse width modulated converters in grid connected operation. The major group of the control techniques are linear and nonlinear. The PI controllers in stationary frame and PR controllers in synchronous frame are presented. Further, state feedback controllers and predictive techniques with constant switching frequency were also analysed. In the current control methods, hysteresis and delta modulation controllers were presented. The modern neural networks and fuzzy-logic-based controllers are also discussed, as well.

Blaabjerg et al. (2010) in their paper discussed the trends of utilization of renewable energy sources by means of power electronics. Transformer-less PV systems and their control are presented for high efficiencies. The control of transformerless topology is discussed and presented.

Twining & Holmes (2003) in their paper proposed a robust strategy for regulating the grid current fed to a distribution network from a three-phase VSI system. It consists of an outer current regulator loop with inner filter capacitor current regulation to stabilize the system. PI current regulators in synchronous reference frame were adapted in the outer loop control.

Noguchi et al. (1998) proposed a novel control strategy for a PWM converter without voltage sensors. This strategy is claimed to have improved power factor and efficiency, even if harmonics are present in the grid voltage. A direct instantaneous power control is used to control the instantaneous active and reactive power directly. Experimental results were presented with a power factor and efficiency of more than 97% and 93% over the load power range from 200 to 1400 W, respectively.
**Timbus et al. (2006)** in their paper discussed different control structures applied to distributed power generation system. The use of proportional-integral (PI), proportional-resonant (PR), hysteresis and dead beat controller in different reference frames were analysed. In each type of controller the current harmonic distortion were presented. The controllers are tested under transient operation like fault in the utility grid etc were also analyzed.

**Weinhold et al. (1991)** proposed a new control scheme for optimal operation of a three-phase voltage dc link PWM converter in the natural reference frame. They used conventional PI controllers for reference tracking and power control.

**Holmes & Martin (1996)** discussed the three basic current controllers for regulating current in grid connected inverters viz. ramp comparison, hysteresis control, and predictive current control. It is argued that the predictive current control results in a more precise current control with minimum distortion and harmonic noise. A predictive current controller implemented in a microprocessor is presented with simulation and experimental results.

**Kadri et al. (2011)** in their paper presented an improved maximum power point (MPP) tracking (MPPT) with voltage-oriented control for fast-changing irradiation condition in PV systems. The control structure has an outer dc link voltage loop and an inner current loop. They have used synchronous frame and the d&q loops are decoupled for independent control. The current is delivered at unity power factor by controlling the q-axis reference to zero. MPPT is achieved through outer loop control.

**Haque et al. (2010)** presented a control scheme for stand-alone permanent magnet synchronous generator working with variable speed wind
turbine. The control strategy of the generator side converter is for MPPT, whereas the grid side converter is to synchronize and take care of the power control. They have used PI controllers in synchronous reference frame for the inner loop and used a feed-forward decoupling for independent control.

Rodriguez (2007) presented a control technique for grid-connected power converters, which will work even under utility unbalance or distorted condition. The non-ideal grid condition is detected using the positive-sequence component of the fundamental-frequency. They have proposed a decoupled double synchronous reference frame phase-locked loop (DDSRF-PLL), which completely eliminates the detection errors of conventional synchronous reference frame PLL's (SRF-PLL). It is declared that their phase detection is fast, precise, and robust even under unbalanced and distorted grid conditions. Both simulation and experimental results were presented to support their strategy.

Ghoshal et al. (2011) presented an overview of current control technique for grid connected converter under low voltage ride through condition and during transients. The current controllers were examined for meeting the requirements like fault, unbalance, harmonic etc., and the author’s modifications in the design were also specified.

Agirman et al. (2003) presented an algorithm to estimate position of line voltage space vector for grid connected VSC. API current controller is used in d axis which acts an angle error signal, to obtain proper synchronization. The initial line voltage phase is estimated first then continuous position estimation by observer is facilitated. There is a q axis which controls the voltage. Both the observers were implemented in synchronous frame of reference
Zmood & Holmes (2003) in their paper found a theoretical connection between the conventional PI and the P+Resonant regulator for grid connected converter control. They have argued that the two regulators attain the same transient and steady-state performance irrespective of the frame of working.

