Improved Design, Analysis and Current Controlled Strategy for Photovoltaic (PV) Grid Connected Converters

By

SHAHAB SHAHID

NUST201260397MSMME62112F

Supervised By

Asst. Prof DR. MOHSIN JAMIL

A Thesis Submitted to the department of Robotics and Intelligent Machine Engineering (RIME) in Partial Fulfillment of the Requirements for the Degree of M.S. in

ROBOTICS AND INTELLIGENT MACHINE ENGINEERING

School of Mechanical & Manufacturing Engineering

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Islamabad, Pakistan

2015.

Dedicated to my beloved mother and father who have guided me in the journey of education.

FORM TH-4

MASTER THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by:

Student Name: Shahab Shahid Registration No: NUST201260397MSMME62112F

Titled: Improved Design, Analysis and Current Controlled Strategy for Photovoltaic (PV) Grid Connected Converters be accepted in partial fulfillment of the requirements for the award of M.S in Robotics and Intelligent Machine Engineering degree with (Grade _______).

EXAMINATION COMMITTEE MEMBERS

1. Name: Dr Shahid Ikramullah Butt Signature: _______________
2. Name: Dr Syed Omer Gilani Signature: _______________
3. Name: Dr Umer Ansari Signature: _______________

Supervisor's Name: Dr Mohsin Jamil Signature: _______________

Date: ________________

____________________ ______________

Head of Department Date

(Dr Yasar Ayaz)

COUNTERSIGNED

Date: _______________ ______________

Dean/Principal

(Dr Abdul Ghafoor)

DECLARATION

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NUST201260397MSMME62112F

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Lastly, a word of thanks to everyone who has helped and contributed in any way but whose name I might have forgot to mention.

Table 1: List of Acronyms

List of Acronyms	
AEDB	Alternate Energy Development Board
WAPDA	Water and Power Development Authority
NEPRA	National Electric Power Regulatory Authority
IPP	Independent Power Plants
RES	Renewable Energy Sources
GCC	Grid-Connected Converter
GCI	Grid-Connected Inverter
O & M	Operation and Maintenance
PID	Proportional Integral Derivative
PI	Proportional Integral
PLL	Phase Locked Loop
THD	Total Harmonic Distortion
PCC	Point of Common Coupling
L	Series Inductor
C	Shunt Capacitor
LC	Inductor Capacitor
LCL	Inductor Capacitor Inductor Filter
LCCL	Inductor Capacitor Inductor Filter
MS	Master-Slave
LQR	Linear Quadratic Regulator
FFT	Fast Fourier Transform
STATCOM	Static Synchronous Compensator
DMS	Demand Side Management
DVR	Dynamic Voltage Regulators
UPQC	Unified Power Quality Conditioners
IEEE	Institute of Electrical and Electronics Engineers
K_C	Inner-loop gain
K_P	Proportional Gain
K_I	Integral Gain

Note: Throughout the text the term inverter and converter has been used interchangeably so the reader is advised that it basically refers to the same thing. The symbols K_C , K_P and K_I are analogous to K_c , K_p and K_i respectively.

Abstract

To utilize the energy from the Renewable Energy Sources (RES) globally, they need to be connected to the grid using the converters. There are many topologies used for interconnection with the grid for e.g., two-level with LCL filter, three-level Neutral Point Clamped (NPC), multi-level, matrix, and interleaved etc. While interconnecting, there are many local and international standards which must be followed. To achieve this, we require a suitable control strategy. The current fed to the grid at the Point of Common Coupling (PCC), where the RES are connected to the grid must be having a Total Harmonic Distortion (THD) below 5%. The classical controllers do not give suitable Gain and Phase Margins at the utility harmonic frequencies and they fail to stabilize the system if the grid current THD>5%. In this thesis we have attempted to study the performance limitations of the classical controllers and also to identify the optimal gains for the proportional (P) and proportional integral (PI) controllers. The topic which has been explored in this thesis is an active research area. Furthermore, the effect of the active damping on the system performance has also been explored in detail. Ideally, we require a controller that has infinite gains at the harmonic frequencies. For this purpose, we have also reviewed the performance of the linear quadratic regulator (LQR), the Proportional Resonant (PR) and the Repetitive Controller. The Proportional Resonant Controller has been identified as a good candidate for our desired objective. We have considered a current-controlled Two-Level Pulse Width Modulated (PWM) Grid-Connected Converter, because the grid impedance is assumed to be fixed so we feed a constant current to the grid. The classical PI controller can give suitable stability margins under varying load impedance, but provides insufficient disturbance rejection which leads to high Total Harmonic Distortion (THD) in the current fed to the grid. We have tried to ascertain the maximum performance bounds of the classical P and PI controllers respectively under variation in grid harmonics.

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- Shahab Shahid Khawaja, Mohsin Jamil, Qasim Awais, Umer Asghar and Yasar Ayaz. "Analysis of Classical Controller by Variation of Inner-loop and Controller Gain for Two-level Grid-Connected Converter". *Indian Journal of Science and Technology*, vol. 8, no. 20, IPL0207, August 2015, ISSN(Print): 0974-6846, ISSN(Online): 0974-5645, (SCOPUS).

Chapter 1: Introduction

1.1 Background, Scope and Motivation

As the world's population is increasing, the demand for uninterrupted electricity is also increasing. Due to this burgeoning demand, third world countries with governance issues adopt means to ration electricity like scheduled/unscheduled shutdowns and sometimes total blackout in some areas. This is a short-term strategy with very negative effects on human resource development, public psyche, communication, trade, education, industry, etc [1]. According to scientists, conventional energy resources like coal, oil and natural gas are facing rapid depletion due to huge demand. By one such estimate, the global demand for fossil fuels increased by 1.8% in 2012 [2]. The socially responsible and environmentally aware researchers and scientists across the world are working day and night to come up with eco-friendly energy technology at cheapest possible rates [3-6]. Another problem with the currently existing generations system is that is suffers from heat and transmission losses and the cost of expansion of the system is very high. Also as of now, the connection of fossil fuel based power generation to the main grid meeting the IEEE standards for generated power distribution and control is a challenging problem. To ensure rural electrification will require longer transmission lines and will unbalance the overall grid. Given the environmental tradeoffs of conventional fuels (fossil fuels, nuclear power, etc.,) and the politics and conflicts surrounding these, it is better to adopt cleaner and much safer means of producing energy.

Pakistan has an installed electricity generation capacity of 22,797 MW as of 2013. Out of the total, the breakup is oil (35.2 %), hydel (29.9%), gas (29%), and nuclear, rental power and solar accounts for barely 6%. Owing to circular debt, non-payment of dues to Divisional Electricity Supply Corporations (DISCOS), reducing of power capacity due to poor maintenance, depreciation/degradation of the grid and also corruption, the International Energy Agency (IEA) has forecasted that the total electricity demand of the country will be 49,078 MW in 2025 [7]. The average shortfall in electricity supply is reported to be around 5,000 MW. We are just talking about the generation side; if we go into the transmission statistics, the actual power that reaches the user will be even lesser. According to some reports, to compensate for the shortfall, load shedding of 10 hrs daily is carried out in the cities and almost 15 hrs daily on average is carried out in the villages [8]. Keeping in view such a grim situation, we should use the resources that are available to us as we still have time to prepare. One such means is the solar power which can be harnessed by using the photovoltaic (PV) cells which are placed on the solar panels.

