DESIGN, ANALYSIS AND DIGITAL CONTROL OF GRID CONNECTED INVERTERS

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DEDICATION

"To my family, especially my mother, all of my respected teachers throughout my education career and to all those children who could not make to get higher education at school, college or university level".

ABSTRACT

Currently, the control of grid connected inverters is an appealing area of research. There exists several control schemes, but this thesis primarily focuses classical control (P/PI) of grid tied inverters under diverse variations such as LCL filter parameter values and grid impedance. The performance of conventional classical PID controller renders down resulting in a large steady state error; high THD level in the output current and in its worse scenario destabilizes the designed system if controller gains are not seleted properly. To achieve efficient results proper tuning of gain parameters is necessary for small steady state error with very low level of THD in the output current. This thesis investigates the limitations of a conventional PID controller considering stability and system response by changing the controller gains in conjunction with LCL filter parameters. The controller gain is varied within permissible range of bandwidth of the system while maintaining the steady state response, frequency response and overall efficiency under strong grid harmonics. The MATLAB/Simulink results are incorporated for the proper analysis of controller behavior with stability range under the influence of grid impedance variations.

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LIST OF ABBREVIATIONS

Band Width (BW)

Low Pass Filter (LPF)

Phase Locked Loop (PLL)

Repetitive Controller (RC)

Resonant Controller (RSC)

Proportional-Resonant (PR)

Dead Beat Controller (DBC)

Hysteresis Modulation (HM)

Fuzzy Logic Controller (FLC)

Neutral Point Clamped (NPC)

Current Source Inverters (CSI)

Matrix Laboratory (MATLAB)

Voltage Source Inverters (VSI)

Frequency Locked Loop (FLL)

Sliding Mode Controller (SMC)

Adjustable Speed Drives (ASD)

Pulse Width Modulation (PWM)

Space Vector Modulation (SVM)

Pulse Density Modulation (PDM)

Total Harmonic Distortion (THD)

Voltage Control Oscillator (VCO)

Combined Heat and Power (CHP)

Linear Quadratic Regulator (LQR)

Electro Magnetic Interference (EMI)

Uninterruptable Power Supply (UPS)

High Voltage Direct Current (HVDC)

Insulated Gate Bipolar Transistor (IGBT)

Real Time Digital Power Systems (RTDS)

Alternate Energy Development Board (AEDB)

National Renewable Energy Laboratory (NREL)

Proportional-Integral-Derivative controller (PID)

Institute of Electrical and Electronic Engineers (IEEE)

Transient Energy System Simulation Program (TRNSYS)

Renewable Alternative Power Systems Simulation (RAP Sim)

Hybrid Optimization Model for Electric Renewables (HOMER)

Simulation and Optimization Model for Renewable Energy Systems (SOMES)

CHAPTER – 1

1. INTRODUCTION

1.1 Motivation

The world's population is increasing every day. The energy consumption demand for this ever increasing population is reaching sky heights. This never ending energy demand results in scheduled or unscheduled power shutdowns and sometimes in its worse scenario, complete blackout in some areas of the large cities of the developing countries, like Pakistan, India, Bangladesh etc. The power shutdown results in poor production of the industries, lowering down the communication efficiency, disturbs the development of socio economic system and commercial activities, raising accident ratio on the roads by switching off the traffic signals in busy hours resulting severe traffic jams, and overall affects the economic growth of the country.

The conventional methods used for power production includes hydro-power, wind power, photovoltaic systems, thermal energy, nuclear energy, biomass energy etc. All the above mentioned methods for power generation have their own pros and cons in terms of design hierarchy, complexity, cost and environmental effects. The huge spike in crude oil prices in the international markets as well as depletion of natural reserves of oil, gas and coal and depreciation in production are the main issues that had created hindrance to generate cheap and low cost energy. The emission of greenhouse gases and their harmful environmental effects not only affects the health of human population but also disturbs the nature therefore scientists and other concerned communities discourages the power generation via thermal power plants based on oil, gas or coal. The research from reliable sources and data analysis of the past decade reveals that the emissions of greenhouse gases are responsible for global warming and as well as the major cause of dramatic changes in the climate all over the world. The Scientists, engineers and technical experts, socially active personals all around the globe are on the way to search for the solution to produce cheap, clean and environment friendly energy to fulfill the desired level of the low cost energy for this ever growing and increasing population of the world [1 – 4].

Moreover the currently existing generation systems severely suffer from heat and transmission line losses and the heavy costs for expansion of the system as well as the challenging problem of integration of the distributed fossil fuel based power generation systems to the main grid meeting the IEEE standards for generated power distribution and control. To power up the population residing in the rural areas away from the main grid requires long transmission and distribution lines results in heavy cost of expansion as well as add line losses and unbalance situation to the overall system.

1.2 Energy Shortfall Scenario in Pakistan

The current energy shortfall scenario in underdeveloped countries like Pakistan has become a challenging problem for the government and forcefully pushed the governing authorities to come up with the permanent solution to fill up the huge gap between energy supply and demand. In past the political parties with bilateral dialog and under the influence of internal and external political pressure has reached on the conclusion to refuse the proposed Kala Bagh Dam power project with the generation capacity of 3600MW. After the refusal of Kala Bagh Dam project the country faced acute water shortages to irrigate agricultural land as recently three consecutive years of floods and absence of water storage resources resulted in food shortages and immense decrease in agricultural growth against expected production target. Also the extreme power crisis and electricity supply shortage had disturbed the economic growth index; additionally a huge reduction in exporting goods in the international markets has been reported as well [5 –6].

The total power generation installed capacity in Pakistan is 21,103MW according to 2012 censes. Out of these fossil fuel (oil, gas, coal) based power generation plants have the capacity of 13,637 MW equivalents to 65% of the total capacity. The hydro power plants contributes 31% of the total to the national power grid with the generation capacity of 6,654MW and nuclear power plants with the generation capacity of 812 MW shares just 4% of the total installed capacity.

While the shortfall of electricity is reported to lie between 3,500 MW to 6,000 MW and in peak hours this shortfall raises up to 8,000 MW driving the power regulation authorities to implement power shutdown strategy. The load shedding in urban areas is up to 8 to 12 hours daily while the situation in rural areas is worse, load shedding of 14 to 16 hours daily is carried out[7 –8].

The only way out to this severe energy crisis is to take serious action to generate electricity commercially via renewable energy sources. Pakistan is blessed with a huge potential of harvesting clean energy from naturally occurring renewable sources like solar energy, wind energy, biogas, geothermal energy.

The issued data regarding collaborative joint project between National Renewable Energy Laboratory, USA and Alternate Energy Development Board, Pakistan for solar power and wind power mapping of Pakistan revealing the actual facts about the potential of harvesting clean energy from these two renewable energy sources alone. The potential for solar power is reported to be 2.9MWh per meter square per year and these values are higher compared to rest of the world solar radiation data truly appealing for Photovoltaic (PV) systems installations [9].

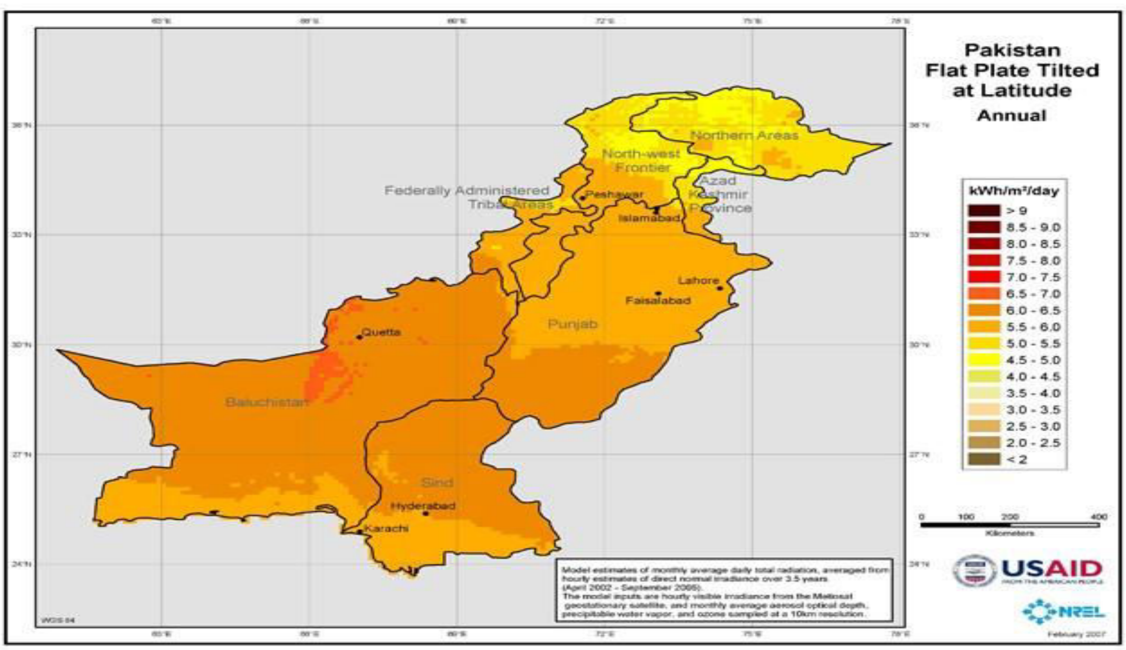

Figure 1.1 Solar power mapping of Pakistan via NREL census [9].

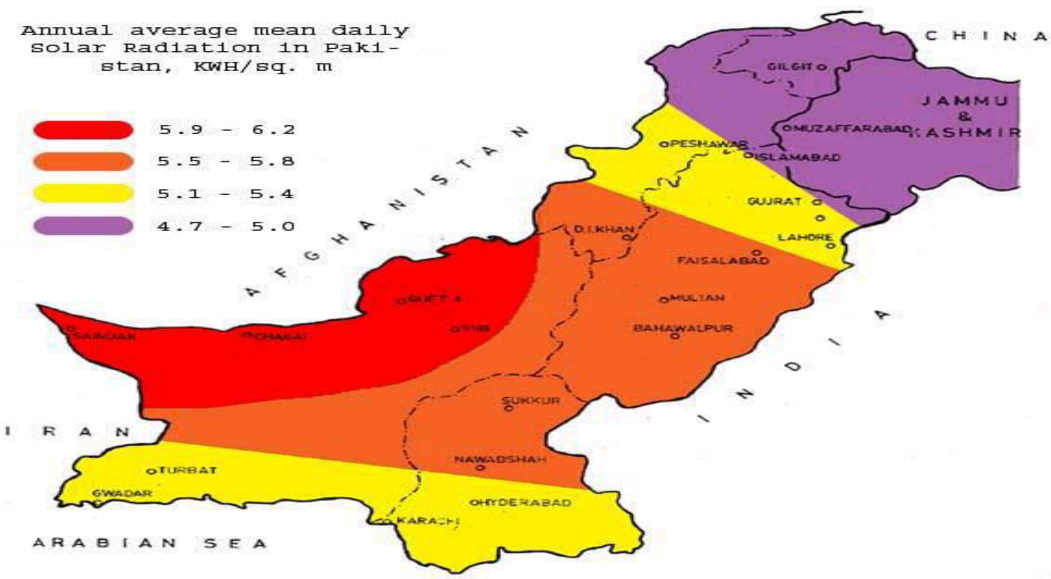

Figure1.2 Annual average means daily solar radiation mapping [10].

The wind power potential of the Gharo-KetiBandar wind corridor, the region in Sindh province is 60,000 MW [10–11].

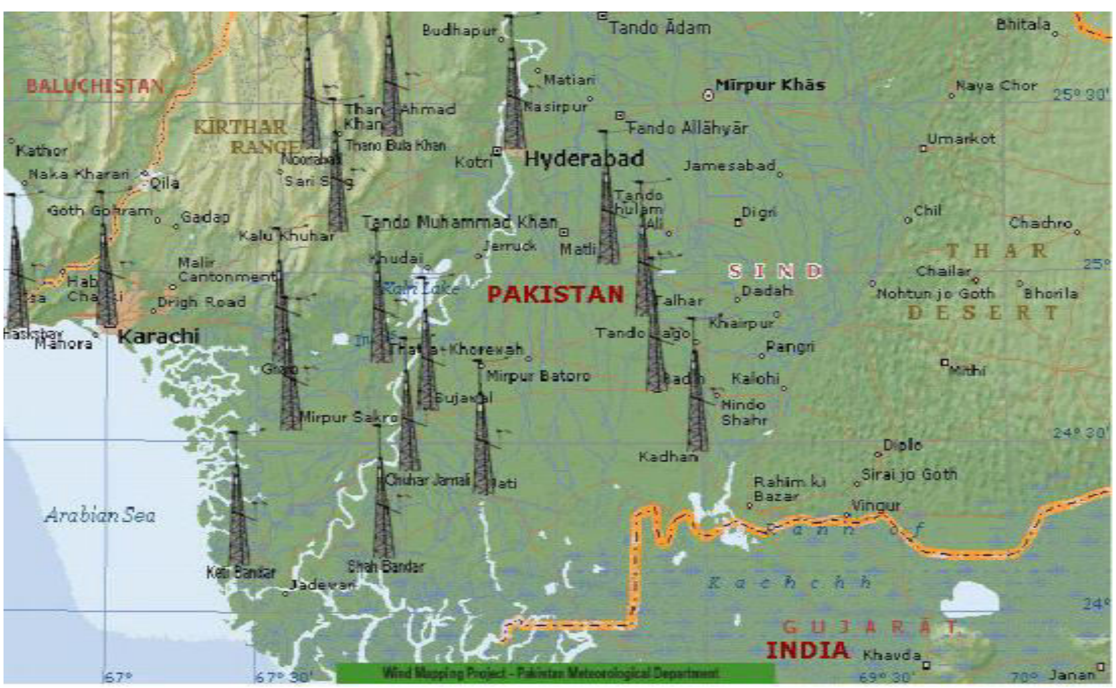

Figure1.3 Wind power stations mapping in Sindh province [10].

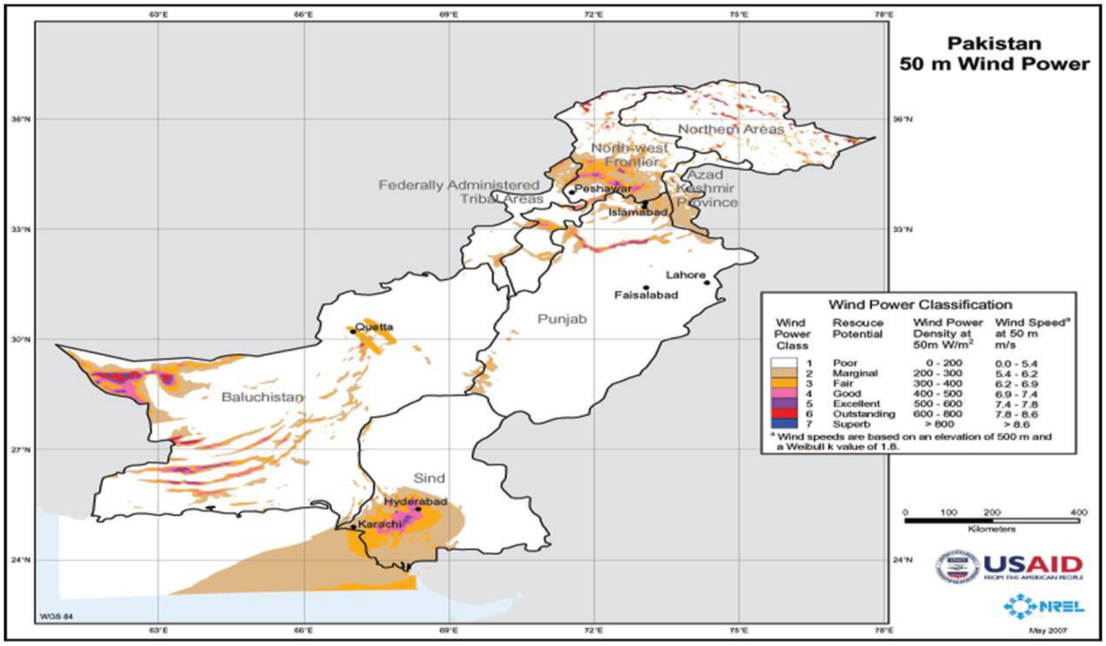

Figure1.4 Wind power mapping of Pakistan via NREL census [12].

The table below reveals renewable resource potential data of both solar power potential and wind power potential in Pakistan [12].

Table 1.1 Renewable energy sources and power potential.

Renewable Energy Source	Power Potential
Solar Energy	1.9-2.3 $MWh/m^2/year$
Wind Energy	60,000MW

1.3 Renewable Energy Sources

The renewable energy sources are the solution to these problems which includes solar power based systems, wind power based systems, biogas power based systems, geothermal energy and micro hydel power based systems [13–14].

For rural areas renewable energy sources provide an easy way of power production, saving heavy cost of power transmission system expansion and reduce transmission line losses as well.

The renewable energy sources occur naturally and the developed countries like America, England, Germany, Spain, China etc. are using these sources at commercial level for clean, environment friendly and economically low cost power generation.

The initial cost for the installation of photovoltaic systems has been reduced with the initiative taken by the government for upholding the custom duty for the import of photovoltaic (PV) panels.

1.4 Micro grid Systems

Micro grid is a grouping of independent energy generation systems such as photovoltaic systems, wind turbine systems, biogas systems, fuel cell etc. electronically connected to local loads via grid connected inverters [15–16].