Malinowski et al. (2001) in their paper proposed a control technique for a three-phase, three-level, neutral-point-clamped PWM converter for a permanent-magnet synchronous generator feeding power to grid. The scheme consists of active and reactive power loops using a virtual flux and filter-capacitor voltage estimators for sensorless operation and active damping of LCL filter.

Malinowski et al. (2009) presented an advanced control strategy for three phase grid connected pulse width-modulated (PWM) converter. The aim is sensorless operation, and active damping for LCL filter. A PWM modulator with dc-link voltage balancing is intended for minimization of switching losses. They proved that it is a robust algorithm, minimizing switching losses, and simple tuning procedure of active damping.

Milosevic et al. (2006) proposes a basic structure for current control of three phase voltage source inverter realized in the synchronously rotating reference frame with feed forward decoupling.

Östlund Stefan (2008) in his book on ‘Electrical Machines and Drives’ discussed various control strategies for both induction motor drives as well as the grid connected inverters. The calculation of the proportional and integral constants for the PI controllers and the space vector control, stationary reference frame control and the hysteresis control in the natural reference frame were discussed in detail.
Fernando Brizet et al. (2000) discussed and analyzed the design of current controllers for AC machines controlled with power converters. A complex vector notation is proposed and used in the work which provides a way of comparing the performance of controller topologies through their complex vector root locus and complex vector frequency-response functions. It is argued that the performance of the proposed controller is better than the synchronous frame proportional PI regulator, and the ways to improve in such controls are also presented.

Behrooz Bahrani et al. (2011) used a basic d-q current control strategy for voltage source converters in synchronous reference frame. The well known limitation of the controller i.e. the cross coupling is removed using a method based on Multivariable PI regulators. It is claimed that the proposed controller provides fast dynamics and zero steady state error. Also it is argued that the implementation of their controller is simple and does not impose excessive structural complexity compared to the conventional PI based ones. The proposed control structure is implemented on a three-phase test system and the performance is experimentally evaluated and presented.

2.7 ISLANDING DETECTION AND GRID IMPEDANCE ESTIMATION

In the stability and control of grid connected inverter systems, grid impedance values are used at various stages viz. controller loop tuning, for islanding detection etc. However, the grid impedance values will vary from system to system. In micro-grids it also varies depending on the operating conditions of the micro grid, so if the grid impedance in micro grids are known accurately then the control and stability can be made independent of the system and the operating conditions. The following papers are giving a brief idea of obtaining the grid impedance through online measurements.
Carotenuto & Pietro Luig (2011) proposed a grid impedance estimation method by perturbing the active and reactive powers. The proposed method is tested with average and switched inverter models and implemented in MATLAB/Simulink. The accuracy of the grid impedance estimation and its effect on the grid are also dealt with in detail.

Santiago Cobreces et al. (2009) presented a method for grid impedance monitoring in distributed power generation converters. The grid impedance is estimated from the voltage measurements at the point of common coupling. The estimation algorithm is based on a recursive least-squares algorithm implemented in the complex field. Also, the quality of estimation is evaluated by the same algorithm itself, for minimizing its influence on the grid and detecting islanding situations.

Lucian Asiminoaei et al. (2005) proposed a grid impedance measurement technique using the injection of a non-characteristic harmonic current and measuring the grid voltage response. Using these measured values the grid impedance directly can be calculated by the PV inverter. It is proposed that this method is a fast and low-cost solution. Also, claimed that this principle provides an accurate estimation of the grid impedance. This paper also presented another new impedance estimation method for online grid impedance measurement.

Roberto Petrella et al. (2009) discussed a grid impedance estimation technique based on additional inter-harmonic injection at the point of common coupling. An injection pattern and a processing algorithm based on a moving window Discrete Fourier Transform and averaging filter are introduced and analysed by the author. The proposed method has a reduction in both current THD and harmonic power losses. The effect of the spectral leakage due to the non-integer ratio between processing sampling and the
inter-harmonic injection frequencies, when the grid frequency is fluctuating are also analysed.

Lucian Asiminoaei et al. (2005), in their paper described the digital implementation of a PV-inverter a robust control strategy and an embedded online technique to determine the grid impedance. By injecting an inter-harmonic current and measuring the voltage response the grid impedance is estimated. They suggested that the proposed method provides a fast and low cost approach for online impedance measurement, which may be used for detection of islanding operation.