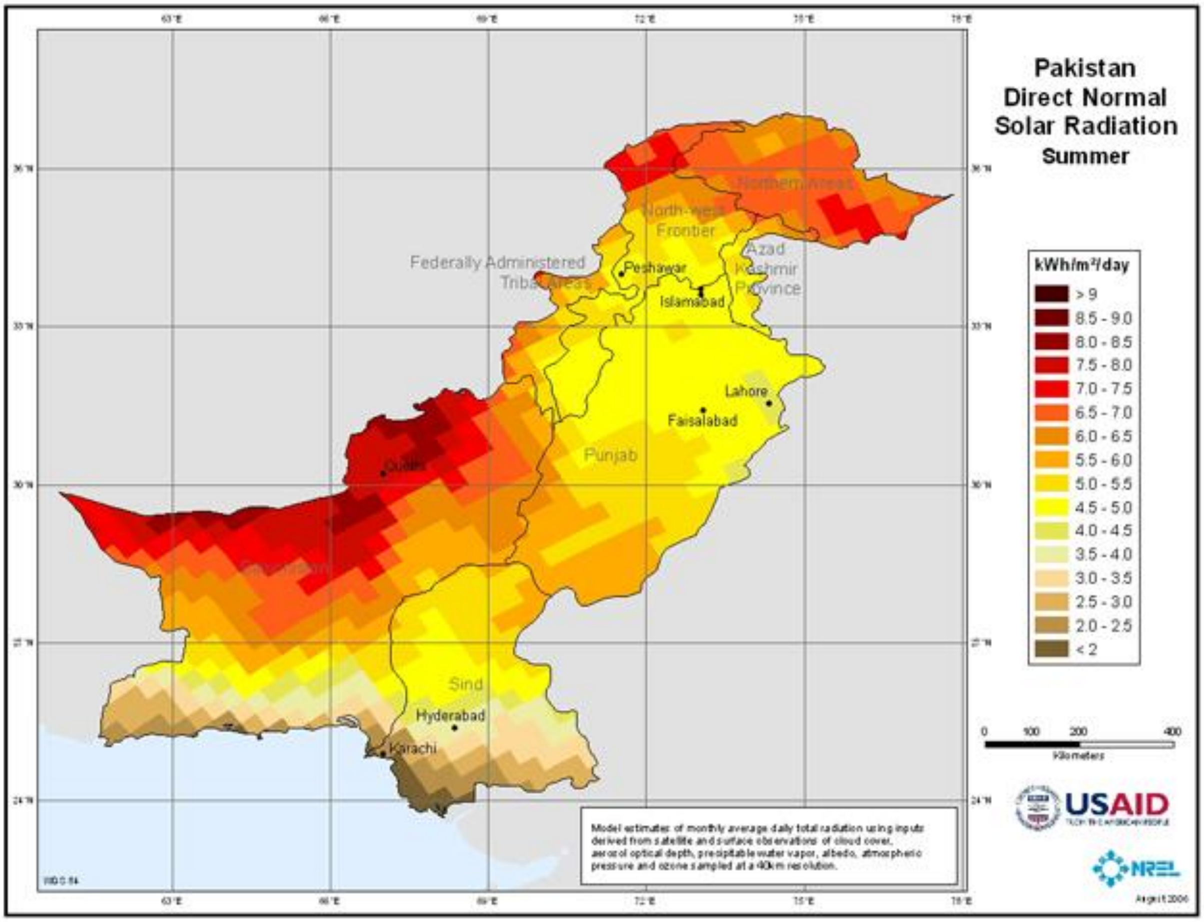

Fig. 1.1 Solar irradiance map of Pakistan [9]

From Fig. 1.1, we can see that the solar irradiance in Pakistan is very high and according to a report it is almost 5-7 Kwh/m^2/day over 95 % of the country's total area [10]. One solar panel consists of many such cells placed in sequence (series/parallel). The issue is that normally the power produced due to solar cells can be used only locally due to issues of harmonics, phase mismatch, frequency offsets, etc [11]. The objective is to attempt to mitigate these impediments so that power produced through PV can be converted to a form which is easier to integrate with the main grid.

A tremendous amount of research has been done on improving the conversion factor and the efficiency of the PV cells which convert the light energy into electrical energy. The lagging has been on the part of using this energy in the grid where it really matters, rather than just as a battery or a secondary source of energy.

A country like Germany which is deficient in sunlight is harnessing the solar energy to feed the domestic consumers [12], whereas a country like Pakistan which is blessed with sunlight the year around is not using this energy in a meaningful way. The challenges we face in energy shortfall cannot be overcome just by sole reliance on conventional energy sources.

The advantage of using the solar energy through grid-connected converters is that this is an environmentally friendly method. Also it will save us a lot of money as the fossil fuels we import cost us in dollars and our imports goes up. As our imports are less, this net deficit is not good for the country. If we reduce our carbon emissions due to using more solar and less fossil fuel, we are also going to get carbon credits as Pakistan is a signatory of the Kyoto Protocol, so we are going to get a few million dollars from that too [13].

A lot of research is being carried out in the alternate modes of energy generation for e.g., solar cells, wind turbines, geo-thermal, tidal energy, bio-gas, solid waste, small turbines on upstream and a plethora of other sources [14]. The issue with all these Renewable Energy Sources (RES) is that they can be used locally for a host of different purposes, but their inter-connection with the main grid provides us with some challenges [15-17]. Firstly is the problem of energy conversion which is not the core issue i.e., some sources like Photovoltaic (PV) generate unvarying electric power which must be converted to varying electric power to be fed to the grid or even for local use in domestic loads. This DC to AC or in some cases AC to AC conversion with change in frequency can be accomplished with the help of converters. The DC to AC conversion is known as inversion, while the AC to DC transformation is called rectification, while change in AC-AC with change is frequency is known as cycle-conversion. The efficiency of the converters varies and it equal to $\eta = P_{out}/P_{in}$. As the RES are depending on some property of the environment, they are inherently unpredictable and affected by changes in the atmospheric conditions. To maintain a constant supply, a backup source like batteries is also connected with the RES to make it more robust. Unfortunately, this makes the system expensive and can also be considered as a limiting factor in the popularization of RES. The second issue is that at the Point of Common Coupling i.e., the point where the RES and the main grid are connected, the current entering the grid should have a Total Harmonic Distortion (THD) less than 5%.

Due to increasing demands of energy, the conventional power generation systems are proving to be insufficient and alternate methods of generation and inter-connection of the RES are being developed [18,19]. Micro-grids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded [18-21]. The main components of a micro-grid are the distributed generators (DGs), loads (energy consumers) and a switch for interfacing the different power supplies. We can achieve higher power quality and greater reliability by using GCC in islanding mode. The transmission losses/line losses (I^2R) can also be mitigated by alleviation or deferment of the transmission network increase. Carbon mono-oxide, lead sulphate and other greenhouse gases, which damage the ozone layer and contribute to global warming are also reduced by increasing the RES share in the power generation mix. The global potential for the different RES are shown in Fig. 1.2.