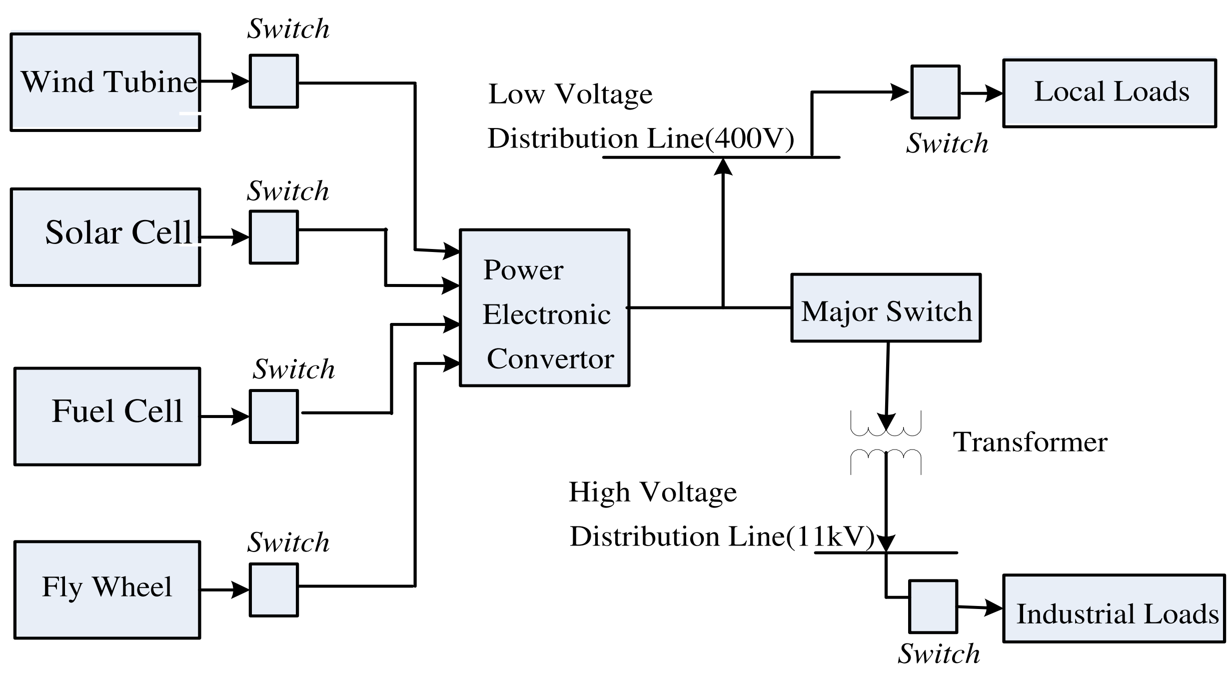

Figure1.5 A micro grid system schematic.

These locally independent power generation systems or groups are responsible for power generation, monitoring of power transmission to the local loads or to the main grid and retain a backup energy storage systems whenever the main grid is disconnected from local loads or micro-grid domains. These generation systems also maintain the power quality and reliability of the system under strong grid variation conditions. To integrate the renewable energy sources with the micro-grid domain, grid connected inverters play a pivotal role by controlling and monitoring power quality and bidirectional flow of energy [17].

Grid connected inverters provide a better and reliable interface between the main grid and the independent energy generation systems for bidirectional flow of power.

This interface of grid connected inverters to the grid raise technical problems which must be dealt with extreme care and it demands to fulfill the International Standards (IEEE Standards).

To meet the IEEE standards the power quality, voltage and current waveforms, removal or minimization of unwanted frequency harmonics, reliability and protection of the system, robust control and smart monitoring of the overall system stability is required and must be maintained at any cost [18].

Currently the robust and efficient control of these grid connected inverters is a very vast and the most promising area of research.

An immense research work has been completed in this field so far but still the solutions to the still existing problems of grid impedance variations and mismatching, search for better filtering schemes, implementation of more robust control needs to be resolved.

1.5 System Description

In literature many control schemes have been implemented using classical controllers such as proportional (P), proportional integral (PI), proportional derivative (PD), proportional integral derivative (PID) controllers [19], proportional resonant controller (PR) [20], fuzzy logic controller (FLC) [21], H-infinity ($H\ \infty$) controller [22], repetitive controller (RC) [23], sliding mode controller (SMC) [24], dead beat controller (DBC) [25]etc. for the control of grid connected inverters.

All of these control schemes have their own advantages and distinctiveness over each other. Depending upon the application and operational requirements of the system the control scheme is implemented.

The research is mainly focused to design and analyze grid connected inverter with classical control (P/PI) in conjunction with LCL filter scheme. Classical controllers are the most simple controllers and easier to implement but they are not robust to grid impedance variations such as frequency variations, voltage and current variations and transients due to their limited tuning range. Classical controllers also suffer from low gain range selection of K_p and K_i gains. By increasing these gains after particular values the system becomes unstable. For efficient power control of grid connected inverters interconnected with large number non-linear loads, classical controllers are not suitable, for numerous non-linear loads, the robust, reliable and perfectly efficient control technique is required to process and accommodate large computational data to mitigate the harmonic content from the output waveform and maintain system stability and reliability.

1.6 Problem Statement

Harmonic distortion is actually the deviation from the original fundamental voltage or current sinusoidal waveforms. Harmonics are integral multiples of fundamental frequency of voltage or current waveforms. Mainly frequency harmonics based disturbance is formed by the presence of numerous nonlinear loads which have been fed power by the micro-grid or main power grid. Nonlinear loads includes switched mode power systems, battery chargers, personal computer, laptops, mobile chargers, incandescent lamps, adjustable speed drives, small as well as large induction motors in industry and other electronic equipment. Nonlinear loads draw abrupt amount of current from the power source and hence produce unwanted frequency harmonics which results in polluting the micro grid as well as main power grid when operating under grid connected mode. The presence of harmonics in power system cause serious problems for continuous and smooth operation of power electronic devices used at domestic, commercial and industrial level. Some critical applications require pure sinusoidal waveform free from harmonics as an input to the system to operate safely. It has been reported that the presence of harmonics in power cables in an industrial environment may affect the small signal communication and even sometimes the control of power related equipment may suffer from failure to operate resulting in poor production. The filtering of unwanted frequency harmonics becomes severe issue when dealing with adjustable speed drives (ASD), if control of ASDs fails it may damage the bearings of a motor, over heating of insulation resulting in short circuit, over hauling of motor and put the whole production unit to complete shutdown [26–27].

While dealing with UPS system, the sine wave inverters not only charge the battery earlier but also increase the battery life saving purchasing cost of a battery. The IEEE standard regarding grid applications based inverters states that the total harmonic distortion (THD) in output current or voltage waveform must not exceed 5%. To maintain the THD level under IEEE standard limit, controller gain should be adjusted in conjunction with suitable filter selection under strong grid variations which is the prime focus of the research work carried out.

Classical controller design approach provides designer to design the complete system with considerable low cost facilitating the end users, boosting their purchasing power with low cost system design, they can fulfill their domestic and commercial needs for continuous power supply with acceptable level of harmonic content present in the output current under the normal grid variations.

1.7 Research Objectives

The following objectives are the prime focus of the research work carried out.

- Develop a linear transfer function model of a two level grid connected inverter via SISO toolbox of Matlab/ Simulink.
- Investigate the system stability, find out gain margin and phase margin using control system design techniques.
- Investigate system stability via root locus method and search for stability values for the poles and zeros of the modeled system by varying controller gain.
- Design and investigate the limitations of a classical controller and analyze the gain variation range under which the system remains stable and reject unwanted frequency harmonics following IEEE standard.

- Analyze the effect for parameterization of LCL based filter on harmonic rejection capability and controller gain variation range.

1.8 Organization of Thesis

Chapter 2 of the research work is dedicated to the intense literature review describing the viable modes of operations of grid connected inverters, a number of inverter design topologies are discussed, harmonic filtering schemes are also presented with possible schematics to give an overview, also phase locked loop (PLL) described to clarify the need for voltage and frequency synchronization with respect to power grid. And in the end controller schemes are discussed for efficient and smart control of inverter output power quality, bidirectional flow energy and monitoring of varying grid parameters to mitigate unwanted frequency harmonics.

Chapter 3 of the thesis deals with the justification of software selection for the design of Simulink model and verification of the proposed control technique via simulation results. It also presents methodology for system design briefly and derivation of transfer function of the whole system considering controller and inverter topology in conjunction with LCL filter parameters.

Chapter 4 is related to the investigation of the proposed design and experimental verification of classical controller combinations such as P and PI for the application of two levels single phase voltage source grid tied inverter using LCL filter for harmonic mitigation and voltage regulation for reliable operation of the system. Control system techniques such as frequency response, root locus, bode plot, phase and gain margin are performed via simulation for proper evaluation and validation of results for system stability and disturbance rejection capability with varying controller gain. Also controller gain limitations are discussed under strong grid harmonics.

Chapter 5 presents the LCL filter parameter variations in conjunction with controller gain limitations to analyze the effect of controller gain and filter parameter variation on system stability and robustness. The comparison provides system level analysis approach for classical controller robustness against efficient harmonic filtering scheme for grid connected inverter application. And in the end conclusion of research conducted and description about future research work aspects and possibilities are elaborated.

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CHAPTER – 2

2. Literature Review

2.1 Operational Modes for Grid Tied Inverters

There are several operational modes regarding grid tied inverters. These operational modes define the system capabilities, performance features and limitations for power generation, power injection to the micro-grid systems and main power grid keeping the IEEE Standards and also power provision to local loads whenever the main power providing source such as grid is disengaged from the loads.

2.1.1Grid Tied Mode

The inverter is tied or engaged to main power supplying grid while providing the power to the local loads in grid tied mode. Actually the inverter feed extra generated energy into the main grid to which it is connected while providing the energy generated to the local loads also, the control of inverter in this situation is more critical and requires special attention for continuous power regulation. For power injection into the grid, the current should be of low THD level following IEEE standards. The THD level must be maintained and must be less than 5% throughout the operational event. In grid tied mode the variation in grid frequency must be dealt critically because it causes the current and voltage output waveforms of grid tied inverter to deviate from the synchronized current or voltage waveforms of the main power grid, giving rise to unwanted frequency harmonics and rendering down the power quality. This synchronization problem is solved either by using phase locked loop based technique for achieving perfect synchronization of phases of the current and voltage signals or by zero cross detection of the main grid voltage[1 –2]. In grid tied mode the bidirectional flow of energy is allowed to occur. The power from the grid can be borrowed if required and power generated from renewable sources can also be injected into the grid if exceeds the required limits.

2.1.2 Stand Alone/Anti Islanding Mode

The standalone mode or anti-islanding mode of operation of inverters becomes active when the connection with the main power grid is lost. In standalone mode, the critically important loads are supplied power via renewable energy sources connected to the inverter. On large scale it represents the micro-grid which is responsible for power regulation between critically important local loads disconnected from the main grid. The small scale system is a UPS system which provides power to a single local user via charged batteries. Micro-grid is actually a system in which numerous local users are provided with the power when grid is not connected to these local loads. In this situation the flow of power needs to be monitored, especially the voltage and frequency must be synchronized when the connected loads are nonlinear. As the numerous inverters are providing power so there should be a method to avoid the load imbalance situation and unequal sharing of loads. The Master slave method is the most suitable method for communication between the several inverters. First inverter behaves like a master, defining the reference values of voltage output and frequency needed followed by the other inverters acting as slaves under this master slave control strategy [3].

2.1.3 Battery Charging Mode

The constant and reliable supply of power demands the required level of efficiency and reliability of the system. For constant power regulation in a micro-grid system and variations in power generation and demand, some sort of storage system is employed for power storage. Large batteries are used to store generated power of the renewable sources whenever the loads are disengaged from the micro grid. These storage batteries provide power to local loads directly engaged to the micro grid while main grid is detached. These storage batteries get charged via power electronic converters embedded in the complete system into which grid tied inverter is attached [4]. The large battery banks are employed to cover up the power shortage, experienced by the critically important local loads as well as the large industrial loads as a backup energy source for smooth and continuous operation of the heavy machines responsible for running large industrial units for a specific interval of time, so that the proper power source such as auxiliary generation systems came into operation to fulfill the demand for bulk amount of energy, required to run these large industrial units.

2.2 Grid Tied Inverter Topologies

Several topologies have been implemented for grid connected inverters to address different issues for performance improvement and to enhance system capabilities for disturbance rejection. Each topology has its own benefits and disadvantages. The invention of a better topology that can address the most challenging issues regarding lowering of losses, improving output quality of current and voltage for power injection into the main grid and managing the power demand of local loads is an appealing area of current research.

2.2.1 Multilevel Inverters

The multilevel inverters include power electronic semiconductors and capacitors acting as voltage sources so that a high output voltage with stepped waveforms can be generated.

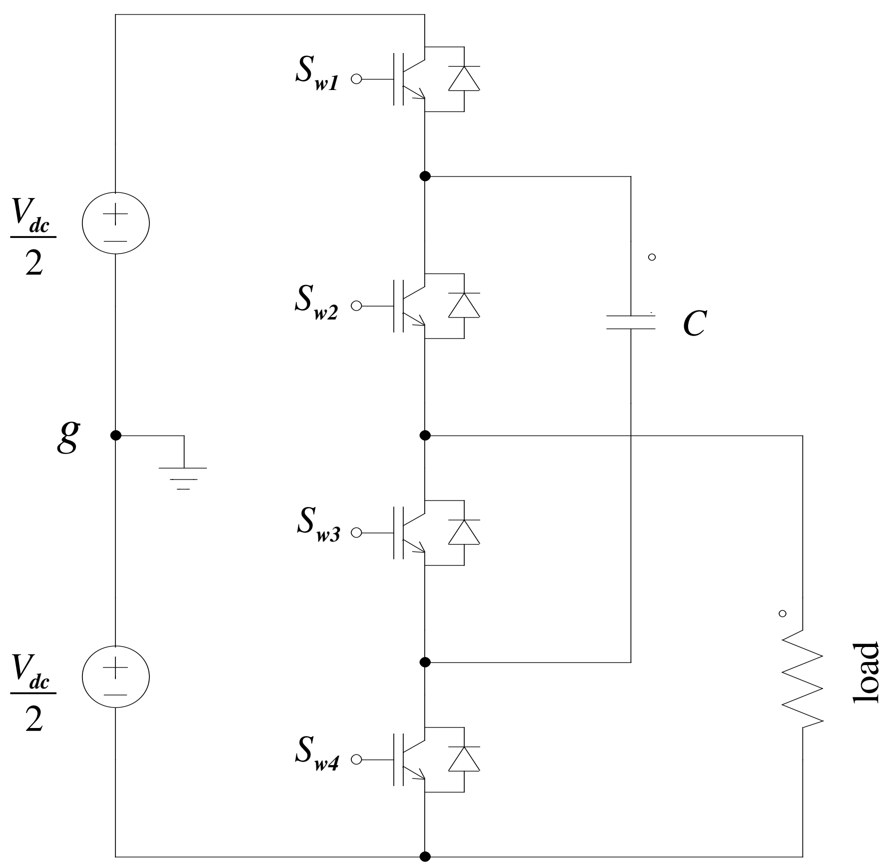

Figure 2.1 A capacitor clamped multilevel inverter schematic.

Multilevel inverters topology was conceived to achieve more synchronized sinusoid waveform by having enlarged the number of required steps in output voltage. Cascaded multicellular is a type of multilevel inverters. The other two types are capacitor clamped and diode clamped [5].

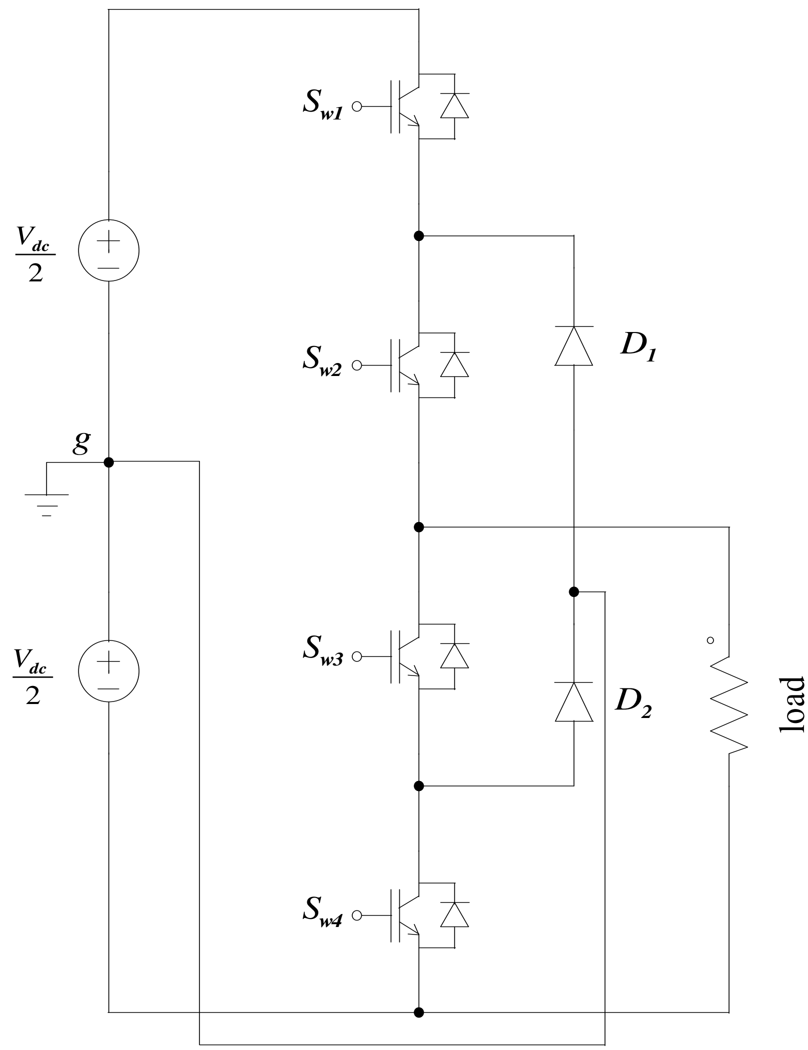

Figure 2.2 A diode clamped multilevel inverter diagram.

The main advantages of using multilevel inverters are their generation of less distorted output voltage, they can be operated with low switching frequency with lower switching losses as a result less amount of heat produced by switching on and off of the IGBTs, the overall bargain in the size of inductor filter results in cost minimization as well to filter out undesired harmonics and it also facilitates the use of pulse width as well as space vector modulation techniques [6 – 7].