Asiminoaei Lucian et al. (2004) discussed the recent increase in photovoltaic (PV) installations. This calls for new and better power quality requirements with respect to connection to the grid supply. Therefore, different methods are typically used for continuous grid monitoring, usually by using external devices. In this paper, a new method for on-line measuring of the grid impedance is presented. It is claimed that it requires no extra hardware, being accommodated by typical PV inverters, sensors and CPU, to provide a fast and low cost approach of on-line impedance measurement. By injecting a non-characteristic harmonic current and measuring the voltage grid response it is possible to evaluate the grid impedance. Practical test on an existing PV inverter validate the new method.

Liu Bohan et al. (2011) introduced and compared three impedance estimation techniques viz. FFT, PSD and CWT. The impedance of proposed system is calculated by using the injected step current transient and the measured voltage response. Both steady and noisy situation is simulated by Matlab/Simulink, and the characteristics of each impedance analyzing method are demonstrated by the achieved impedance results.
Beltran Hèctor et al. (2006) in their paper checked the validity of some of the active and passive anti-islanding methods. They concluded that some of the algorithms are shown to work properly with any kind of utility and local loads in the potential island. Also the authors found that some other available algorithms would not disconnect the power generator when the total power of the local load matches that of the generator. The non-detection zone (NDZ) is wide in some cases and in some cases there is no NDZ.

Timbus Adrian et al. (2010) proposed the idea of the islanding detection scheme if used with the communication infrastructure of the smart grids. For e.g. in metering, feeder automation, etc. In these applications the communication based islanding methods will become cost competitive with the active methods without their weaknesses. They presented their idea on communication based methods and analyzed the influence of bidirectional power flow on the existing methods. In the same paper the authors also proposed a new method for grid impedance measurement in a smart grid infrastructure

Bower Ward & Michael Ropp (2002) described various methods and circuits which are commonly used in PV inverters for islanding detection. The distinct difference between the active and passive methods of islanding detection is compared and analysed. The authors conducted a survey on the existing methods and proposed that because of the absence of NDZ, the active methods are better compared to the passive methods.

A Report PVPS from Sandia Labs (2002) on the evaluation of islanding detection methods for photovoltaic utility-interactive power systems discussed various islanding detection methods used for PV applications. Both active and passive methods are analysed and the recommendation of different grounds have been reported. It is also proposed that the grid impedance estimation method is a better method for islanding detection.
2.8 THE MATHEMATICAL MODEL OF PV CELL AND SOLAR PV EMULATOR

For conducting intense testing of the PV power converter’s functionality, its closed loop control, its performance when subjected to grid disturbances, a real-time hardware infrastructure is essential. Thus the simulators are primarily intended as a power source to the converter in experiments to verify the reliability and repeatability of operation of the converter in steady state as well as in transient conditions of all possible insolation/grid conditions. Such an emulator has to produce dc outputs effectively as will be given by a PV panel at any operating condition. The heart of any emulator is the mathematical model of the PV array which controls the emulator.

Hiroshi Nagayoshi et al. (2002) in their paper described the basic characteristics of the PV module/array simulator circuit implemented in hardware. For obtaining the solar cell characteristics the authors magnified the output of a small pn photo-sensor using analog circuits. A variation in fill factor is made available for the user, thus making the simulator a general purpose one which can simulate many kinds of PV modules or arrays.

Hiroshi Nagayoshi et al. (2003) in their second paper developed a photo-sensor temperature based 30 W module/array simulator circuit using an I-V magnifier circuit. The voltage and current gain was independently adjusted using the feedback control of the current signal from the photo sensor. An LED light output controls the simulator output power. The experimental results of the simulator was claimed to exhibit the temperature dependence characteristics of PV modules.

Jaakko Ollila (1995) in his paper introduced strategies to simulate photovoltaic arrays with arbitrary and reproducible insolation conditions. It is
argued by the author that the operating point of the simulator is controlled and it is found to be stable leading to a better compatibility for electrical tests. A 1kW simulator hardware was built using a switch-mode converter. It is declared that this new control strategy can be used in many applications in power electronics acting as a source of PV panel.

Eftichios Koutroulis, et al. (2006) proposed a novel real-time PV simulator using FPGAs. It consisted of a Buck converter controlled by an FPGA generating the PWM pulses. The user can select the type of PV module and the ambient conditions. It can be used in the prototype development of power converters. The experimental results showed an accuracy of 1.03% for the emulated I-V characteristics.