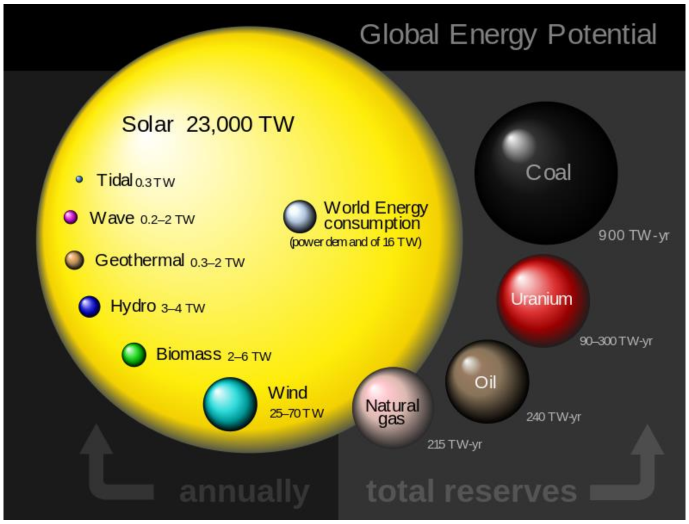

Fig. 1.2 Global energy potential by source [22]

From Fig. 1.2, it is obvious that the potential for solar energy is by far the most and eclipses the others by a huge margin, but if we look closely at Fig. 1.3, we would come to the conclusion that this technology is under-utilized. The solar potential is 23,000 TW which is in yellow, whereas the total power requirement of the world is 16 TW. If this energy is properly harnessed, it can easily satisfy all present and future requirements. The fossil fuels have the disadvantage of CO_2 emissions which damage the environment, whereas the nuclear waste has to be disposed off in a very secure manner and it is not bio-degradable i.e., it remains in the radioactive state for all eternity.

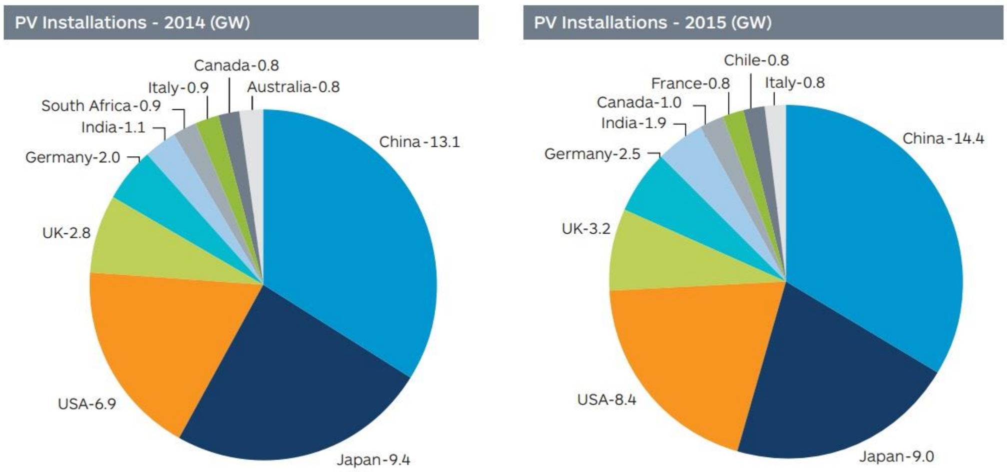

Fig. 1.3 PV installations in 2014 and 2015 [23]

The purpose of showing these figures is to give an idea about the monetary potential of this area, because the technical efforts are directly related to the commercial scope. Unless the economics are related with the research, its sustainability and continuation becomes difficult. The per-unit cost of the PV cells is also decreasing, which is also a facilitating component to the interest in DER. The reason that it has not achieved a very major percentage of the total energy breakdown is that there are still technological issues in interfacing these PV units with the main grid like DC/AC inverters efficiency issues and Total Harmonic Distortion (THD) issues with regard to grid interconnection.

1.2 Controllers

The fundamental bottleneck regarding the converter design is that harmonics in the converted signal that must be fed to the main grid should be less than or equal to 5%. Now some of the basic controllers like Proportional Integral Derivative (PID) for e.g., cannot even cater for a sinusoidal signal which has a distortion of greater than 5% and completely breaks down. Proportional Integral (PI) cannot be applied directly and a transform scheme is required using conversion to alpha and beta transforms. The controllers like repetitive [24], adaptive [25, 26] and neuro-fuzzy controllers [27] have been studied. The proportional integral PI controller has been used to control the output current and to bring it to track the desired reference current in the presence of disturbances, but this has proved to be of limited utility. The proportional resonant (PR) controller has the ability to give infinite gains at the resonant frequencies, but the controller performance degrades very severely if the grid-frequency varies [28]. The various DER are connected across the different loads in parallel and their output to the grid is controlled through switches [29].

1.3 Types of Converters

The most commonly used types of converters can be classified into online converters and line-interactive converters [30]. The online converters are more efficient and have zero transfer time as the power supplied during both backup and normal operation is being produced by the converter. They operate on the principle of double conversion whereby the input AC is first converted into DC and this DC is converted into AC which is fed to the loads. The advantages are faster switching speed, better transfer time, conditioned output, less AC ripples and DC injection, safer in terms of over-current/under-current or over-voltage/under-voltage. The disadvantage of online converters is its cost. The line-interactive converters are used more often due to economic reasons. They have a bypass switch and in the normal operating mode, the AC output is the same supply that is entering the converter from the mains, while some portion of the input supply is used for charging the batteries. In the backup mode, the batteries' power is converted into AC which is then fed back to the loads. The disadvantage is higher transfer time, less modulation of current and voltage in normal operation mode, heating losses and saturation currents related to transformer. The transformer is there to provide isolation so that there are low transients in the output current. Due to lesser knowledge on the part of the user, overloading of the transformer results in more current being drawn which shorts the transformer and the life of the converter is reduced drastically. There are also some rotary converters which take input from an AC motor to drive a DC machine and this DC machine drives an AC generator. These are used in industry mostly and also a combination of static and rotary converters known as hybrid converters are also used. Also nowadays, there are converters which use both solar energy and mains AC to supply the loads. Converters are also being used to charge car batteries which then in turn drive the car's motors such as Tesla Motors Model S, which introduced the application of converters to the car industry [31].

1.4 Aims and Objectives

- Detailed introduction and analyses of the Three-Phase Two-Level Grid-Connected Converter with LCL filter model.
- Modeling of Grid-Connected Converter using Matlab/Simulink simulation tools.
- To compare the disturbance rejection and tracking capabilities of different controllers under different conditions of THD.
- To investigate the effect of the variation of the inner-loop gain on the system performance.
- Analysis of performance degradation of classical controllers proportional (P) and proportional integral (PI) under variation in gains.
- Studying the effect of the change in parameter values of the LCL filter on the system performance.
- To identify the optimal controller gains and also the inner-loop gains to be used by this system to achieve maximum performance.

1.5 Contributions of Thesis

A detailed study of the classical proportional (P) and proportional integral (PI) controllers is carried out. The performance evaluation results for e.g., current output plots, output current THD (%), bode plots, etc are presented. The ideas and information that have been acquired as a result of these activities have resulted in this publication.