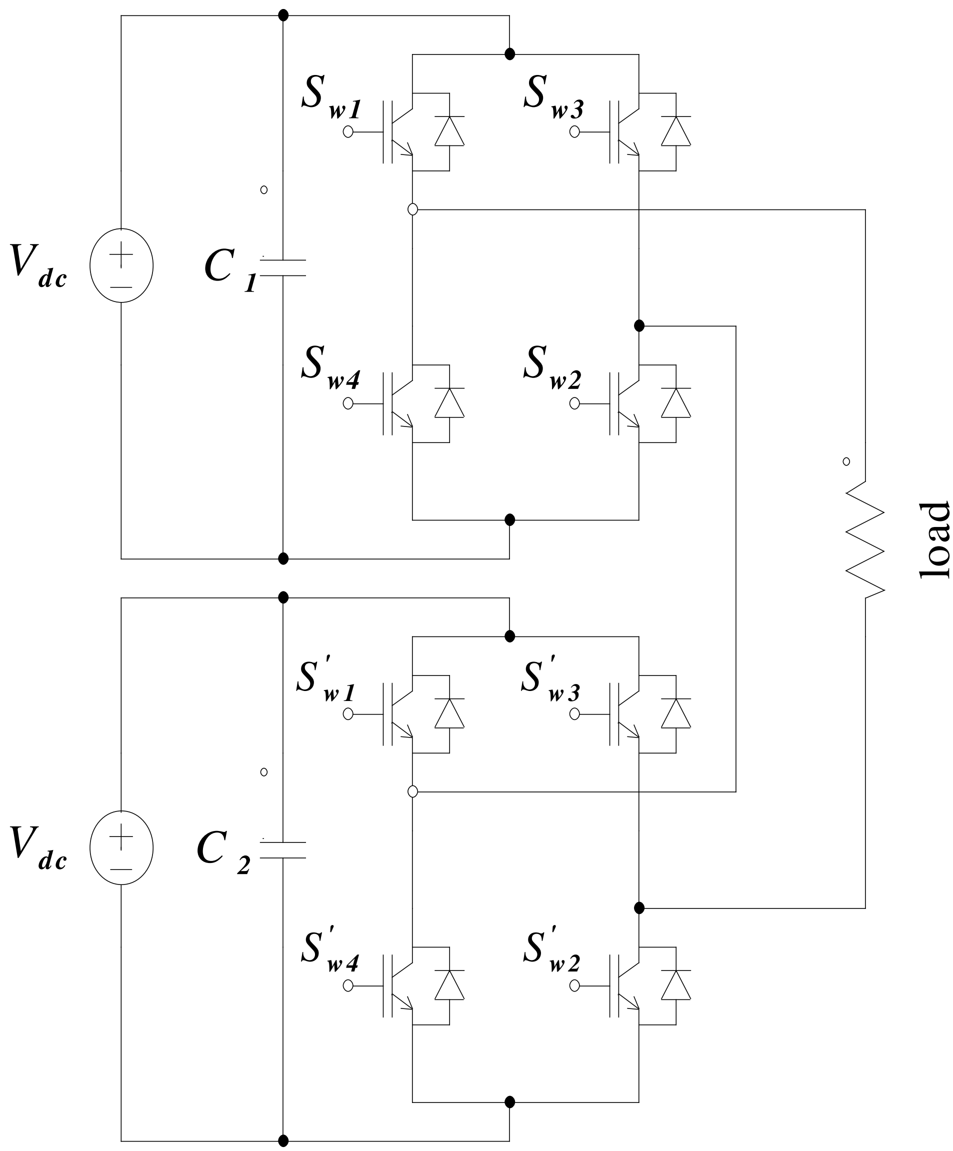

Figure 2.3 A schematic diagram of a cascaded multicellular inverter.

2.2.2 Interleaved Inverters

The interleaved inverter is an alternative topology to multilevel inverters. In this topology different cell of two levels or three level inverters depending upon the design are connected in a parallel way to form channels and the switching instants of the channels are phase rotated over a specific switching period. Equal phase shifts in parallel power stages the required equalized phase rotations results in cancelation of ripples. Ripples in the output current can also be removed via output filter capacitor by ripple cancelation effect [8 – 9].

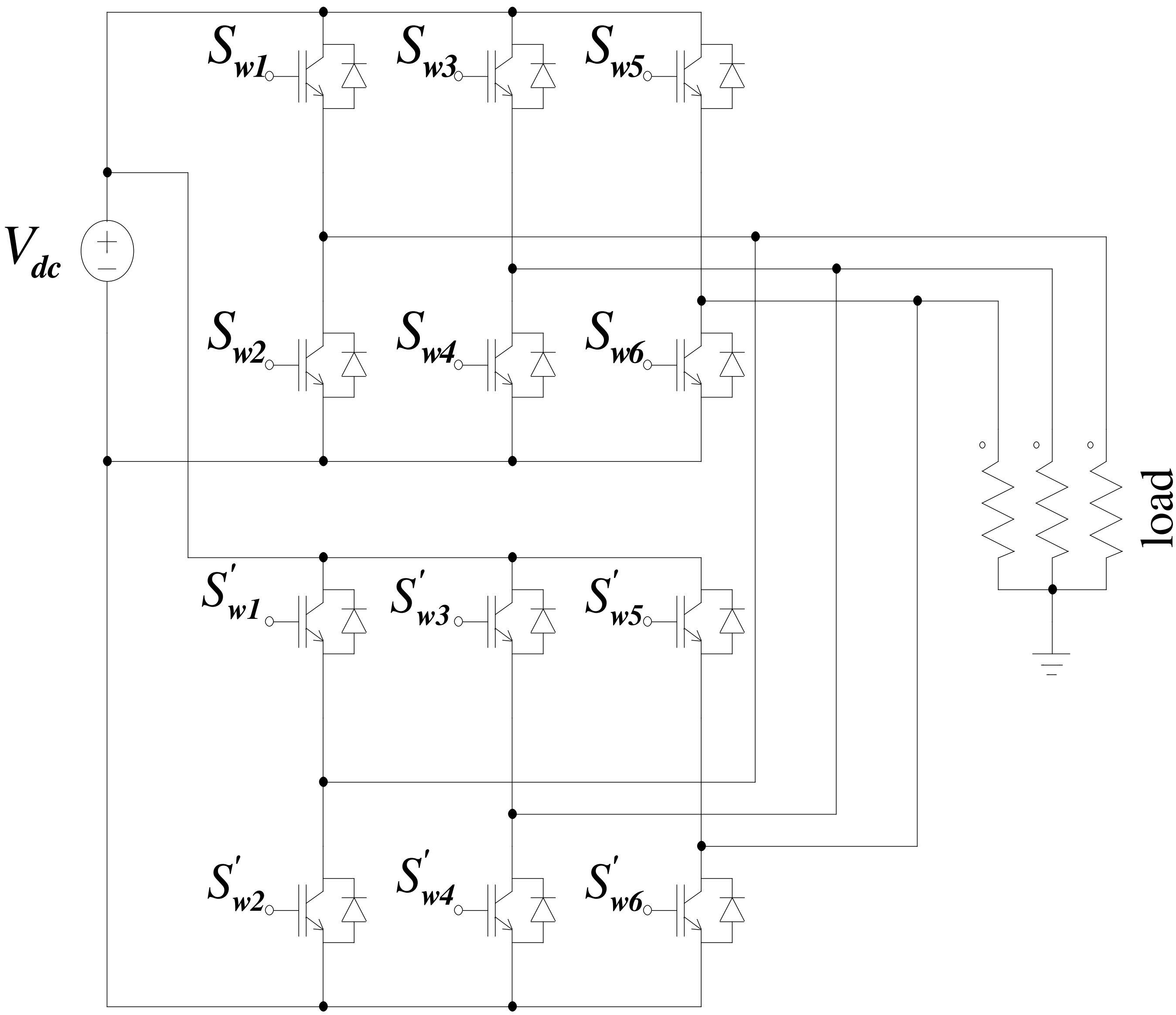

Figure 2.4 A schematic diagram of an interleaved inverter.

By using lower current rating devices switching at high frequency is possible which results in small size of the output filter inductor. There is a tradeoff between the number of channels of the interleaved inverter, output filter size and cost for development of the complex control circuitry for achieving robustness.

2.2.3 Matrix Inverters

The matrix inverter is mainly used for variable frequency wind turbine generation systems, as it connects three phase AC sources directly to the three phase loads.

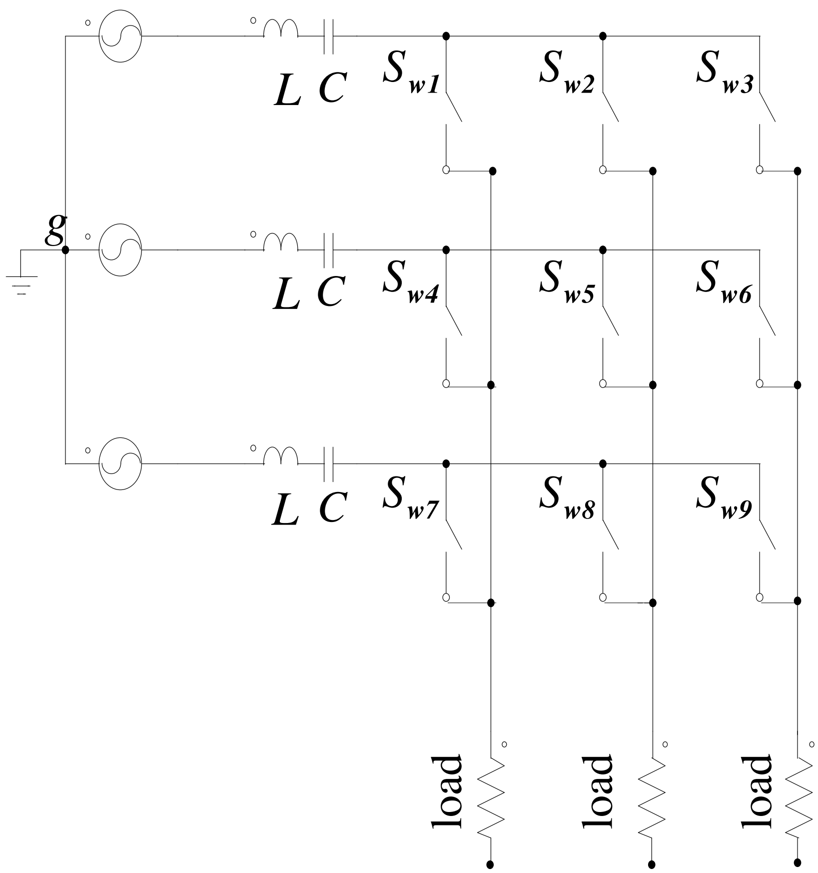

Figure 2.5 A schematic diagram of a matrix inverter.

The matrix inverter topology mainly consists of bidirectional switches which facilitate the bidirectional flow of energy. Another advantage of matrix inverter is that it omits the requirement of AC to perfect DC conversion state as well as the need for directly attached DC link capacitor or inductor for controlling the current or voltage respectively [10].

2.2.4 Voltage and Current Source Inverters

The voltage source converter is another type of basic topologies regarding grid tied inverters and current source converter is the other.

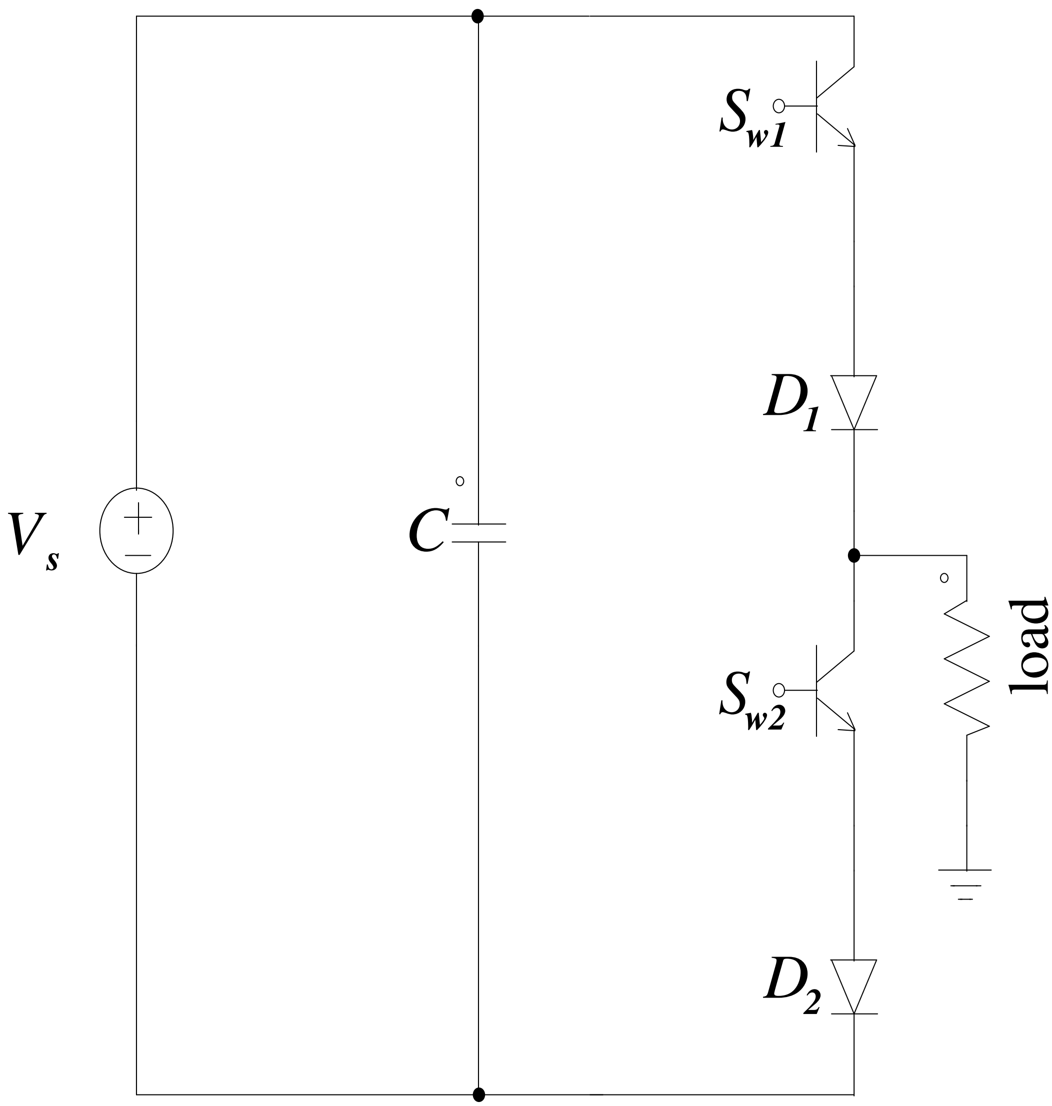

Figure 2.6 A single phase voltage source converter diagram.

In voltage source inverter as the name shows, the voltage is the source of power. To perfectly maintain the required DC link voltage, a capacitor is placed in parallel across the voltage source.

While in case of current source inverter, power is provided by using current source. Current is the prime source which is required to be controlled under strong grid harmonics. To regulate the current, an inductor is attached in series with power source [11 – 12].

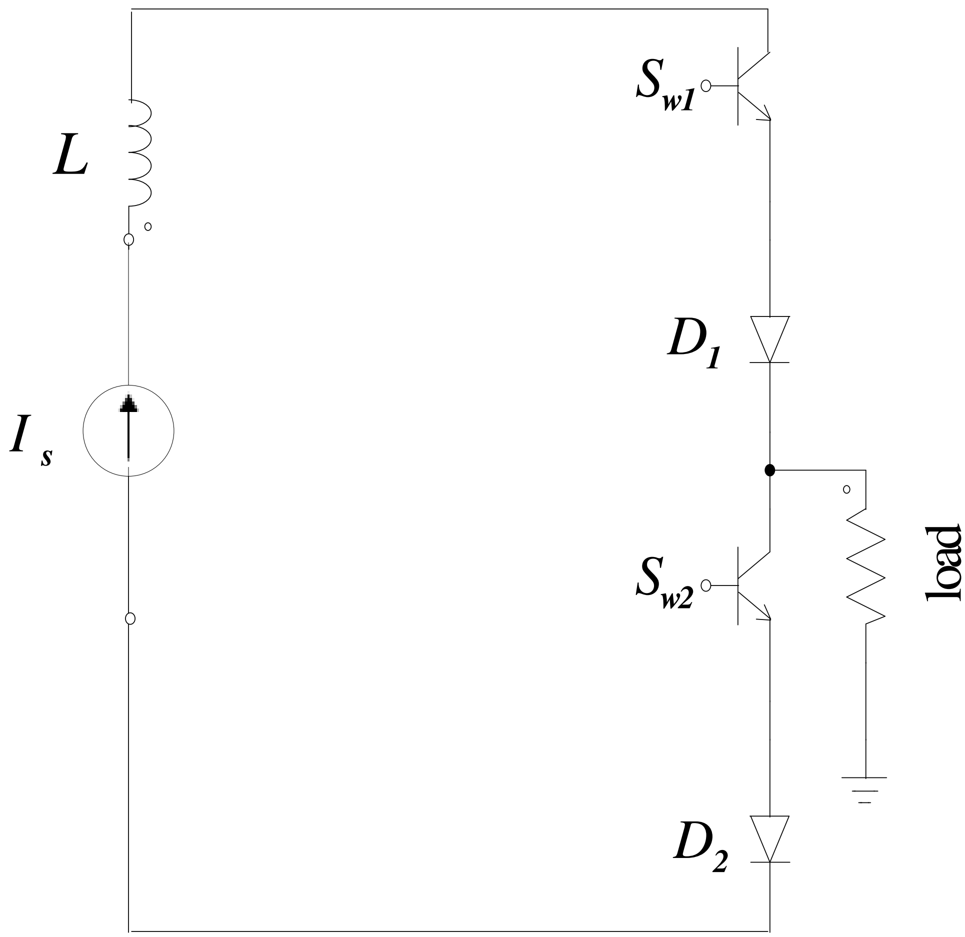

Figure 2.7 A single phase current source converter schematic.

2.3 Modulation Strategies for Grid Tied Inverters

Several modulation schemes have been implemented for grid tied inverters. These modulation schemes provide the switching strategies for inverters. Every modulation schemes demands a complete different pattern to follow for system design and control.

Switching losses for inverters is the main issue for grid tied inverter systems employed in micro-grid systems which has been addressed by each modulation scheme in a very unique aspect. These Modulation schemes mainly include Hysteresis, Pulse Width, Space Vector and Pulse Density Modulation etc.

2.3.1 Hysteresis Modulation (HM)

The hysteresis modulation is the simplest and easiest modulation scheme to implement. This type of modulation scheme is widely used to control output current a grid tied inverter.

Switching devices such as (IGBTs) are switched in a manner such that to track the output waveform. HM provides the robust tracking of reference signal with efficient dynamic response and accurate steady state operation. Additionally it offers the wide range of command tracking bandwidth.