Yuan Li (2009) presented a hybrid control strategy for photovoltaic (PV) emulator. The mathematic modelling of the I-V curve of PV arrays is presented and the emulator can work in four different modes. The control unit of the emulator is designed using TMS320LF2407 DSP. A 2-kW prototype is reported to be built and tested with a variable resistive load and a constant power load. The results were claimed to be suitable for further experiments of inverters and the maximum power point tracking in the PV system.

Martin-Segura et al. (2007) in their paper proposed a PV array emulator with new model for PV array. The proposed system consists of a 4.4 kW AC/DC power converter based on a DC/DC full-bridge structure and High Frequency (HF) transformer, that allows testing PV inverters' performance up to 4 kW with a 650 V and 7 A input.

Di Piazza et al. (2010) discussed a simulator of a photovoltaic (PV) field in which the I-V characteristic is obtained either with a fully analytical model or with a numerical model. The power circuit used is a dc-dc buck converter controlled by the I-V relation of the PV array. The new
algorithm for the PV array modelling is as follows: A continuous surface in the irradiance domain is considered and a relation between temperature and irradiance is obtained by least square regression method, and a thermal constant of the PV field is introduced. A PV simulator prototype is experimentally tested.

**Atlas & Sharaf (2007)** presented a simulation model for photovoltaic array (PVA) in Matlab-Simulink. The model is developed using basic circuit equations of the photovoltaic (PV) solar cells including the effects of solar irradiation and temperature changes. The testing of the model is done with dc as well as ac loads. The test results were also presented.

**Tsai et al. (2010)** in their paper presented a novel model of photovoltaic (PV) module which is implemented in Matlab/Simulink. The effect of irradiance and temperature is taken into account for the proposed model. The output current and power characteristics are simulated and analyzed using the proposed PV model. The model verification has been confirmed through an experimental measurement.

**Mummadi Veerachary (2006)** presented a simple and accurate PV model suitable for circuit-oriented simulator like PSIM. The mathematical model of the solar cell is discussed. The verification of the model, i-v characteristics are generated and compared with the experimentally obtained characteristics.

**Kashif Ishaque et al. (2011)** in their paper proposed an improved PV cell modelling using differential evolution method. This approach computes the model parameters of the PV module using only the manufacturer’s data sheet. Three PV modules viz. multi-crystalline, mono-crystalline and thin-film are tested with the developed model.
Yoo et al. (2001) in their paper presented a solar cell emulator. A mathematical model of solar cell is used to control the power converter, and the simulation studies are made and the results were presented.

Walker Geoff (2001) in his paper presented a method for accurate PV modelling of a PV module. The Shockley diode equations were used to build the mathematical model and the non-linearity like series and shunt resistance etc. were added. The model parameters were extracted from the practical module and the results were evaluated through simulation studies. The results were presented for MPPT with variation of insolation conditions.

A circuit based model of photovoltaic array (PV) suitable for simulation studies of solar power systems is proposed by Azab, Mohamed (2009) in his paper. The proposed model is realised using MATLAB/SIMULINK. But it can also be developed using standard simulation software such as PSPICE also. The results are presented in uniform as well as mismatched PV conditions.

Tsai et al. (2008) presented model of a PV cell using Matlab/Simulink. The model was designed with icons and a dialog box like Simulink block libraries. The effect of irradiance and cell temperature is taken into consideration. The output current and power characteristics of PV model are simulated and results are presented.

2.9 CONCLUSIONS

After surveying the issues related to the control of grid connected converters, in micro-grid environment viz., various configurations, control algorithms, maximum power point tracking, filter choices, the working frame of references, the choice of regulators, system stability and finally the method of testing proposed and tested by different authors some conclusions have
been derived. Weighing the merits and demerits of various aspects, the researcher feels there is a scope for improvement in the control of grid connected converters. This improvement is felt necessary especially under dynamic conditions, in MPPT and also in the reliable testing methods of the developed converters.

The expected outcome of this research work is to design, develop and test a micro-grid connected converter with a dynamic, effective and reliable control scheme with MPPT which can work satisfactorily even during transient conditions. Furthermore, the work also aims at developing a testing platform through which the reliability of the developed power converters can be tested.