- Shahab Shahid Khawaja, Mohsin Jamil, Qasim Awais, Umer Asghar and Yasar Ayaz, "Analysis of Classical Controller by Variation of Inner-Loop and Controller Gain for Two-Level Grid-Connected Converter", in International Conference on Green Computing and Technology (ICGCET), Dubai, July 2015.

The areas of application of this work are the following areas:-

i. Power Distribution.
ii. Control Theory
iii. Telecom Industry
iv. Manufacturing Industry
v. Services Industry
vi. Society as whole

1.6 Organization of Thesis

The chapters of the thesis are organized as such. Chapter 1 details the background and objectives of this thesis report. Chapter 2 is a comprehensive literature review of the work that has been done so far in this field and also to gain an idea about the field of grid-connected converters in general and the issues and limitations that are preventing the proliferation of this technology on the international level. Chapter 3 delves into our work and how we have identified optimality limits. Chapter 4 deals with the application of Linear Quadratic Regulator (LQR) controller. Chapter 5 deals with the conclusions that we are offering and also the future work that can be undertaken in this area.

Chapter 2: Literature Review

2.1 Overview of Photovoltaic Systems and Converters

There has been a rise in the interest level for renewable energy in the past few years due to demand for energy, increasing oil prices and environmental concerns [32]. As a result a lot of renewable energy projects are being undertaken. The dwindling supplies of conventional hydro-carbon based fuel, the high losses of the CHP systems have forced the people to research about the sustainable energy sources. Due to environmental catastrophes such as the British Petroleum oil spill of the Gulf of Mexico or the Fukushima reactor blast due to the tsunami the eco-friendly sources such as solar energy have become desirable. The international governments and world organizations are offering incentives to promote the usage of RES. In Pakistan the Alternate Energy Development Board (AEDB) was established in March 2003 under the aegis of the Ministry of Water and Power [33]. The scope of this department was to create awareness about the different renewable energy resources and also to gather investment (both local and foreign). Till date the only achievement of this organization has been the successful auction of the wind farms in Gharo and Jhimpir. The RES are based on a smaller scale and are distributed around the grid. They comprise of the sources like solar, wind, tidal wave power, etc. The solar energy produced from photo-voltaic (PV) cells is becoming significant due to zero fuel cost, low maintenance cost and less losses due to lack of rotating parts. Theoretically, this is an ideal power source, but practical impediments include the high cost of installation, low energy efficiency factor (η) and interconnection to the grid. The energy produced by Photovoltaic (PV) produces Direct Current (DC) which must then be converted to Alternating Current (AC) to be interfaced with the grid or even for local use in domestic loads. The power produced using RES are already being used in the world in both islanded and grid-connected mode [34-36]. This DC to AC conversion can be accomplished with the help of converters. The converters used for PV panels are not unique; rather they are used for wind turbines, tidal waves, fuel cells and motor drives with slight modifications. The DC to AC conversion is known as inversion. The efficiency of the converters varies and it is equal to $\eta=P_{out}/P_{in}$. As the RES are depending on some property of the environment, they are inherently unpredictable and affected by changes in the atmospheric conditions like sunlight, clouds, seasons, humidity, etc. To maintain a constant supply, a backup source like batteries is also connected with the RES to make it more robust. Unfortunately, this makes the system costly and can also be considered as a limiting factor in the popularization of RES. The second issue is that at the PCC 5%. In this chapter we shall review the international standards related to inter-connection of the distributed RES to the grid. We shall also discuss the characteristics of solar energy and a few converter and panel topologies.

2.2 Grid connection Standards

While interfacing the RES with the main grid, there are a few standards [37-39] that must be considered. These standards are formulated by the Standards Committee of IEEE after consultation with the Industry and Academia experts and ensure best practices to be followed. As each country has its own distribution voltages and grid currents and also the span of its transmission system varies, these standards can be changed to accommodate for local settings. Also as they are not binding, one may choose not to follow them. The two standard committees which merit mentioning are

- International Electro-technical Commission – IEC
- Institute of Electrical and Electronics Engineers – IEEE

It is a good idea to ensure that system is backward compatible with the previous standards and also that it can be modified in the face of major changes in a new standard which is released after deployment of the system. Some of the standards which are still valid and significant are

- IEEE Std 1547-2003
- IEC 61727
- IEEE Std 929-2000

2.2.1 Compliance Requirements

After reading the standards and understanding them, we can mention some of the aspects that must be considered in the design of a grid-connected converter to safely and efficiently connect it to the grid. The key factors are mentioned below.

I. Grounding / Earthing:-

Grounding is the process of connecting a path of least resistance from the body of the system to the real ground of the earth through the socket or connection. If current is present in the system body due to connection faults the current will follow the path through ground, otherwise a person touching it will provide ground and get a big shock. Also we normally consider the terminal at low potential to be ground i.e., -ve terminal. We want that the low potential terminal of the PV panels is grounded.

II. Power Quality:-

The quality of power is assessed by calculating the DC current injection, flicker, distortion, frequency variations, power factor (lagging/leading) at the point of interconnection.

III. Voltage:-

There are two types of grid-connected converters i.e., (i) voltage-controlled (ii) current-controlled. Voltage controlled converters are preferred in those situations where the load is variable or in other words the impedance changes. In these, the converter controls the output voltage and current is dependent on the load attached. In current-controlled type the current is fixed while the voltage can vary. The current is kept fixed because the impedance of the transmission and distribution network is well-known and we assume them to be fixed for the range of operation. Mostly current-controlled converters are used so there is no active voltage control. In order to detect abnormal conditions, we must define some normal operating conditions. The response of the Grid-Connected Converter (GCC) to the over and under-voltage conditions are given in Table 2.1.

Table 2.1: Normal operation, over-voltage and under-voltage conditions

Voltage (volts)	Maximum trip time (seconds)
$V < 50\%$	0 - 1
$50\% \leq V \leq 85\%$	2 - 0
$85\% \leq V \leq 110\%$	Continuous operation
$110\% \leq V \leq 135\%$	2 – 0
$135\% \leq V$	0 – 5

If the disturbance condition exists for the times mentioned in the table, the GCC must disconnect the supply of power to the grid, but the sensing part will still monitor the cycles. This monitoring mechanism is necessary to ensure reconnection after the disturbance condition has passed.

IV. DC-injection:-

The GCC output current being fed into the grid cannot have the DC component ≥ 0.5%

V. Flicker:-

The limits for flicker are given in Table 2.2.

Table 2.2: Short-term and Long-term flicker conditions

Short-term flicker	Long-term flicker
≤ 1.0	≤ 0.65

VI. Frequency:-

The GCC must also monitor the frequency of the grid current and if it varies by ± 2 % for a period of 0 – 2 seconds, the converter shall cease to power the grid. The grid frequencies are either 50 Hz or 60 Hz, with the former being used in Pakistan.