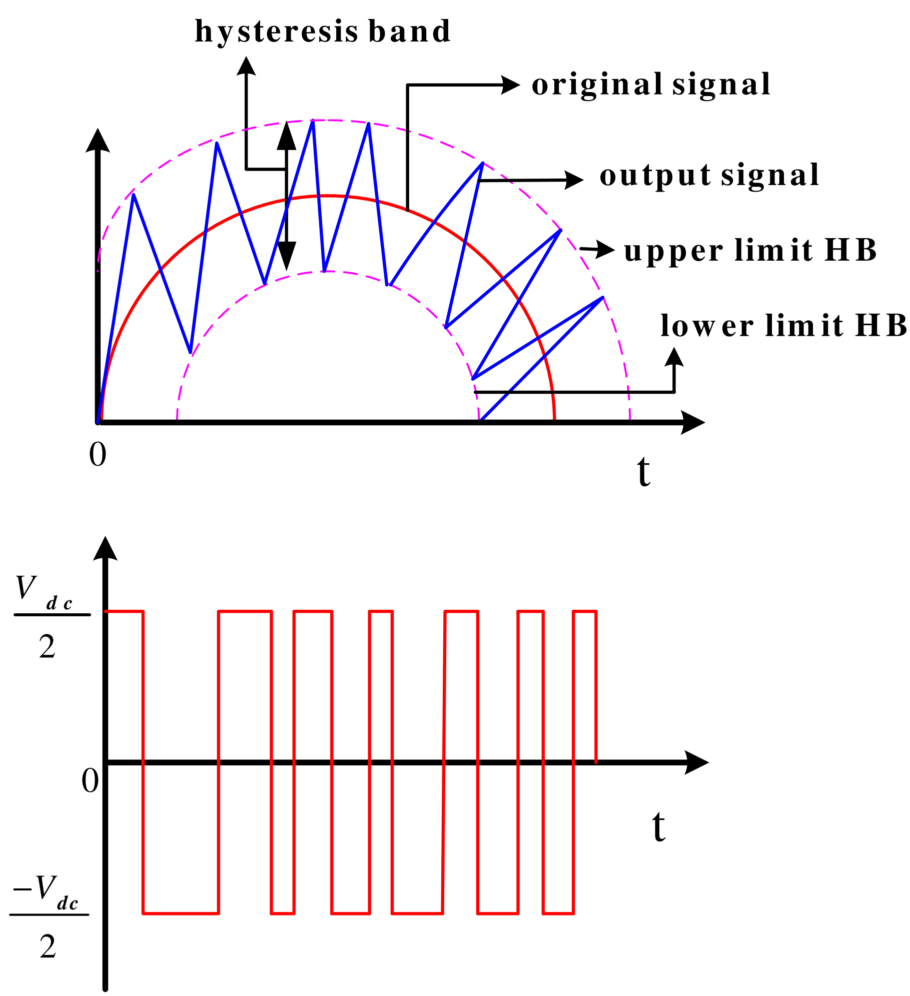

Figure 2.8 Switching waveform of hysteresis modulation scheme.

In this method the controlled variable (current) is compared against the designed hysteresis band (HB) for the generation of switching sequences of power devices (IGBTs).

Whenever the output current surpasses input current against the designed hysteresis band (HB) the output voltage is shifted to its lower value which is $\frac{-V_{dc}}{2}$ by setting $x = -1$ and vice versa to adjust the value of the output current. For $x = -1$ switches are set to their programmed logical levels i.e. $S_{w1} = 0$ and $S_{w2} = 1$. Similarly for $x = 1$ the switches are set to $S_{w1} = 1$ and $S_{w2} = 0$ [13 – 14].

2.3.2 Pulse Width Modulation (PWM)

The most widely used modulation scheme is pulse width modulation for grid tied inverter applications. In this modulation scheme the width of the pulses is controlled by applying frequency modulation on the carrier wave (saw tooth wave or triangular wave).

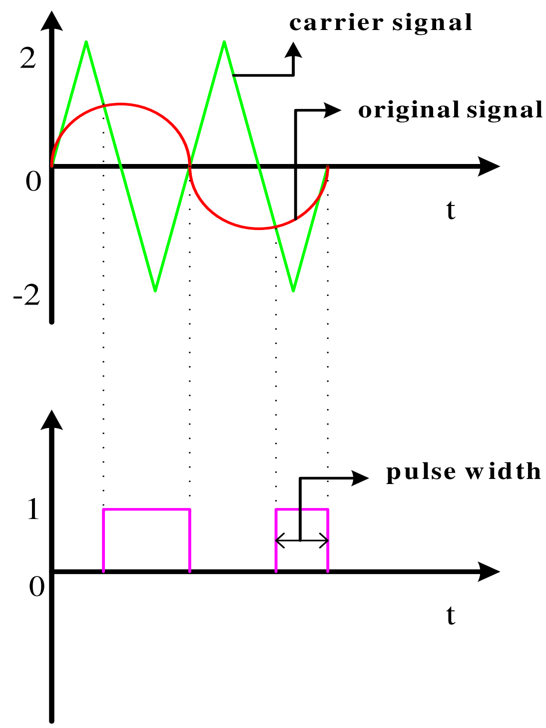

Figure 2.9 Switching waveform of pulse width modulation scheme.

The input or fundamental component of the original signal or waveform remains unchanged. By comparing the amplitude of fundamental signal with the amplitude of the carrier signal pulses are generated. These pulses are used for the switching of the semiconductor devices (IGBTs). When the amplitude of original waveform exceeds over the amplitude of a carrier wave a small pulse will be generated which in turn switches on the IGBT and vice versa. Proper control of the switching of the devices results in reducing the switching losses. To achieve desired output quality and low switching losses modified pulse width modulation schemes have been developed and successfully implemented in the literature [15 –17].

2.3.3 Pulse Density Modulation (PDM)

The pulse density modulation scheme mainly corresponds to the amplitude of the fundamental signal. In this modulation scheme a bit stream of pulses are generated in such a manner that +1represents the highest degree amplitude value for the basic fundamental waveform while -1 represents the lowest degree of amplitude value for the fundamental waveform. The concentration (number of pulses) of the pulses defines the amplitude value of the fundamental sinusoid. An alternate +1 and -1 represents zero amplitude of the considered original signal. The implementation of the PDM scheme is complex but the results achieved are far more reliable. The major drawback of PDM scheme is its requirement of more bandwidth compared to PWM [18 – 20].

2.4 Harmonic Filtering Schemes

The removal of harmonic content present in the output current or voltage waveform via filters is the most essential part of a modern grid connected inverter system design. Various filtering schemes have been implemented practically and published in various literatures such as simple L-type filter, LCCL filter, L-C filter and most renowned of all is LCL filter etc.

2.4.1 L–type Filter

The most simple of all filtering schemes is the use of L-type filter for filtering the unwanted current harmonics present in the output waveform of the grid tied inverter. These unwanted harmonics if not filtered will definitely give rise to the total harmonic distortion (THD) level beyond permissible limits.

The dynamic response is mainly affected by the unwanted current harmonics and it may also renders down the steady state response. The L-type filter which only consists of an inductor used to filter out current harmonics before injecting the power into the main grid for meeting the IEEE standards regarding grid connectivity and bidirectional power flow.

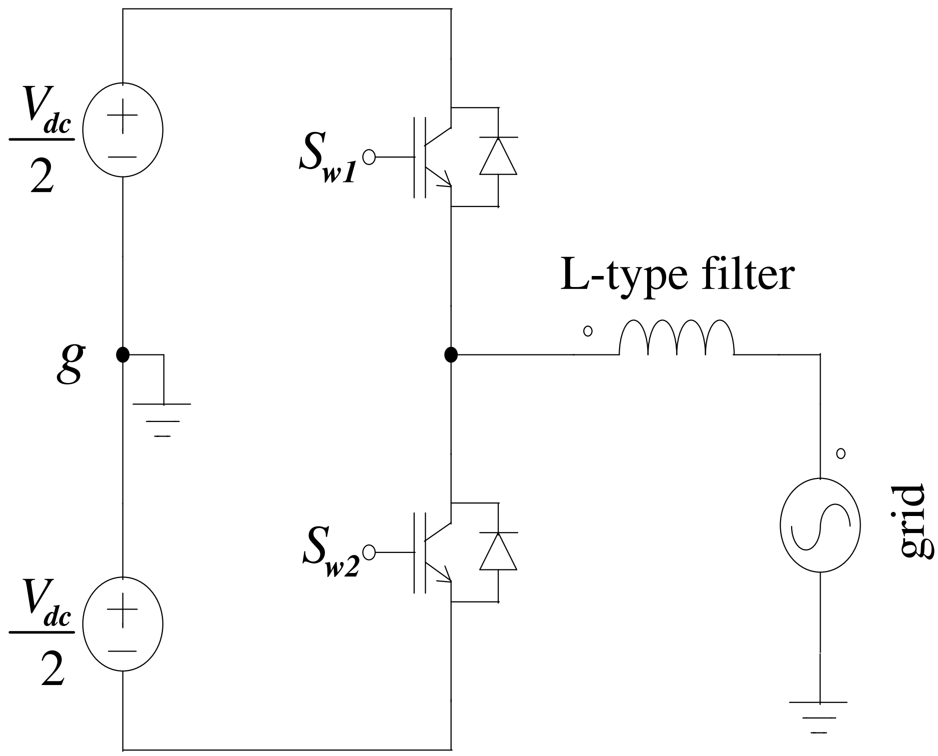

Figure 2.10 Grid connected inverter schematic with simple L type filter.

The main advantage of using simply an inductor as a filter simplifies the circuit complexity and thus reducing the cost of the whole system. The shortcoming of using this filter is its high inductor losses when connected to high rating devices for high power applications. For high power applications the required inductor size is more and therefore results in increased cost for making large size inductor [21 – 22].

2.4.2 LC Filter

LC another filtering scheme consists of only an inductor and a capacitor. The LC filter provides efficient filtering results as compared to simple L-type filter suits better for large power oriented system designs.

LC filters which is comparatively much smaller from simple L-type filter and hence inductor losses can be compromised. LC filter provides a different range of resonance selection by changing the filter constraints. The main problem that LC does not cater for is impedance mismatch while in grid tied mode. This impedance mismatch raises serious problems regarding performance of the filter to reject undesired current harmonics. Additionally it also challenges the controller robustness and hence results in significant reduction in the tuning and stability range thus deteriorating the performance of the controller and decreasing the overall efficiency of the system [22 – 23].

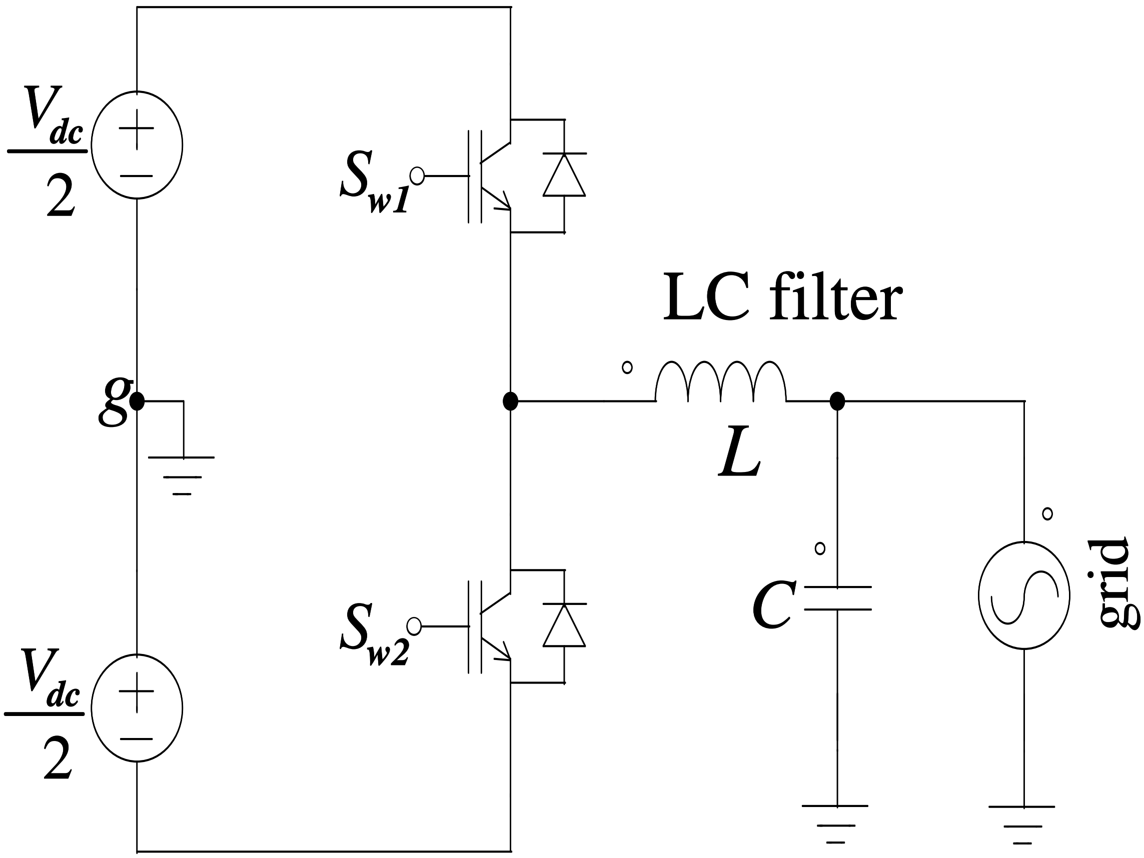

Figure 2.11 Grid connected inverter schematic with LC filter.

2.4.3 LCCL Filter

The LCCL filter scheme is basically consists of two inductors and two capacitors. LCCL filter is indeed a further extension of LCL filter to address the impedance mismatch issue and to mitigate the filter resonance problem. In LCCL filter the LCL capacitor value is distributed into two capacitance values.

This distribution of capacitance values and sophisticated selection of filter parameters can reduce the transfer function of the filter to first order. This will make the transfer function calculations and derivation easier as well as the designing of the controller will be less complex.

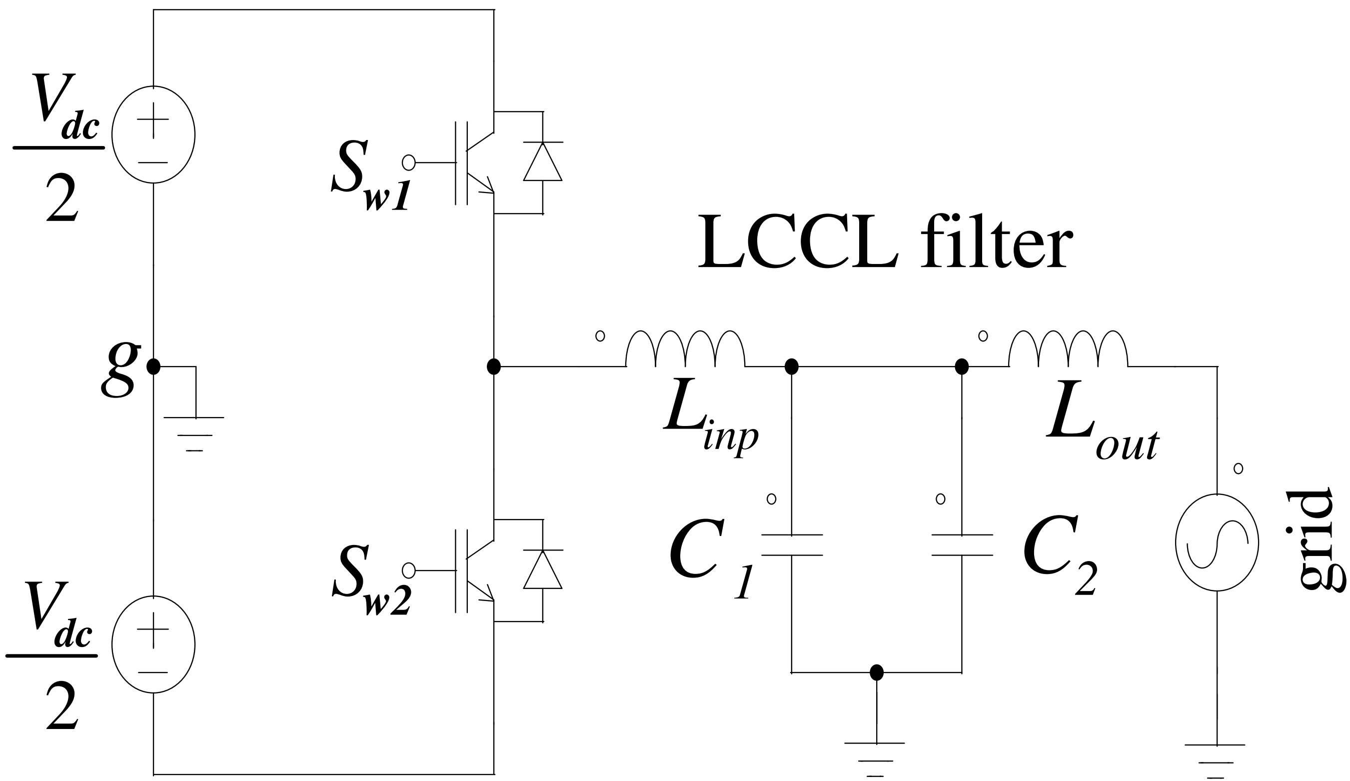

Figure 2.12 Grid connected inverter schematic with LCCL filter.

The current is feedback after the first capacitor so that the controller stability range is increased and making the dynamic response appealing to reject the unwanted current ripples produced due to fast switching of the IGBTs and also the steady state error is improved [24].

2.4.4 LCL Filter

The LCL filter scheme is so far much efficient and widely used than other filtering schemes. LCL filter resolves the issue of filter resonance and provides a reliable solution to the impedance mismatch problem efficiently.

Also the smaller size of an LCL filter reduces project cost hence ensuring the lesser amount of inductor losses with achieving the desired output results. Proper selection of LCL filter parameters provides a suitable tuning range of the controller and reasonable bandwidth for undesired current harmonics rejection. Under this reasonable range of bandwidth and enhanced stability range, the controller's response is more robust towards rejecting switching frequency current ripples. LCL filter parameter values are selected based on switching frequency, required level of DC link voltage for smooth operation and the maximum allowable harmonic content [24 –25].