VII. Distortion / Harmonics:-

The standards for grid inter-connection [37, 39] mention that the output current of the DER which connects to the grid should have THD less than 5%. The distortion limits mentioned in [38] are listed below

Table 2.3: Distortion limits as recommended in IEEE Std 519-1992 for converters

Odd Harmonics	Distortion Limits
3^{rd} - 9^{th}	< 4.0 %
11^{th} - 15^{th}	< 2.0 %
17^{th} - 21^{st}	< 1.5 %
23^{rd} - 33^{rd}	< 0.6 %
Above the 33^{rd}	< 0.3 %

The distortion limits mentioned in the Table 2.3 give us an idea about the effect of the particular harmonics in the overall THD. The formula to calculate the THD is

$$THD = \frac{\sqrt{\sum_{k=2}^{n} V_k^2}}{V_1} \quad (1)$$

where V_1 is the RMS voltage (230V) of the fundamental frequency (50Hz) and V_n is the magnitude of the nth harmonic.

VIII. Power Factor:-

The standard for output current of the GCC w.r.t power factor is given in Table 2.4. In some situations a reactive power output is required, so the converter should have the capability to regulate the output power. Lagging means that the voltage cycle reaches before the current cycle or in other words the phase difference between the current and voltage waveform is negative. We know that $v(t) = V_m \sin(2\pi f t + \varphi_v)$, $i(t) = I_m \sin(2\pi f t + \varphi_I)$. Here V_m and I_m are the peak voltage and current, f is the frequency of the signal and φ_v, φ_I are the phase offsets respectively.

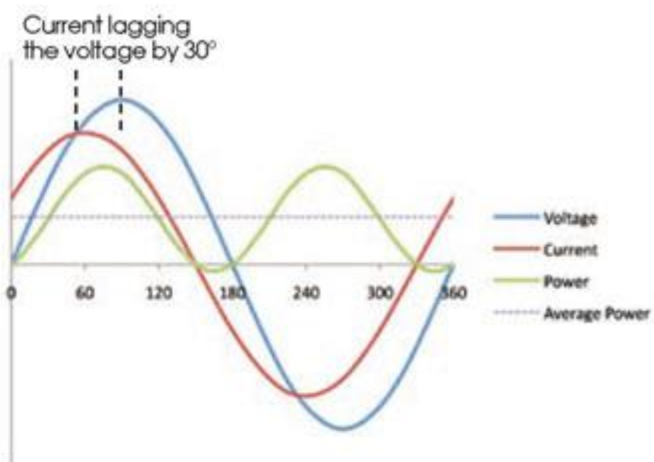

Fig 2.1 Lagging Power Factor [40]

Table 2.4: Power Factor Limits

Converter Output Current	Power Factor
> 10 %	> 0.85 (lagging)
> 50 %	< 0.9 (lagging)

IX. Anti-Islanding:-

An islanding situation can occur i.e., a grid-connected inverter is producing AC which is coupled to the AC of mains supply. If the mains AC is not present, our inverter will still be giving power to the load, whereas at this point it should disconnect from the load and supply power locally. The issue that exists in reality is the definition of islanding and also how many cycles of AC must be observed before initiating the connection or disconnection process [41]. Much has been written about this issue but still no definitive statement so everyone deals with this in their own way. If the inverter cannot detect islanding condition it can lead to safety hazard or just plain inefficiency. Islanding refers to the condition in which a DER supplies power locally even though the mains AC is absent. It is dangerous as people working on the power lines may be under the assumption that they are unpowered. If the GCC detects that there is an outage in the grid it must also stop producing power. The issue is that hardwiring an islanding condition is not as simple, but we can give some guidelines to the converter to stop producing power if certain conditions are met. Some of them are:-

- The mains is in islanding condition when the nominal voltage and frequency ranges are not being met.
- There is a mismatch of at least 50 % between real power load and inverter ouput
- The power factor of the islanded load is < 0.95 (leading or lagging)

The converter must stop powering the grid line and disconnect from it within 2 seconds of the detection of this fault condition.

2.3 Operating Modes of GCC

There are several modes in which the GCC can operate. These operational modes determine the system performance and its application areas. A micro-grid is a localized grouping of electricity resources and loads that normally operate in synchronism connection with the main grid, but can also function as an independent grid if a situation arises.

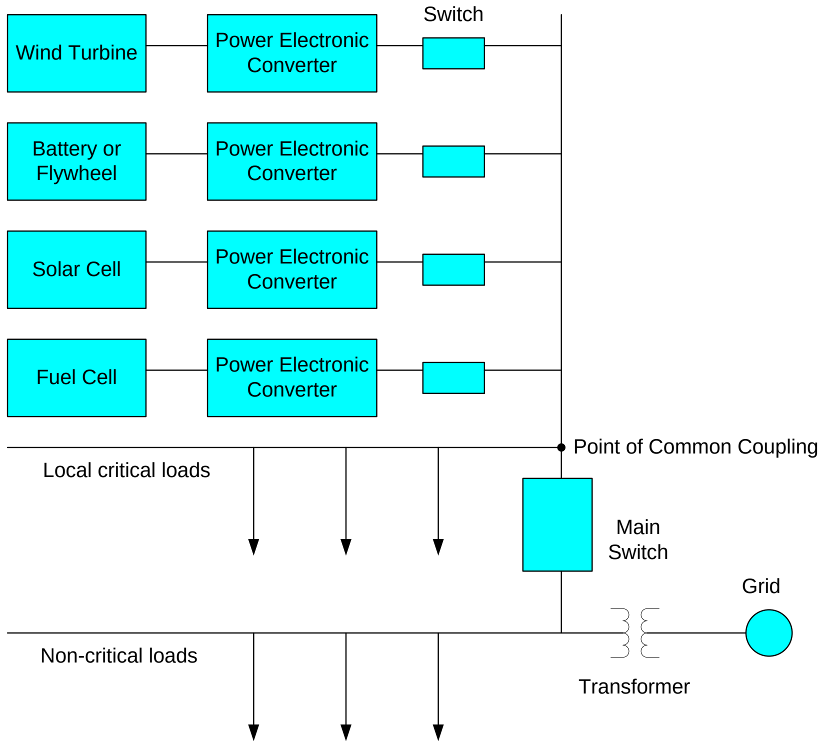

Fig 2.2 Simple modular layout of a micro-grid [29]

2.3.1 Standalone Mode

The inverter operates in the standalone mode when the main power supply is absent. In this mode, only the critical loads are powered. In the absence of the grid supply, the local loads along with the RES connected to the converter can be considered as a micro-grid i.e., a sub-grid that can operate independently within the larger national grid. When the Grid-Connected Converter is operated in standalone mode, it functions as Uninterruptible Power Supply (UPS) giving 230Vrms to loads. In this mode the GCC is behaving in the voltage-control mode as the voltage is being set to a particular reference value and the current drawn depends on the load attached. It can be considered to be an Uninterruptible Power Supply (UPS) or backup supply.

2.3.2 Grid-Connected Mode

In the Grid-Connected mode, however, the GCC operates in the current-control mode and the output current is being regulated. The current-control method has found to be more efficient as compared to the former and that is the method we have considered in this thesis. If we want greater current we can connect the inverters in parallel. The inverter is connected to the main grid while also providing the local loads. The surplus power produced by the RES is fed into the main grid. The control of the inverter is of vital importance and requires continuous current regulation. For current injected into the grid, the current should be within the THD limits of 5 %. Also, the variation in frequency must be catered for as it causes the output current and voltage to deviate from the synchronized voltage and current of the grid. If unchecked, this can cause harmonics and degrade power quality. Synchronization is achieved by using Phase Locked Loop (PLL) or by zero crossing detection [42-43]. This topology has a bidirectional sharing i.e., local loads can be provided from the grid if demand exceeds and the excess produced for local loads can be fed into the grid. There are also a few provisions for reverse metering i.e., net bill= energy consumed from grid (kWh) – energy provided to grid (kWh).

2.3.3 Battery Charging Mode

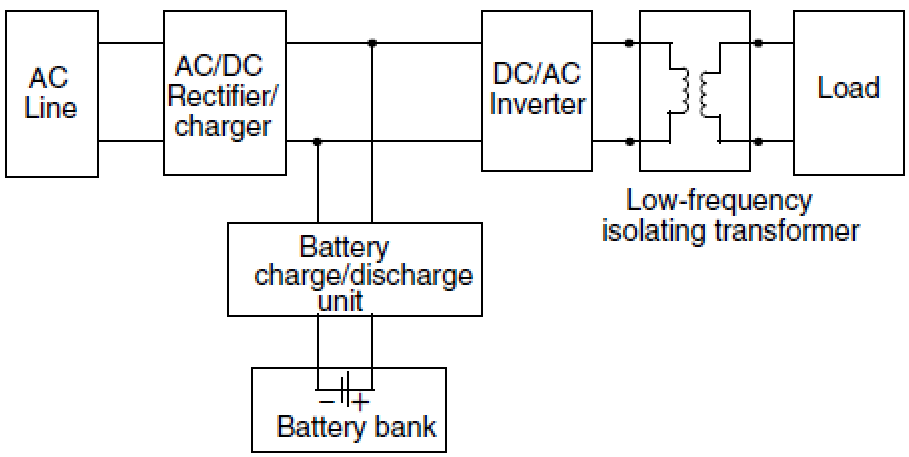

Fig 2.3 Battery charging mechanism of the converter [30]

The defining characteristics of converters are their robustness and availability. This property is most dependent on the type of batteries used in the system. The batteries must be of such a rating (Volts and Ampere Hours) that they can supply backup power in offline mode. The most commonly used batteries are Valve-Regulated Lead-Acid Batteries (VRLA). It consists of a set of positive and negative electrodes made of lead coated with a paste of lead compounds. These batteries are designed to provide backup current ranging from a few seconds to a few hours. The internal resistance of these batteries is kept low so that they can furnish high currents with minimal loss. However, this low internal resistance can also be problematic as they lead to AC and DC ripples which heat up the batteries and degrade the battery life. This phenomenon is also known as High-Frequency Shallow Cycling (HFSC).

The charging strategy for these batteries is a constant current (CC) or a constant voltage (CV) source. Initially, when the no load potential of the battery bank is low, it is charged using the CC mode. After a certain potential threshold is reached, the batteries are charged using CV mode. Also there is the Intermittent Charging (IC) in which battery is charged at 100 mV over-voltage for a small duty cycle. There are two types of IC (i) one in which the battery is charged periodically for e.g., 10 minutes/hr and (ii) trigger voltage in which a defined potential value initiates the charging and continues until the battery State Of Charge (SOC) is 100%. Common battery failures can be broadly classified into low impedance, high impedance and capacity deterioration. There are three ways to monitor the batteries (i) voltage-based, (ii) current-based and (ii) impedance-based [44]. In (i) lookup tables in the system's memory relating voltage to discharge current and time are compared with the current state. In (ii) information gathered from discharge current is analyzed. In the (iii) the values of V and I are used to calculate the impedance and check its variation from standard values.

2.3.4 Control Strategies for Converters

We are going to mention a few of the methods used for the control of the inverters. The first is the concentrated control, in which PLL is used to synchronize output voltage frequency and phase with the voltage of the critical bus, ensuring equitable load sharing between the inverters. A control unit connected in parallel detects the load current per unit inverter I/n and sends this information to each inverter. This signal is used as a reference for the inner-loop, which takes feedback through the inductive filter. The error is fed back to the voltage regulator to ensure balanced sharing of the reactive loads [45].

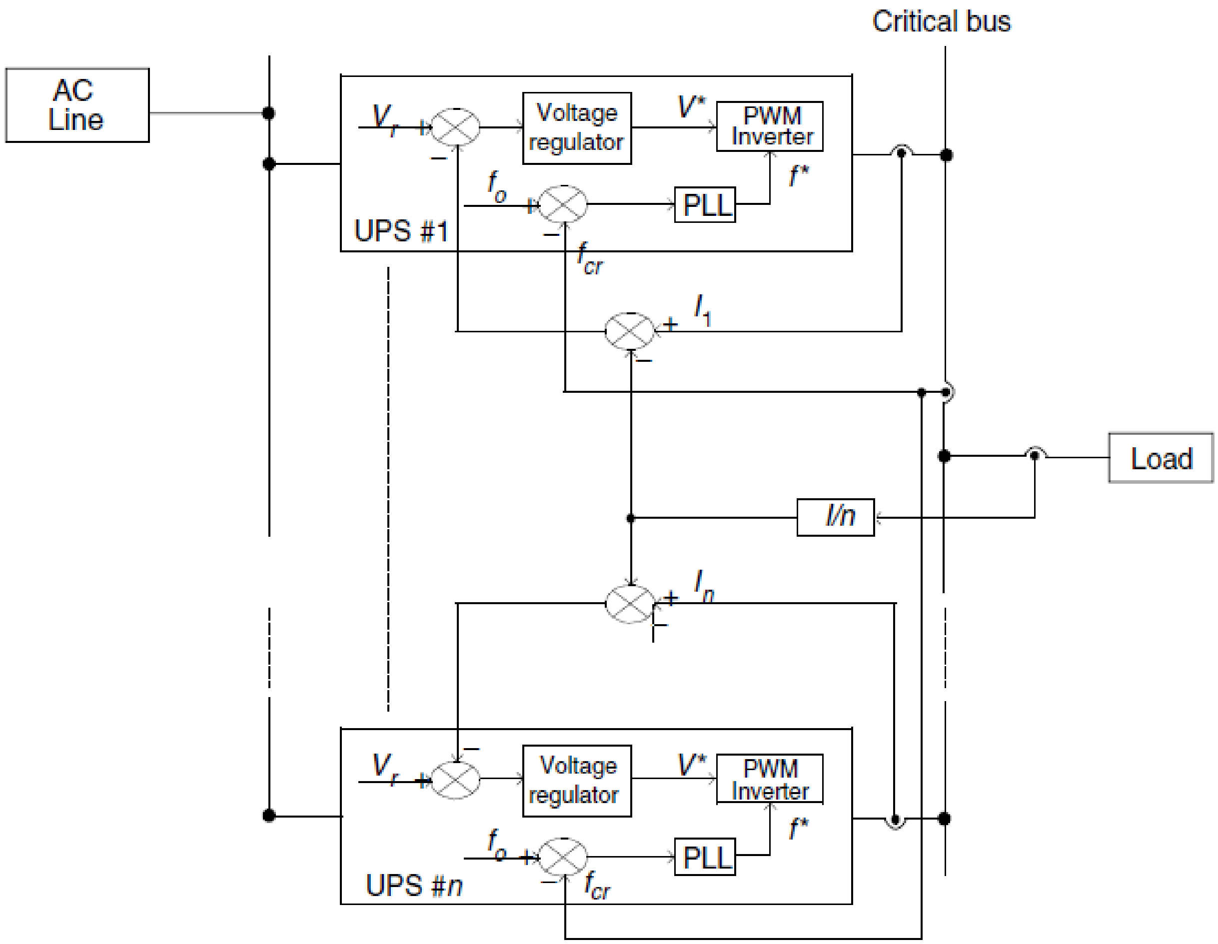

Fig 2.4 Topological layout of a concentrated control strategy [30]

In M-S control methodology, the master unit enables PLL to provide a constant sinusoid voltage at the output, which is in voltage and frequency synch with the critical bus voltage. The other inverters work as slaves to track the reference current provided by the control unit. If the master fails, it is replaced by one of the slave units.