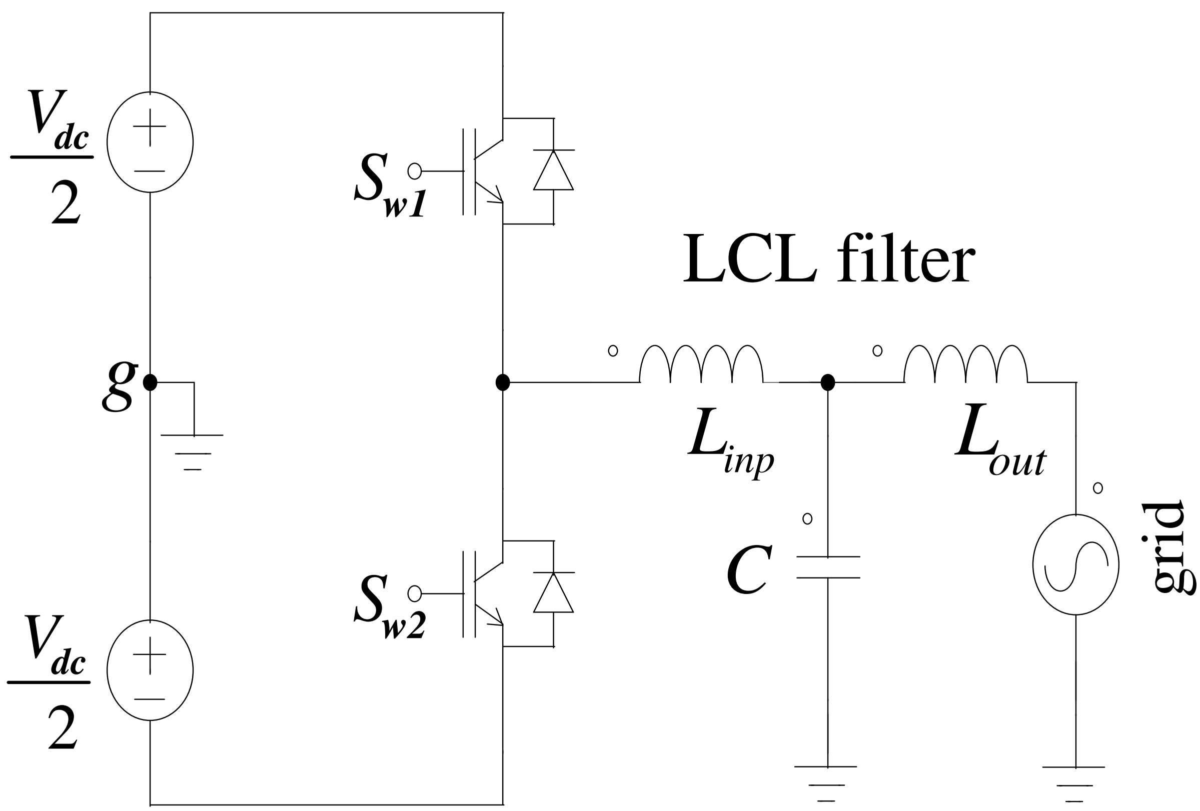

Figure 2.13 An LCL filter schematic.

2.5 Phase Locked Loop (PLL) Schemes

Referring grid disturbances, the unbalanced or mismatch in any phases among the three phase high powered grid causes the desired voltage quality for overloaded phase to drop down under permissible limits. The phase imbalance situation produces overload and noise in three phase powered equipment such as transformer, induction motors etc. Output current or voltage in three phase system must be synchronized to avoid mismatch forming the three phase system theoretically balanced system. The classical method of grid voltage synchronization is zero crossing voltage detection technique. The more sophisticated and advance technique is phase locked loop which is implemented by using analog circuits or by the use of digital systems. The theoretical introduction of phase locked loop scheme for communication system applications was first published by a French scientist H. de Bellescize in 1932 [26]. The application of phase locked loop scheme in power system took place after the invention of modulation schemes and revolutionary advancement in power electronic semiconductor devices. In 1968 Ainsworth proposed the addition of a voltage control oscillator (VCO) in the feedback path of the control system loop of a large voltage direct current system for minimizing the effect of harmonic instability and stress [27]. The phase locked loop scheme is actively being used for grid engaged inverter systems for phase and frequency synchronization with the power grid parameters.

2.5.1 Phase Locked Loop (PLL)

A wide range of applications related to challenging engineering fields such as communication engineering, control system engineering, process control engineering, industrial engineering etc. frequently apply phase locked loop for better and efficient results.

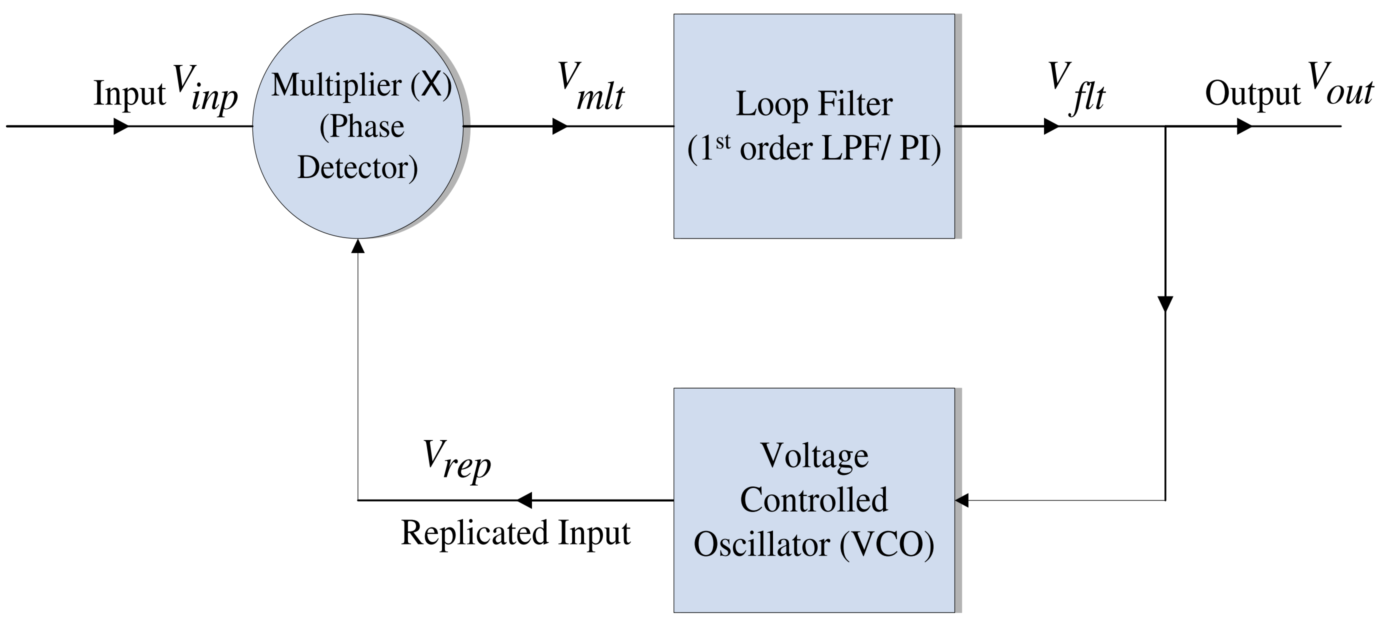

Figure 2.14 Phase locked loop (PLL) block diagram with PI regulator.

The basic components of a phase locked loop in general are given below

1. Phase detector or phase comparator (Multiplier circuit)
2. Loop filter circuit
3. Voltage controlled oscillator circuit (VCO)

For perfect and reliable synchronization of the phase and frequency of input signal phase locked loop techniques are the first choice of a good system designer. PLL is used for phase angle detection and estimation while frequency locked loop (FLL) is normally used for frequency detection and estimation of the input signal waveform (voltage or current) [28].

2.5.2 Park PLL

The phase locked loop schemes are used for phase angle detection, estimation and synchronization with the reference signal (grid voltage and current waveforms).

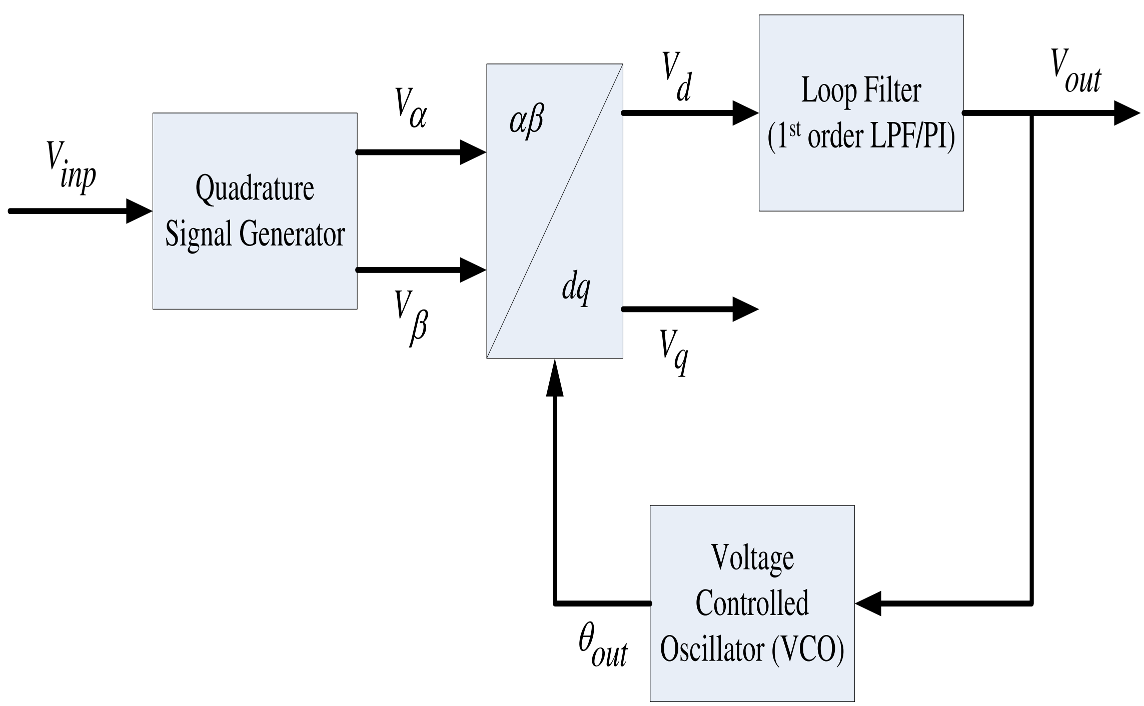

Figure 2.15 Park transformation based phase locked loop (PLL) block diagram.

The phase locked loop schemes have been extensively used in the proper detection and efficient extraction of voltage or current output signals from highly distorted grid voltage or current waveforms. The park phase locked loop (PLL) uses park transform which is used to transform three phases of AC Voltages or currents into two DC quantities for facilitating and simplification of calculations. These transformed imaginary DC quantities are then treated under specific, complex and important calculations for achieving the desired results. These transformed results are easier in handling i.e. the two DC quantities rather than dealing with three AC quantities. After performing required calculations these DC quantities are then transformed back into the actual three phase AC quantities (voltage or current waveforms) by applying inverse transformation.

Park transformation is also called as dq0 (direct quadrature zero) or 0dq (zero direct quadrature) transformation because it is actually similar to the transformation initially given by Robert H Park in the year 1929 [29].

The Park transform is represented below mathematically in eq. 1.

$$P = \frac{2}{3}\begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \tag{1}$$

The dq0 transformation for current waveform in mathematical form is given in eq. 2.

$$I_{dq0} = T\ I_{abc} = \sqrt{\frac{2}{3}}\begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{pmatrix}\begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} \tag{2}$$

2.5.3 Inverse Park PLL

The inverse park PLL scheme is used for the retrieval of original signal from the transformed signal by implementing the inverse scheme against park transformation.

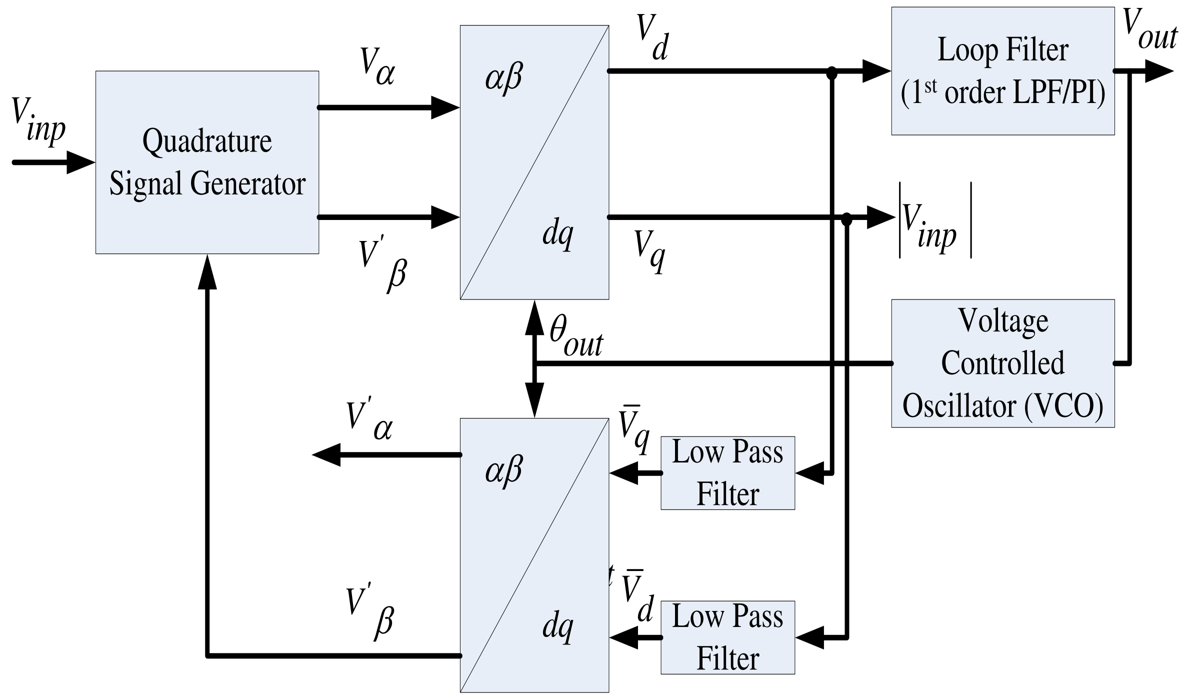

Figure 2.16 Block diagram of Inverse park transformation based phase locked loop (PLL).

All the three AC quantities are retrieved by applying inverse park transformation on the two processed DC quantities.

The mathematical representation of inverse park transformation is given in eq. 3.

$$P^{-1} = \begin{pmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{pmatrix} \qquad (3)$$

The transformation is given in eq. 4.

$$I_{abc} = T^{-1} I_{dq0} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos(\theta) & -\sin(\theta) & \frac{\sqrt{2}}{2} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{pmatrix} \begin{pmatrix} I_d \\ I_q \\ I_0 \end{pmatrix} \tag{4}$$

2.6 Controller Designs

The controller design for grid connected inverter application in micro-grid, smart grid and power system plays a pivotal role in monitoring the power quality, bidirectional flow of energy and power sharing between loads of different nature i.e. linear, nonlinear, domestic, commercial or industrial. In domestic, commercial and industrial loads, classical controller design provides sufficient control and satisfactory results for minimizing the undesired disturbance caused by switching of linear or nonlinear loads. Classical controller design facilitates low power systems or the system constraints are not strict or compromised, additionally reducing the overall cost of the system. Advance and robust controller design is implemented when system constraints are strict and can't be compromised at any cost such as in high power grid applications where the harmonic level beyond permissible limits of a power injecting system is considered to be a pollutant to the system which renders down the power quality of the power grid thus violating IEEE standard. The use of advance controller scheme raises in general power equipment manufacturing cost, additionally it demands efficient protection system to avoid any sort of damage to the costly equipment.

2.6.1 Classical Controllers

The classical controllers basically consist of simple combinations of proportional, integral and sometimes include derivative controls. These classical controllers are easy to implement, low cost, easily controllable and show good steady state response for simple and particular applications. For grid tied inverter applications when the load is linear the results of classical controllers for current harmonic rejection are satisfactory. But when, the grid impedance variations such as frequency variation, voltage or current variation occurs, the performance of the classical controller decreases rapidly. In grid imbalance situation the classical controller's the dynamic response to reject unwanted current ripples becomes questionable. Grid imbalance situation also contributes to large steady state error and challenges system stability as well. The controller gains are raised to achieve the system stability and desired output result with less than 5% THD level in the output current. The grid impedance variations cause a considerable reduction in the tuning range of the classical controllers. And after certain limit the classical controller fails to respond to reject the current harmonics with gains variations. Hence classical controllers have very narrow tuning range for the gain adjustment, therefore they fail to track sinusoidal input waveform of the current or voltage and their harmonic rejection capability ultimately suffer from low loop gain. Other control schemes are conceived and developed to cater the severe problem of gain variation limitations to enhance the controller's capability to meet the application requirements. These modern/advance control techniques are explored in the section below. The PID controller is shown with plant system in fig. 2.17.

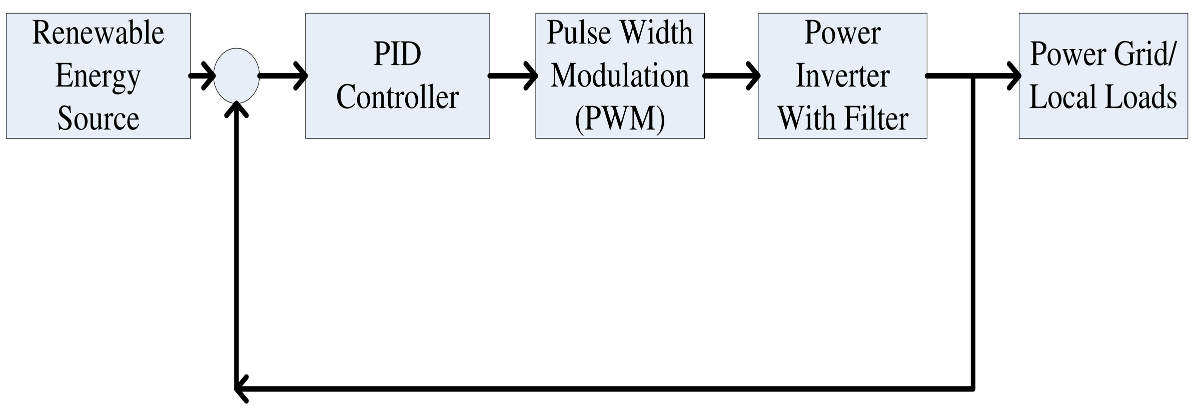

Figure 2.17 The PID controller with micro grid system.