Another technique is the distributed control which overcomes the issue of single point of failure that is present in the other techniques. All the converters communicate with each other in an autonomous and decentralized manner.

The last method we will discuss is the wireless independent control, in which there are no physical connections between the units. The control is dependent on each inverters individual parameters i.e., voltage, frequency and current. The frequency variations due to load changes are the communicating signals between the inverters connected in parallel.

2.4 Topologies

In this section, we will overview the converter topologies that are commonly used and their defining characteristics. Many different topologies have been implemented on the GCC to control its performance. There are pros and cons of each and it depends on the application that we intend to use it for. Performance improvement of GCCs is an area of continuing research and the objective is to minimize the switching losses and switching time, improving reliability, reducing failures and inverter shorting and improving the overall quality of the output current. The most commonly used topology is the voltage source Two-Level Pulse Width Modulation (PWM) inverter [46], although there are other topologies such as Interleaved [47], Three-Level, Multi-Level, Neutral Point Clamped (NPC) [48], Multipoint Clamped (MPC) [49] and Matrix Converters [50]. Until 2012, the majority of the voltage source converters (VSC) were Two-Level ones. It can be thought of as a six-pulse bridge composed of IGBTs with inverse-parallel diodes with a capacitor placed in shunt for smoothing the output waveform. The Two-Level converter has two switching states corresponding to the value of the DC bus. When the top level IGBT is turned on for the positive AC cycle, the output voltage is $U_{dc}/2$. Similarly, when the bottom level IGBT is turned on, the output voltage is $-U_{dc}/2$. The two levels in the same leg must not be switched on at the same time as it will lead to shorting of the inverter. The loss in the two-level converter is about 2-3 %.

The three-level converter gives three output levels $U_{dc}/2$, 0, $-U_{dc}/2$. A commonly used three-level converters is the Neutral Point Clamped (NPC) converter, where each leg is composed of four IGBTs and two clamping diodes. To obtain the positive output voltage, the two top switches are switched on, for negative output the two bottom switches are switched and for 0 the middle two switches are switched on. The sine generated by these inverters is not a perfect sine, but rather an approximation of stepped square pulses that cumulatively appear to be as a sinusoid. The more the number of steps, the better the Form Factor (FF) of the output wave. As the switching frequency is lowered, the switching losses are also reduced.

Another topology that is being popularized is the interleaved converter. In this type, the cells (2 or 3 level) connect in parallel to form channels and the switching instants of the channels are phase rotated over a specific switching period. The advantage is that the output current ripple is reduced and also that the filter inductors size decreases as well as cost.

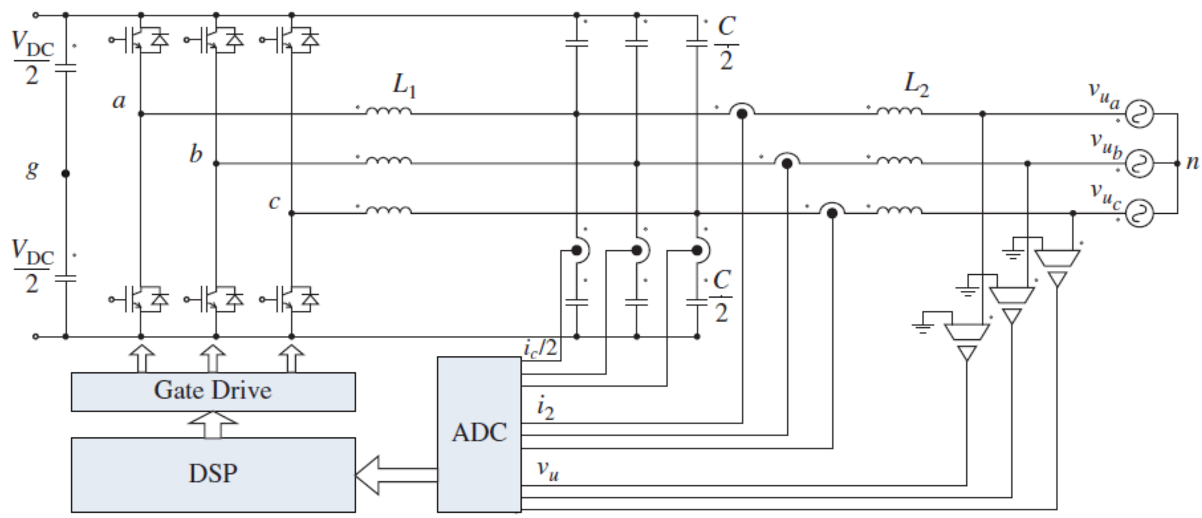

Fig 2.5 Two-Level Pulse Width Modulation (PWM) based Grid-Connected Converter [51]

2.5 Selection of Filter

The different filters for smoothing the ripples or the DC component in the AC output have also been studied. The commonly used methods are using a series inductor (L), a shunt capacitor in parallel (C), LC, LCCL and LCL filters [52-55]. The disadvantage of using a simple L filter in series with the load is that its size increases with the switching frequency of the inverter and it becomes a very costly and unfeasible proposition. Similar is the case with the simple shunt capacitor filter in parallel with the load. The LC filter has better filtering properties but is susceptible to resonance effect which occurs at the frequency $1/2\pi\sqrt{LC}$. The best filter is the LCL which requires the values of the components which are very manageable, both in terms of size and cost and is also resistant to the resonance affect which can make the system unstable.

2.6 Smart-Grid

A smart grid is an automated electrical grid that uses analog or digital communication among the various components of the grid to gather information about the trends of supply and demand to increase the efficiency and quality of the grid current. It also oversees, safeguards and optimizes the operation of its sub units.