2.6.2 Advance Controllers

The modern/advance controllers include state feedback controller, dead beat controller, fuzzy controller, H-∞ controller, linear-quadratic regulator controller (LQR), resonant controller (RSC), proportional resonant controller (PRC) and repetitive controller (RC). The combinations of these advance controllers can also be used considering the system and the equipment compatibility with application requirements. The modern/advance control schemes are more robust; provide excellent stability and wide range for tuning of gains of the controllers. The steady state error of these modern controllers is very small with efficient steady state response. The modern controllers can track reference sinusoidal waveform efficiently due to their fast dynamic response towards disturbances which have been introduced into the system due to abrupt switching of non-linear devices/loads. These disturbances also include the switching current ripples because of the fast switching of the inverter IGBTs.

2.7 Summary

The emerging trend towards power generation via naturally occurring renewable energy sources is getting popularity among governmental power generation departments as well as masses all across the globe. Also smart grid and micro grid system and the development of cheap and efficient equipment with successful implementation in developed and advanced countries has provided hope, source of motivation and courage to take initiative for the implementation of these viable techniques for harvesting cheap and clean energy in the under developed countries of the world. The mode of operation of grid connected inverter discussed above play a pivotal rule for its consumer or commercial based applications; additionally converter topology provides the bases for efficient and cost effective design. Filtering schemes related to harmonic filtering and to reduce electromagnetic interference (EMI) for reliable operation has also been elaborated. Grid synchronizing system is also essential for tracking of reference signal to abide by international standards for power grid interconnected systems. And of course the control system, the heart and life line of the grid connected inverter system, described above in detail is responsible for maintaining power quality, controls equal power sharing among dissimilar types of loads, monitors bidirectional power flow and facilitates efficient harmonic filtering, and leads other operational and protection system functions under strong power grid variations. There is a tradeoff between all these design parameter selections for specific and general applications regarding grid connected inverter system to operate in smart grid or micro grid system following IEEE recommended practices.

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CHAPTER – 3

3. Software Selection and Design Methodology

3.1 Design and Simulation Software Tools

In literature, the use of several design and simulation software tools and hardware systems have been reported and successfully implemented for the design, analysis and optimization of renewable energy resources based grid connected inverter systems. The combination of both software tools and hardware systems suffices the analytical study, design and integration of these renewable energy powered hybrid generation systems with smart grid, micro-grid and main power grid to feed in and borrow power from the system as required by the connected loads.

3.1.1 Design and Optimization Software Tools

RAPSim (Renewable Alternative Power Systems Simulation) is designed and developed focusing renewable energy based inverter systems integrated or in operation with grid connectivity and its operational modes. RAPSim facilitates the modeling and simulation grid tied or standalone modes of operation of main power grid system, smart grid or micro-grid system in conjunction with solar, wind, fuel cell or biomass energy based generation system to produce clean and reliable electricity [1 – 2].

Originally HOMER another simulation oriented platform was designed in USA. HOMER Energy has commercially launched and distributed HOMER to global renewable energy markets [3]. HOMER is the user friendly power optimization software for the implementation of hybrid systems because it contains a wide range of necessary tools for system design and optimization [4]. HOMER contains the wide range of system modeling blocks and facilitates modeling of different control parameters, additionally it has the ability to optimize renewable powered energy systems consists of photovoltaic panels, wind energy turbines, fuel cells, DC batteries, biomass from animal wastes, combined heat and power (CHP) systems [5 – 6].

SOMES, developed by the scientists conducting research on renewable energy resources at Utrecht University, Holland. SOMES has the generic ability for simulation modeling and analysis to study behavior and assist in achieving required level of performance of the renewable energy systems integrated to photovoltaic (PV) arrays, wind energy turbines, fuel cell battery storage systems and multiple types of inverter systems under strong harmonic disturbance [7].

HYBRID2 project was mainly designed and developed by research scientists from University of Massachusetts, USA. HYBRID2 was designed to model, analyze and study a wide variety of renewable energy powered hybrid energy generation systems supporting wind turbines, photovoltaic cells, universal battery storage systems, and different types of diesel generators providing very precise simulation results for these modelled systems [8 – 9].

TRNSYS generically based on FORTRAN language. Thermal power based systems were designed and perfectly modeled via TRNSYS. TRNSYS is commercially available since 1975 developed by the research scientists at University of Wisconsin, USA. TRNSY is a hybrid energy generation system simulator which includes photovoltaic arrays, wind power turbines, solar power thermal systems, HVAC systems, renewable powered energy systems, fuel cell based energy systems. The simulation results by TRNSYS are extremely appealing with minimum error, but it does not support system optimization [10].

3.1.2 Real Time Implementation Simulators

RTDS (Real time Digital Power Systems) Technologies is the industry standard simulators for power generation systems. The RTDS Simulator is the most powerful tool designed especially to simulate and test the performance of the electrical power systems in conjunction with physically interconnected devices for its control and protection such as relays, circuit breakers, fuses, isolation transformers, etc. under grid imbalance [11 – 12]. RTDS also provides an efficient platform to design and validate renewable energy sources for grid tied inverter application for load flow analysis. RTDS simulator is in fact world’s benchmark for running real time power system simulations [13].

PSCAD™/EMTDC™ is generally a multi-purpose time domain simulation tool for modeling and control of multi-phase renewable powered inverter integrated into grid power systems. PSCAD offers a wide array of possible solutions regarding system integration, modeling and control of solar power energy systems and wind power systems and to investigate into their environmental impacts. Thus PSCAD offers a wide range of unbound possibilities for performance evaluation, testing and protection of power system design via precise and efficient simulation results. In PSCAD a comprehensive library for system modeling credit it to be an attractive choice for researchers conducting research in the most challenging field of renewable energy sources based hybrid power systems for grid tied inverter systems application [14 – 17].

In the late 1970's Cleve Moler, at that time the chairman of department of computer science at University of New Mexico initiated the development of MATLAB. Later on, Jack Little, a control system engineer from Stanford University and MIT, was introduced to MATLAB concept by Moler at Stanford University in 1983. Jack Little joined the research and development group and developed MATLAB initially using only C language.

Commercially MATLAB was launched in 1984. The most frequently used simulation tool for power system analysis is Matlab/Simulink developed by Math Works founded in California, USA, 1984 [18 – 19].

3.2 Justification for the Selection of the Software

MATLAB (Matrix Laboratory) is the most powerful simulation and programing software developed ever in the field of applied mathematics and the most multi challenging inter-disciplinary fields of engineering. MATLAB is a multi-paradigm 4th generation programing language and numerical computing software environment, which deals with the very wide and broad range of system models and blocks related to electrical/mechanical/chemical engineering topics; control system, communication networks, telecommunication, power electronics, process control, robotics, aeronautics, image processing, signals and systems, analog and digital signal processing, RF circuits, neural networks and many more [20].

The software used for the design, analysis and simulation results for grid connected inverter is PSIM, Microsoft Visio, Math Type and MATLAB. The Matlab/ Simulink software has been selected to model, analyze and simulate the system because it is user friendly compared to other design software tools and it also facilitates the user much more in terms of designing the simulation model using SISO design tool box of Matlab and evaluate the design parameters via running simulation using Simulink. The blocks such as PWM generator block, universal bridge of power semiconductor devices, series RLC blocks etc. are already provided and easily available in Simulink to design the simulation model for achieving simulation results for grid connected inverter. The Simulink also provides other blocks regarding control systems, signal processing, communication system tool blocks to integrate and design different overlapping engineering domain projects and run simultaneous simulations necessary for accomplishing the required decree of performance and overall response relevant to the designed system under observation. By using Matlab one can easily analyze the system behavior and determine the errors or flaws of the system. Matlab commands are very simple for determining the open loop response, closed loop response, root locus and bode diagrams for analyzing the gain margins and phase margins of the system, frequency response and Nyquist response etc. SISO tool box is used for the linear analysis of the system as well as analyzing open loop, closed loop behavior of the system [21].

PSIM and Microsoft Visio assisted in designing the figures and block diagrams of grid connected inverter system in conjunction with renewable energy sources and their control technique.

Math type is used to write the necessary mathematical equations regarding system modeling and mathematical design analysis.

3.3 System Modeling and Design Methodology

The system with LCL filter is modeled using two level inverter while applying the classical control schemes to analyze the system behavior, response as well as system stability under the control strategy applied whilst the system is under the influence of strong grid harmonics. The prime focus of system modeling is to achieve a well optimized and balanced system which responds efficiently to the disturbance caused by switching of linear or non-linear loads connected to micro-grid systems. Different combinations of proportional-integral-derivative (PID) controller have been applied such as P, PI, PD and PID controller combinations. The fundamental layout for LCL Filter with a 3-phase grid tied inverter is publicized in Fig. 3.1

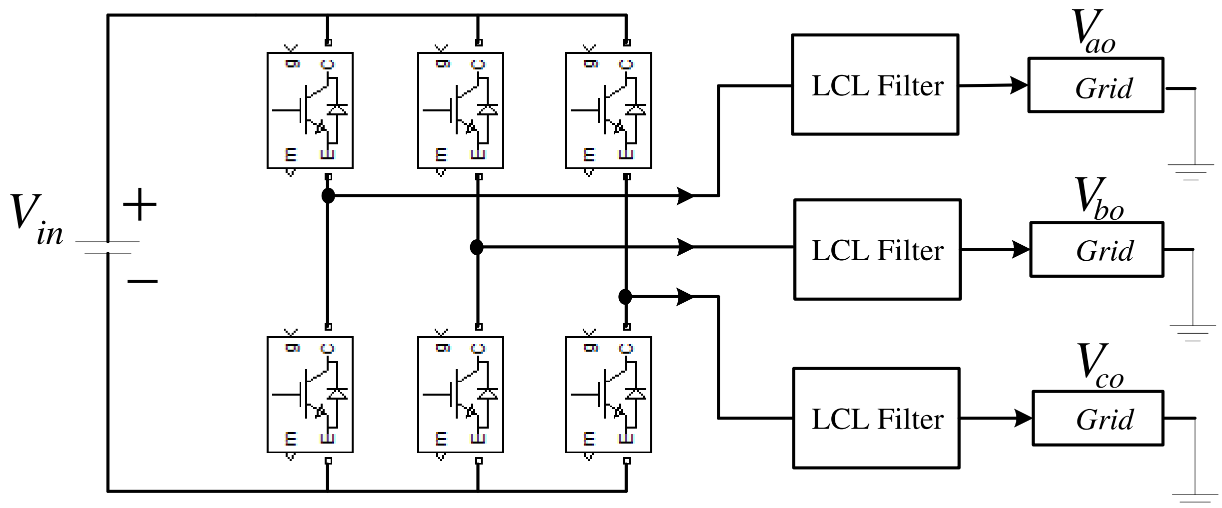

Figure 3.1 The layout for LCL Filter with 3-phase two level grid tied inverter.

The linear model of the single phase grid engaged inverter system in conjunction with a simple LCL filter scheme is depicted in fig. 3.2.

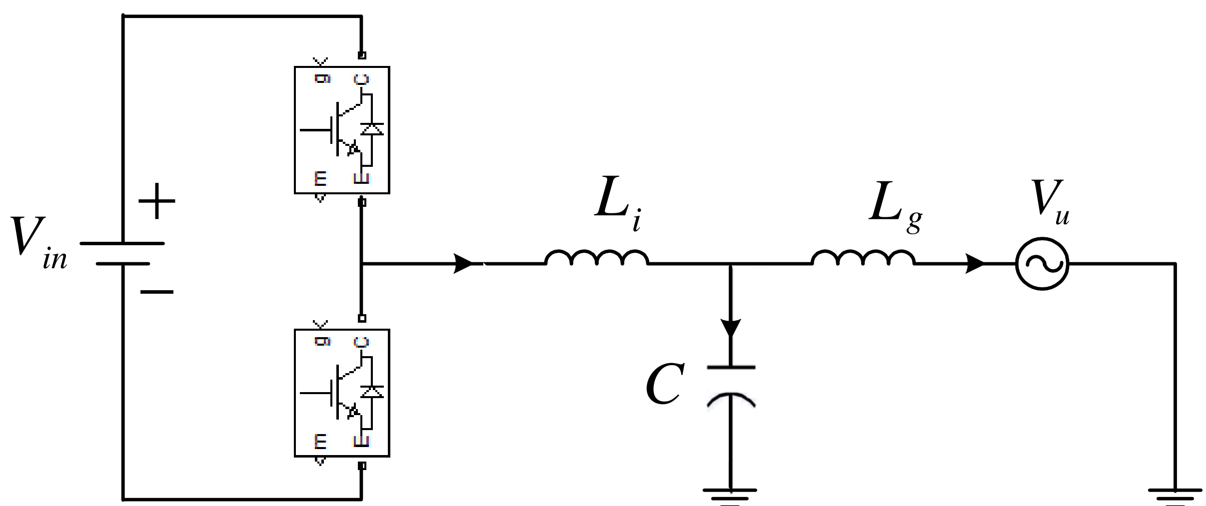

Figure 3.2 A schematic of linear model for single phase grid engaged inverter system in conjunction with a simple LCL filter.

Analysis and derivation of LCL filter equations is performed utilizing the fundamental techniques of electrical systems KVL and KCL [21].

$$V_{in} - V_c = L_i \frac{dI_i}{dt} \quad (1)$$

$$I_c = I_i - I_g \quad (2)$$

$$I_c = C\frac{dV_c}{dt} \quad (3)$$

$$V_c - V_u = L_g \frac{dI_g}{dt} \quad (4)$$

Ignoring disturbance introduced in the system and utilizing the all above mentioned expressions, the system transfer function is given as

$$I_g = \frac{1}{(L_i L_g C)s^3 + (L_i + L_g)s} I_{ref} \quad (5)$$

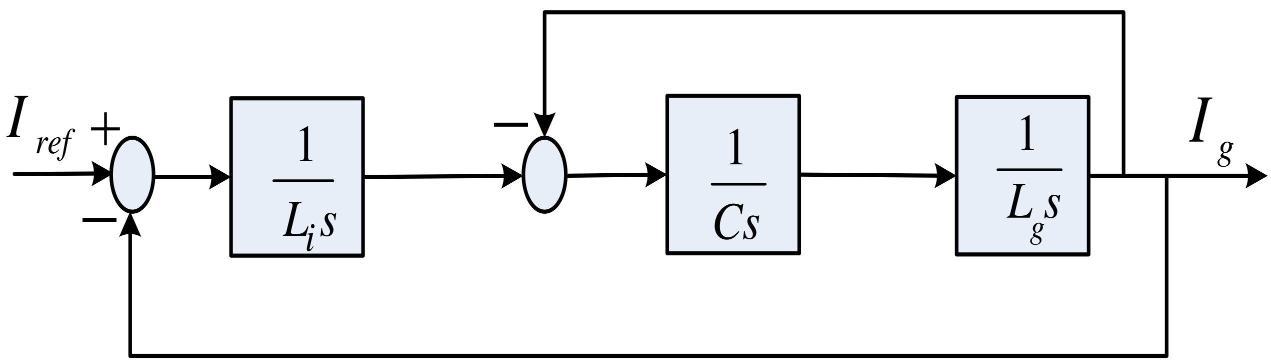

Figure 3.3 A transfer function based equivalent model schematic for single phase system.

In above expression (5) damping is missing leading the system, highly unstable. A feedback path of current through the capacitor is introduced for system stability.

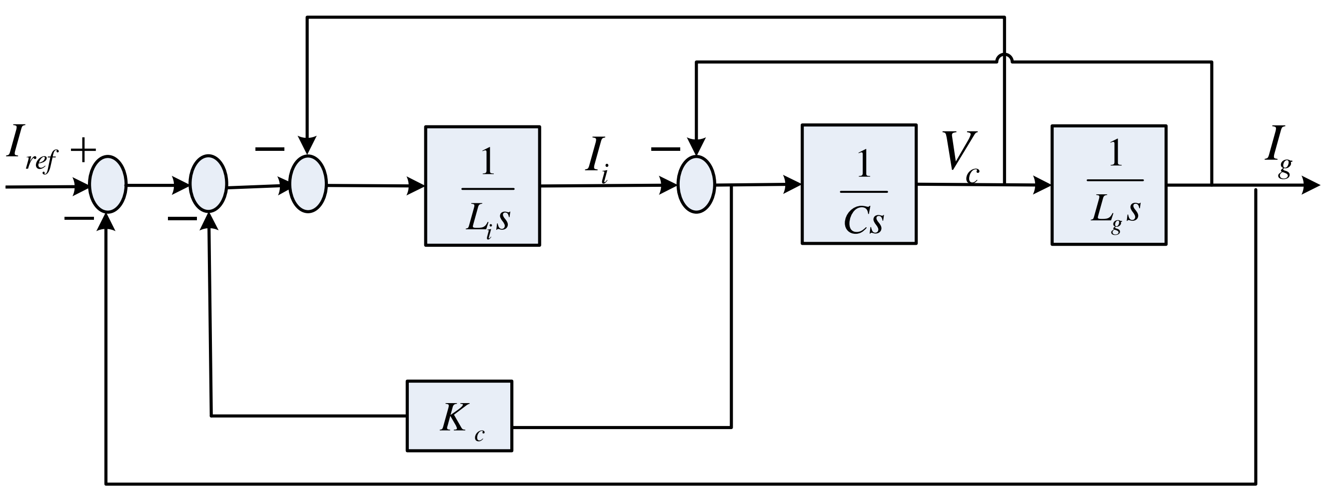

Figure 3.4 A Transfer function schematic with feedback current flowing through capacitor.

So the expression (5) transformed as

$$I_g = \frac{1}{(L_i L_g C)s^3 + (K_c L_g C)s^2 + (L_i + L_g)s} I_{ref} \tag{6}$$

System transfer function is in expression (7).

$$G_p(s) = \frac{1}{(L_i L_g C)s^3 + (K_c L_g C)s^2 + (L_i + L_g)s} \tag{7}$$

With the addition of controller gain G_C into the system, the transfer function schematic is given below.

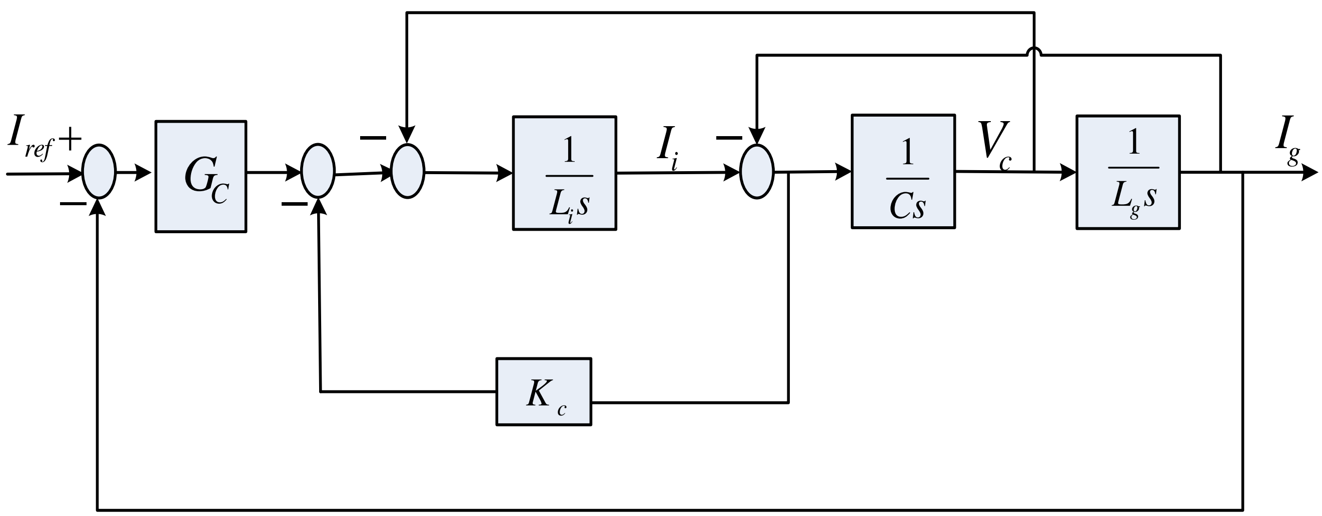

Figure 3.5 A Transfer function block diagram of the overall plant and controller gain and feedback current through capacitor.

Complete transfer function is given in expression (8).

$$G_o(s) = \frac{G_c(s)G_p(s)}{1 + G_c(s)G_p(s)} \tag{8}$$

3.3 Summary

In this chapter a brief overview of optimization and simulation software tools is given for grid connected inverter system applications. The single phase two level grid tied inverter in conjunction with a simple LCL filter scheme and classical control strategy oriented linear model is developed and transfer function is derived to apply simulation based verification method using MATLAB/ Simulink.

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CHAPTER – 4

4. MATLAB /Simulink Results

4.1 P and PI Gain Variation Simulations

The P and PI controllers based MATLAB/Simulink oriented results by the selection of most appropriate controller gain values have been confirmed and validated. The system modeling is carried out utilizing SimPower Toolbox a specialized feature of MATLAB. SISO design tool facilitated in tuning and selection of most appropriate controller gains.

The electrical system design parameters provides a standard platform for testing the simulation model results and facilitates in achieving the desired output current results while keeping the harmonic level within limits. The P/PI combination of classical PID controller is applied for through study of the behavior as well as response of the well modeled and perfectly designed system to reject the unwanted frequency harmonics in the output current waveform. As the system is modeled for feeding extra generated power into the main interconnected power grid, current waveform of the inverter is essentially monitored and synchronized with the grid current waveform so that the IEEE standard for power regulation between the generation system and the grid must be maintained i.e. the current THD level must not exceed the permissible limit of 5% [1].

Initially when the disturbance introduced into the model is less, the controller's response is satisfactory and the rejection capability for undesired frequency harmonics of the conventional PI controller is in accordance with required level, maintaining the THD level less than 5%. But when disturbance introduced into the system is of high level, the performance of the PI controller deteriorated. Unfortunately the allowable THD level which is 5%, is not maintained thus the quality of the output current reduces effectively. The output waveform of the current gets distorted with the external disturbance introduced into the system and the feedback information about the current is given back to the PI controller so that the disturbance can be rejected to achieve the desired level of the output current fed to the power grid should be distortion less [2 – 3].

The electrical design related constraints for desired output results via simulation are tabulated in below given table. 4.1.

Table 4.1. Electrical constraints for modeled system

Electrical Constraint	Symbol	Related Values
DC link potential	V_{dc}	750 Volts (dc)
Single phase voltage for power grid	V_p	230 Volts (rms)
Inductor attached to power semiconductor	L_i	350 micro Henry
Capacitor	C	22.5 micro Farad
Inductor attached to grid	L_g	50 micro Henry
IGBT's switching frequency	f_s	10,000 Hertz
Fundamental frequency of the grid	f_g	50 Hertz
Maximum allowable output current	I_g	100 Ampere

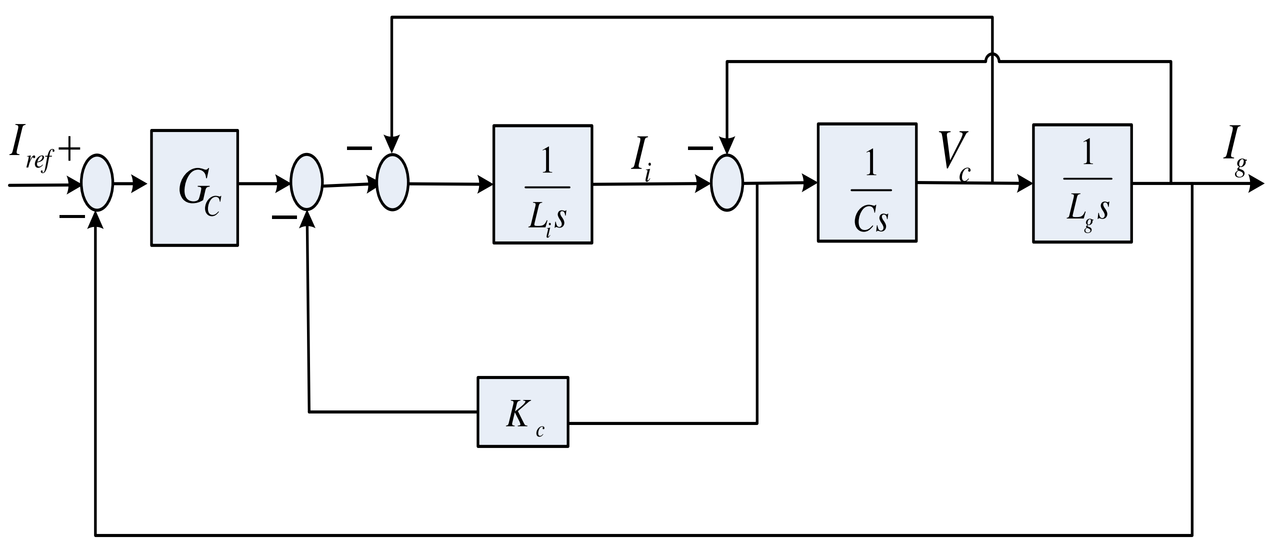

Figure 4.1 A single-phase equivalent model schematic for simple LCL filter.

The designed system is considered as a dual loop system. The internal feedback loop is provided with the gain, K_c which in combination with the current flowing through the capacitor provides sufficient value of damping thus fulfilling the necessary requirement for stabilizing the designed system, depicted in Figure 4.1 also the internal feedback loop gain is retained to particular value which is $K_c = 3.0$ [4].

The classical controller gains K_p for proportional gain and K_i for integral gain are tuned. By varying the conventional PI controller gains the designed system is capable of rejecting unwanted harmonics within certain limits. Beyond the limitations, further variation does not stabilize the system. To achieve the desired output current waveform while maintaining the IEEE standard, the controller gain is varied. In PI controller, the two gain values K_p and K_i are varied to boost the unwanted frequency harmonic rejection capability of the PI controller while the system is under the influence of strong grid harmonics. Initially the gains are set to $K_p = 1.0$ and $K_i = 1.0$ while the disturbance introduced externally is high. The output current waveform is not synchronized with the reference current waveform. The result is evident in figure 4.2 which compares clearly the reference input signal waveform followed by controller's current output waveform. The output current signal is not perfectly matched or synchronized with the input current signal.

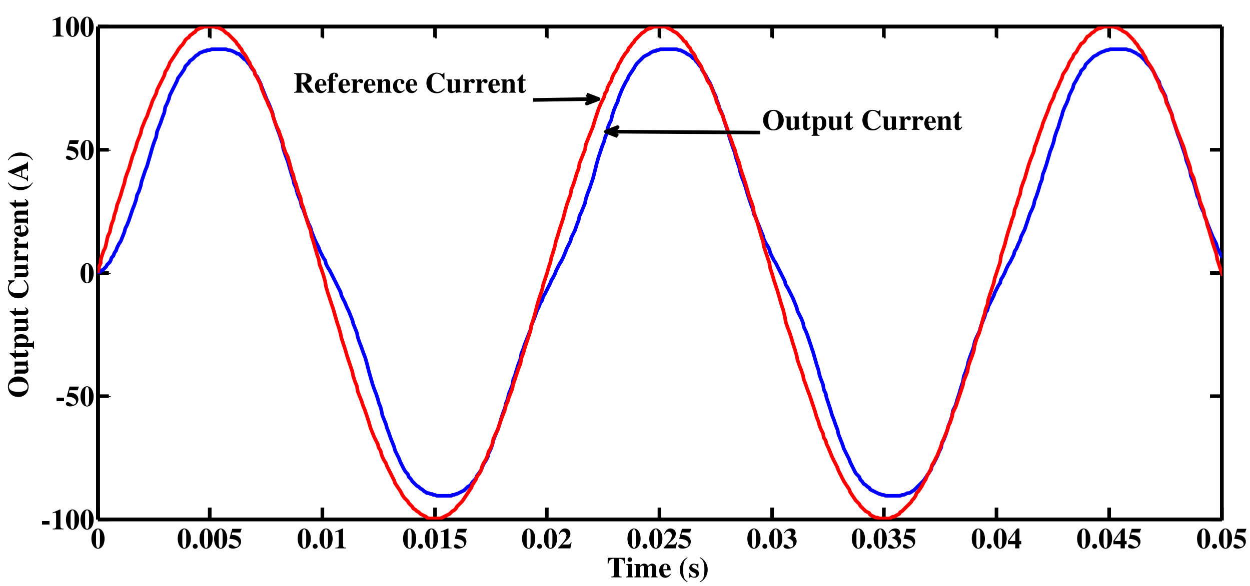

Figure 4.2 Input and output current waveforms.

The simulation based outcomes unveiled that primarily when the chosen gains for K_p and K_i are of lower value i.e. K_p = 1.0 and K_i = 1.0, the output of the system under observation is highly contaminated with harmonics. Additionally the output is not perfectly matched or synchronized with the input reference signal due to presence of unwanted harmonic content. The controller gains are further increased to minimize the effect of unwanted frequency harmonics to recover system stability also it ensures to maintain the quality of current output being delivered to directly connected local loads as well as to the main interconnected power grid.

Simulations outcomes unveiled that the most appealing gain values are
K_i = 2.8, K_p = 2.8 as illustrated in Fig.4.3.

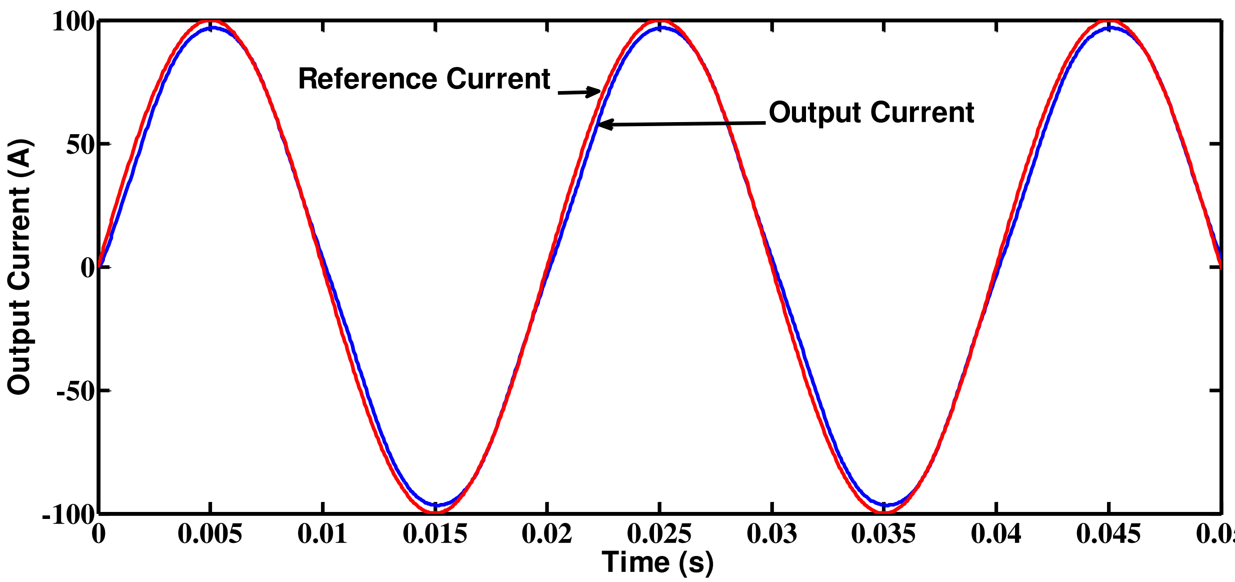

Figure 4.3 Perfectly stable current output with perfectly selected gains K_p = 2.8, K_i =2.8, K_c =3.

The above selected gain values of K_i and K_p provides the system to snub perfectly undesirable frequency harmonics thus resulting in achieving tremendous outcomes from the inverter in terms of efficient and perfectly matched current output signal. The controller is highly capable of tracking the reference input current signal compared to output current signal at these adjusted gain values perfectly matched with the system requirement while maintaining the system stability efficiently. The system is perfectly stable until the controller gain values are not raised up to K_p = 3.4, and K_i = 4.0.

System is destabilized and the output current waveform cross the controllable limits of violating the IEEE output quality standards even the gain value is further raised to 0.1such that K_p = 3.5. The controller's current output waveform is shown in figure Fig. 4.4.

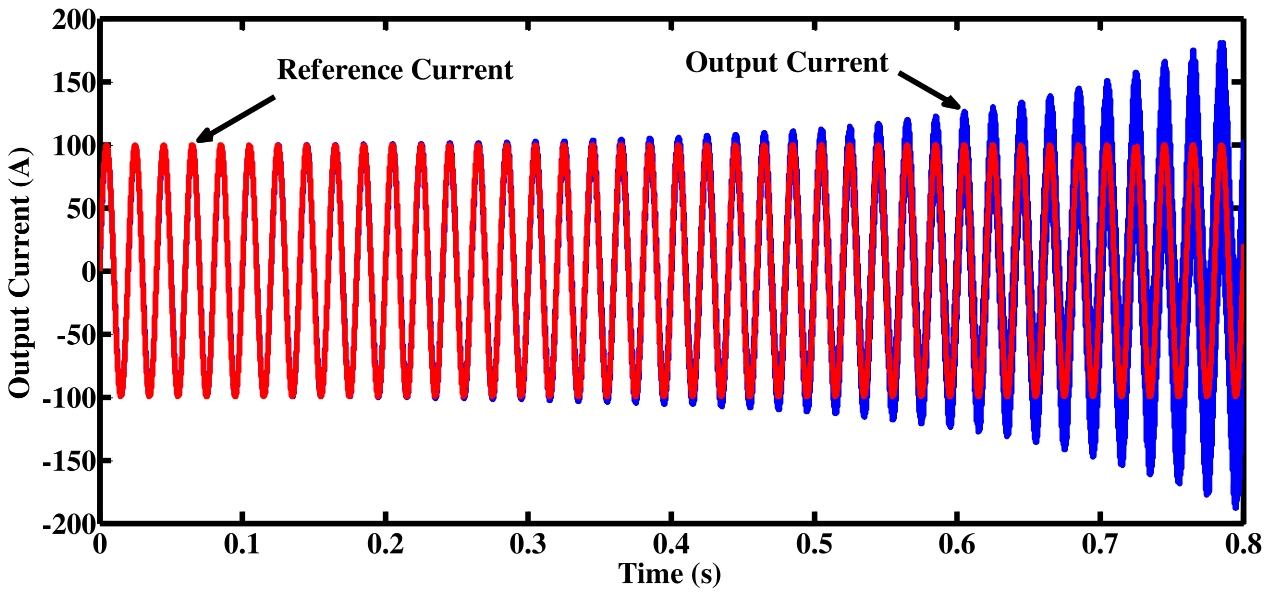

Figure 4.4 Highly unstable and undesired system response with K_p = 3.5, K_i =4.0, K_c =3.

The controller gain is further increased to find out the gain variation limits under which the output current waveform is less deteriorated and synchronized with the reference current waveform maintaining the IEEE standard.

The altered gain values are listed in tabulated form in table 4.2 to disclose the experimental stability range.

Table 4.2 Parameters for conventional PI controller

K_p (Proportional gain)	K_i (Integral gain)	K_c (feed-forward gain)	System Stability Evaluation
1.0 – 3.40	1.0 – 4.0	3.0	Stable
2.8	2.8	3.0	Most Stable
3.5	4.0	3.0	Unstable

4.2 Effect on Root Locus by Gain Variation

The root locus outcome of the designed system is illustrated in figure 4.5. The designed system is marginally stable and also third order because one the system pole lye at the origin of the graphical representation. To validate the stability of the system under observation the controller gain is varied to K_p = 1.0, 2.8 and 3.4 such that the pole must reside in the left half plane. A far from the specific value which K_p = 3.4, system stability is challenged by shifting of poles exactly on the imaginary axis. Further increment of the gain drives the system poles to shift inside the right half plane. The illustration in figure 4.5 reveals the outcome of gain variation effect on the system poles. The most appealing proportional gain value for the highly stable system with minimum distortion is K_p = 2.8.

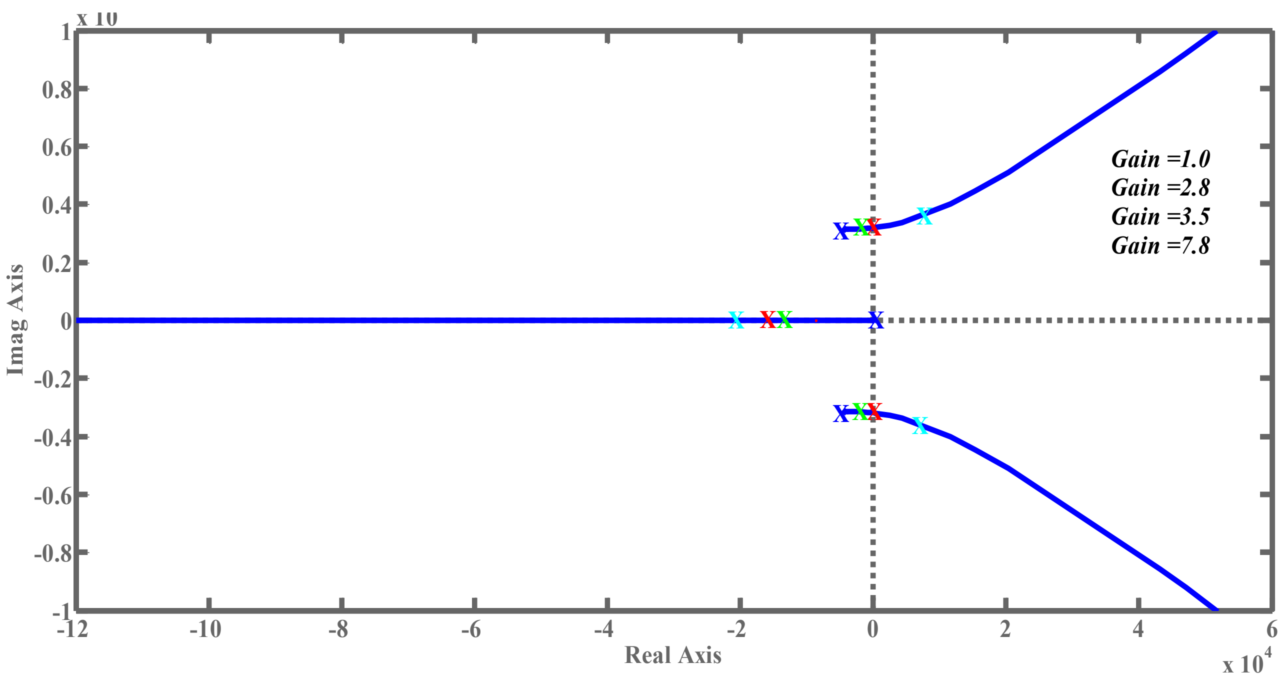

Figure 4.5 A root locus schematic for system stability with varied gains.

4.3 Summary

In this chapter the effect of gain variation is validated by running real time simulations for the system under experimentation.

The gain variation reveals that the controller’s response to snub the undesired frequency harmonics is satisfactory unless gain is varied within certain range.

The controller’s performance readily lowers down beyond the gain variation limit against strong disturbance thus rendering down the current output quality.

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CHAPTER – 5

5. LCL Filter Parameter Variations

5.1 Filter Selection

In most of the research papers, several filtering techniques have been applied experimentally which includes simple an L-type filter, an LC filter, an LCL filter and advance LCCL filters [1 – 4].

The prime focus of installing any filter towards the utility side especially for grid engaged inverter applications is to protect and avoid the failure or severe damage to the costly equipment attached to interconnected power grid also to retain the frequency harmonics present in the power line to enter towards inverter side. The implementation or installation of an isolation transformer provides extra protection for the electronic equipment integrated with the grid connected inverter system joined into the main power system hierarchy.

Each filtering scheme owes certain benefits and inadequacies. Nature of the applications and system requirements defines the proper filter selection which is a challenging task for an expert design engineer. Selecting only L-type filter may seems to be very appealing but the main shortcoming of L-type filter is its large inductor size thus system design cost increases. Additionally for highly rated power equipment and applications such as grid tied inverter, high inductor losses raise serious issues and thus cannot be compromised at any cost. L-type filter is therefore, not suitable for power related applications.

Another type is LC filter, which is small sized filter and revealed much better outcomes comparatively than the simple L-type filter described above. Also by varying filter parameters it provides a wide range of resonance selection necessary to mitigate harmonics. The major problem faced by the system integrated with LC filter is impedance mismatching which renders down the system performance against harmonics and also affects the controller robustness as well as limits of stability.

Solution to impedance mismatch problem can be resolved via integrating LCL filter into the system. LCL filter provide a flexible range of selection of system bandwidth by LCL parameter variation facilitating classical controller to rebuff unwanted harmonics with greater robustness.

LCCL filter may be another choice for an expert designer because the capacitance is distributed into two equal parts and current through first capacitor is feedback reducing the transfer function order from third to first order system. Additionally the filter size reduces resolving resonance problem faced by L- type filter also to Also the small size of filter enables impedance matching with utility or grid.

5.2 Effect of LCL Filter Parameter on Simulations

The LCL filter constraints are carefully selected $L_i = 350\mu$H, $L_g = 50\mu$H, $C = 22.5\mu$F. Finally selecting LCL filter parameters with ±10% variation, classical controller gains K_i and K_p are repeatedly tuned for validating output current signal.

The LCL constraints with ±10% variation are listed in tabulated form in Table 5.1.

Table 5.1 ±10% Variations in the LCL filter parameters

Original LCL Constraints	10% reduced LCL Constraints	10% enhanced LCL Constraints
$L_g = 50\mu$H	$L_g = 45\mu$H	$L_g = 55\mu$H
$L_i = 350\mu$H	$L_i = 315\mu$H	$L_i = 385\mu$H
$C = 22.5\mu$F	$C = 20.25\mu$F	$C = 24.75\mu$F

With a 10% increment in LCL filter constraints the values obtained are $L_i = 385\mu$H, $L_g = 55\mu$H and $C = 24.75\mu$F, the current output signal at higher values of controller gain is not perfectly synchronized with the reference input signal.

Conversely, when the LCL filter constraints values are reduced by 10%, the outcomes attained revealed a greater ability comparatively to reject system disturbances, with high amplitude and closely synchronized to the reference input signal.

For the 10% reduction in filter parameters, finally the values obtained are L_i =315μH, L_g =45μH, C =20.25μF.

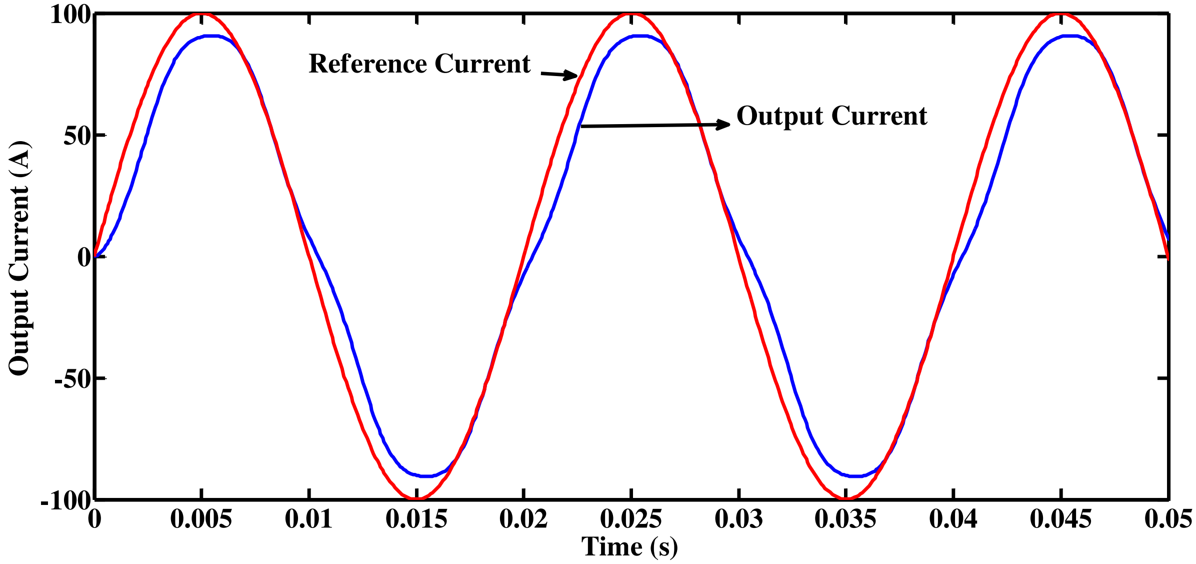

Figure 5.1 LCL parameters varied–10%, K_p =1 K_i =1 K_c =3.

From controller gain variation point of view, low gains reveal almost the same outcomes for both ±10% filter constraints variations.

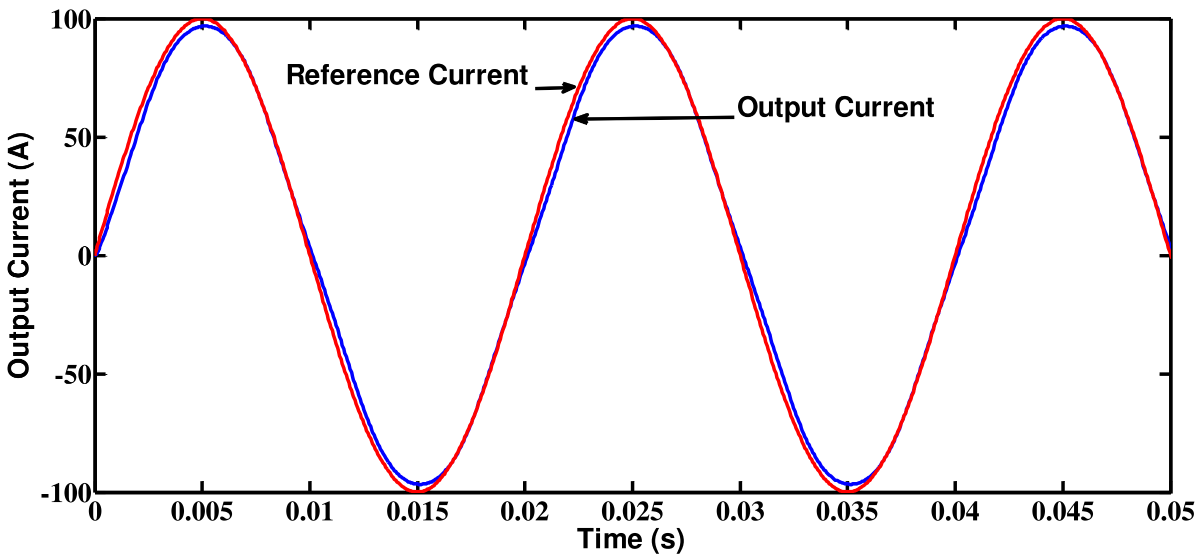

Figure 5.2 LCL original parameter values result with K_p = 1 K_i = 1 K_c = 3.

The best outcomes are obtained by selecting the original values of LCL filter constraints quantified in above table.

While in Figure 5.2 original LCL parameter values result is demonstrated which reveals that the original filter parameter values best suited for the designed and implemented system with classical controller.

The Figure 5.1 and Figure5.3 illustrates dissimilar outcomes attained by varying the LCL filter constraints values.

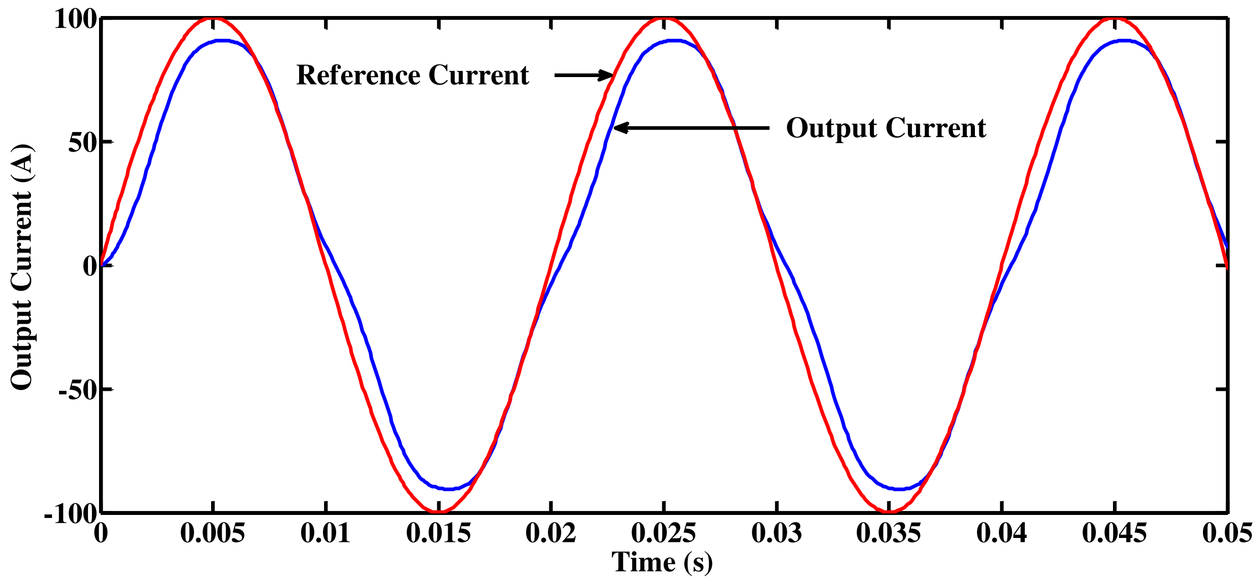

Figure 5.3 LCL constraints with + 10%, K_p=1 K_i=1 K_c=3.

5.3 Effect of LCL Filter Parameter on Bandwidth

The effect on bode diagram of the designed system is plotted between output of the inverter and external disturbance introduced into the system is illustrated in Fig 5.4. LCL filter constraints are consecutively changed to acquire dissimilar system outcomes. All the three cases outcomes when compared reveal the rejection of harmonics with same -9dB gain. The system bandwidth (BW) i.e. BW=3.2kHz for mitigation of frequency harmonics is comparatively less for LCL filter constraints with decrement of with 10%.Conversely, the increment of 10% in LCL filter parameter the bandwidth for harmonic mitigation is more which BW=3.9 kHz. The bandwidth of the system with original unvaried LCL filter constraints is BW=3.5kHz.

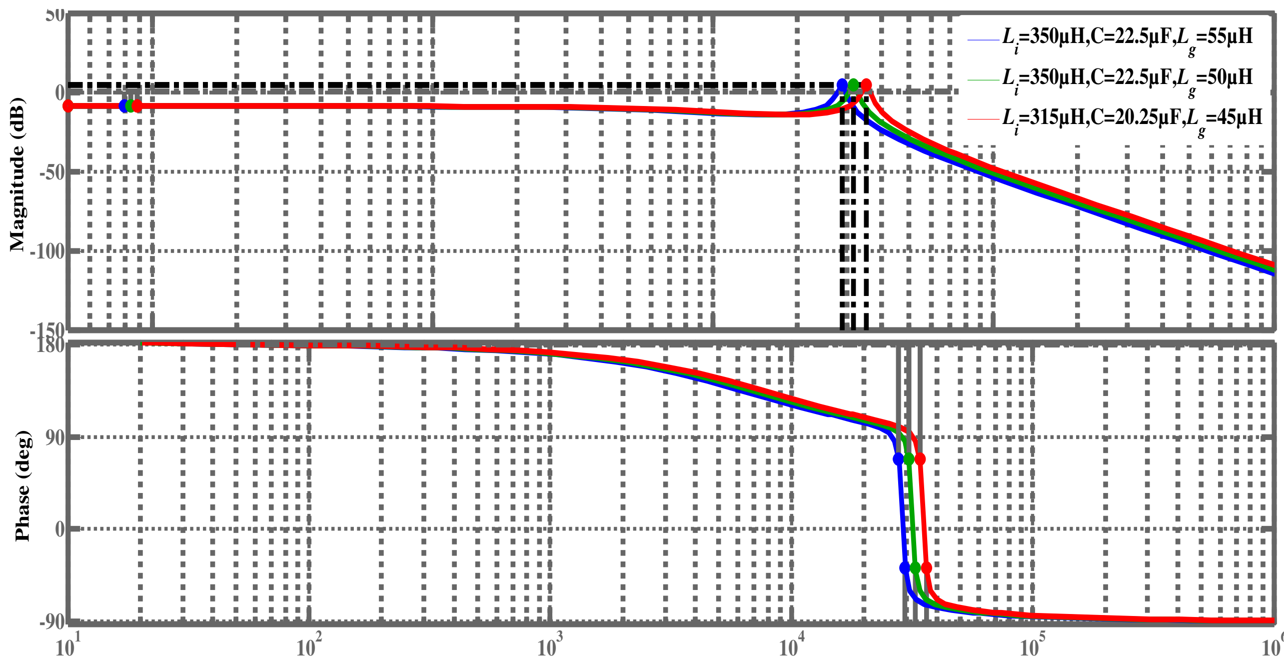

Figure 5.4Bode plot between output and disturbance injected

The inductor attached towards grid side gets saturated in the presence of current harmonics which results in rendering down of output current quality with high content of undesired ripples in the output current [5]. The resonant frequency f_r must be one half of the selected switching frequency f_s and indeed must be ten times higher than the actual grid frequency f_g to avoid filter resonance problem. By selecting the original LCL filter parameter values provides the preferred value of resonant frequency, f_r=5kHz which is ten times higher than the actual grid frequency which is f_g=50Hz also one half of the chosen switching frequency, f_s=10kHz [6].

5.4 Conclusions

The simulation results are used to describe the actual performance limitation of conventional classical controllers (P/PI) via MATLAB. The proper combinations of controller gains offer a highly stable system under the influence of grid harmonics. The main restriction for the classical controller is its narrow range of selection of permissible gain variation values for harmonics mitigation whilst the harmonic content for grid application is very high. The controller robustness is mainly affected and system stability becomes a serious issue by raising controller gain to rebuff harmonics for better output results. The research work is primarily focused to evaluate the system performance under the presence of strong grid harmonics in conjunction with controller gain variation limitations as well. The simulation data and the outcomes revealed that the controller's capability for rejecting the disturbance lowers down beyond certain limits. LCL filter parameters must be selected properly to maintain sufficient bandwidth necessary for harmonics elimination effectively. The consideration of system level approach (filter and controller parameter variations together) is essentially important and must be adopted to achieve the required outcomes following IEEE standards.

The classical controllers (P/PI) are not perfectly suitable for sinusoidal reference tracking application under severe disturbance or large frequency variations. Other controllers or combinations of classical and advance controllers such as proportional resonant, H-infinity, LQR and repetitive controllers can be appealing alternatives. This approach of combinational controllers will be studied and investigated in future research work.

5.5 Recommendations for Future Research Work

- Combination of classical and other controllers forming a hybrid control strategy can also be evaluated.
- Other inverter topology such as interleaved, matrix converter can also be used with classical control.
- Repetitive and neuro fuzzy control combinations will be investigated for grid connected inverter and robot control applications.
- Harmonic filtering can also be achieved by using line reactors instead of or in conjunction with different filter options can be an appealing concept.
- Isolation transformer with harmonic filters may be a good choice.

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