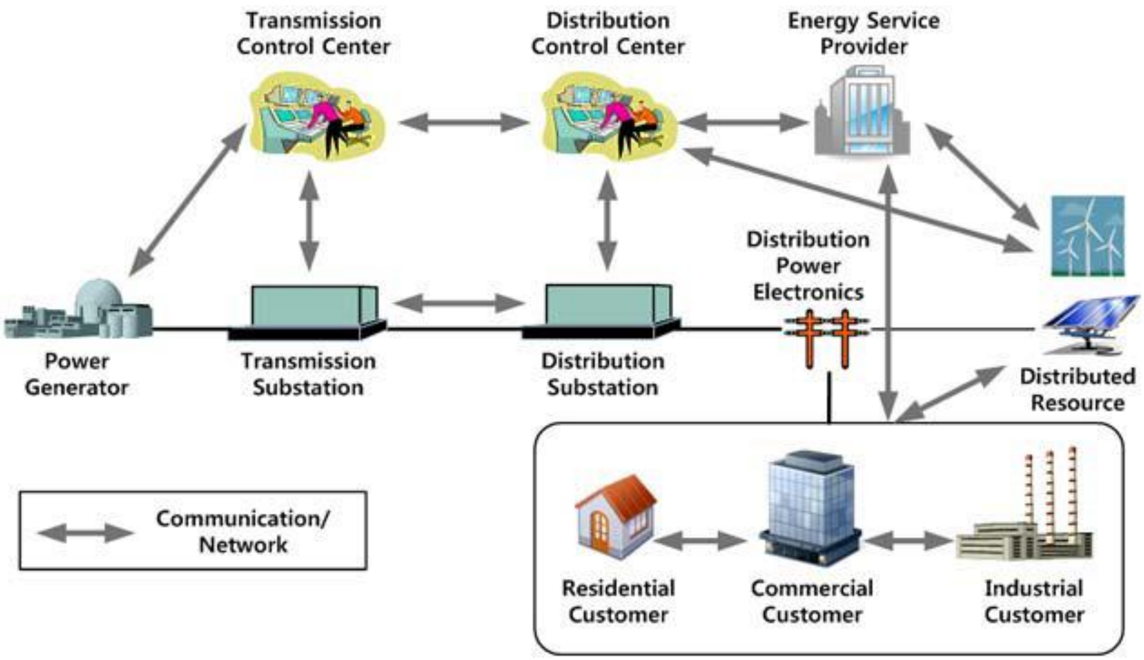

Fig. 2.6 A schematic diagram of a micro-grid [36].

The smart grid delivers power to the consumers along with a bidirectional digital communication system to ensure an efficient supply as well as efficient utilization of the grid. The advantage of the communication is that the grid can then rectify faults and load imbalances instantaneously, thereby improving the reliability and reducing the cost. A few of the enabling technologies that have contributed to the rise of smart grid are:-

- Smart Meters
- Field area networks
- Meter Data Management
- Integrated communication systems
- Information Technology
- Security of Information
- Electricity Storage devices
- Load Management
- Distributed Generation
- Alternate Energy

The advantage of this technology is that it detects a fault condition very quickly and then acts to rectify it. It is able to incorporate the Customer Premise Equipment (CPE) into the overall grid topology. The grid is robust and can overcome any sort of attack. It also ensures utility power conditioning and compliance with the standards of distribution, generation and protection. It can integrate a wide variety of RES like Combined Heat and Power (CHP), Wind, PV, etc. The backbone infra-structure that needs to be in place before the smart grid can be realized are:-

1. Advanced Metering Infrastructure is required as most of the meter reading systems are either manual of handheld. The utilities should be able to get real-time data regarding the consumption patterns of the consumers so that they can use this to plan for future demand strategies. The meter data should be available globally and also the rights to manage them to detect disruptions and mitigate losses. Provide customers with time-dependant pricing options to ensure effective management of demand.
2. The advantage of the Meter Data Management (MGM) is that each utility can view all the data of the other utilities existing within the grid network through the usage of the Advanced Metering Infrastructure (AMI).
3. Geographical Information System (GIS) provides a list of the grid distribution facilities and their physical locations. This provides us with a reference to analyze the various parameters of the grid at different locations and also to view past trends of specific areas.
4. The Enterprise Asset Management (EAM) is software which is used to manage the total life cycle of the assets in the business. The key variables are the planning of construction, investment, O&M and disposal of assets once the business activity has ended. It is a sort of Management Information System (MIS) which takes inputs from the various managers and communicates this information across all levels. The main activities in a project require a lot of human effort and paper work, but we can optimize these activities using this method. The added plus is the transparency that is achieved from the open-access to data.
5. With the passage of time, the distribution system gets overloaded which leads to inefficiency in the whole grid. The manual distribution systems are very expensive and offer less control and also lead to customer resentment. The tools required to implement the automatic distribution network are computers, Remote Terminal Units (RTUs),

breakers, Switched Capacitor Banks, OLTC (On Load Tap Changer) Transformers, Auto Reclosures, Sectionalized, AMR Systems and Communication Systems. This network enables utilities to have real-time optimal control and also results in improved efficiency.

The smart grid comprises of the following major areas:-

1. Metering and Meter Data Management.
2. Distribution Automation Distributed Control System(DCS), Supervisory Control And Data Acquisition (SCADA).
3. Demand Management System (DMS).

Chapter 3: Methodology

3.1 Modeling and Simulation

There are numerous design and simulation software which are commonly used to analyze the performance of electronic circuits and the models of real systems. A few among them are Multisim, PSPICE, ORCAD, Wolfram Mathematica [56-60]. Almost all of them have some strength and some weaknesses and the preference of one over the other is based on user preference or skill in that particular software. Our requirement is a software that is computationally efficient, uses less memory resources, gives a range of features to analyze the performance of systems and is user friendly i.e., has a Graphical User Interface (GUI). Also another feature that is of concern especially in research is that the results can be reproduced by others working in the same area and also the quality of results is pictorially high i.e., having a high number of dpi so they can be used in journals and conference papers. We want to simulate the linear model of a Two-Level PWM based Grid-Connected Converter for a PV module. The software we choose is known as Matlab (Matrix Laboratory), which offers a wide array of mathematical and graphical tools for analyzing research problems [61-64]. There is an additional graphical package known as simulink which enables the designer to model systems using click and drag boxes. There is also a specialized toolbox for control systems related problems. We have found this software to be sufficient for our needs and are sufficiently satisfied with the results. It is also modular and we can create subsystems to abstract a complicated system. Furthermore, the amount of documentation available means that a large amount of help is also available online in the form of demos and tutorials. It is a standardized practice that before the fabrication of the prototype, extensive testing of the model is done so that only minor adjustments remain to be made in the design before moving to industrial scale production. Matlab has also provided us with the feature to apply our desired controllers like proportional (P) and proportional integral (PI) and also caters for applying Linear Quadratic Regulator (LQR), proportional resonant (PR) and repetitive controller (RC). There is also a feature of matlab known as porting i.e., converting the matlab code into C code for real-time hardware implementation. This code is not optimized, but still it saves a lot of effort and is a huge help for completing projects in short deadlines.

The parameters that we have considered for our system are as mentioned in the Table 1 [65].

Table 3.1 Constituents of the GCI system

Components	Description	Rating Values
P_{inv}	Rated Power	80 KVA
V_u	Utility Phase Voltage	230 V (rms)
I_u	Utility Phase Current	100 A
V_{DC}	DC Link Voltage	800 V DC
L_1	1^{st} Inductor of LCL Filter	350µH
L_2	2^{nd} Inductor of LCL Filter	50µH
C	Filter Capacitance	22.5µF
f_{sw}	Switching Frequency	10 KHz
f_s	Sampling Frequency	20 KHz
F	Utility Frequency	50 Hz
N_s	Number of samples per period	400

We start with the diagram of the GCI (Fig 3.1). It is known as Two-Level because each leg consists of two levels or two switching devices i.e., IGBTs, MOSFETS, BJTs one for the conduction of the positive DC voltage $V_{dc}/2$ through the IGBT and the other for the conduction of $-V_{dc/2}$ through the diodes.

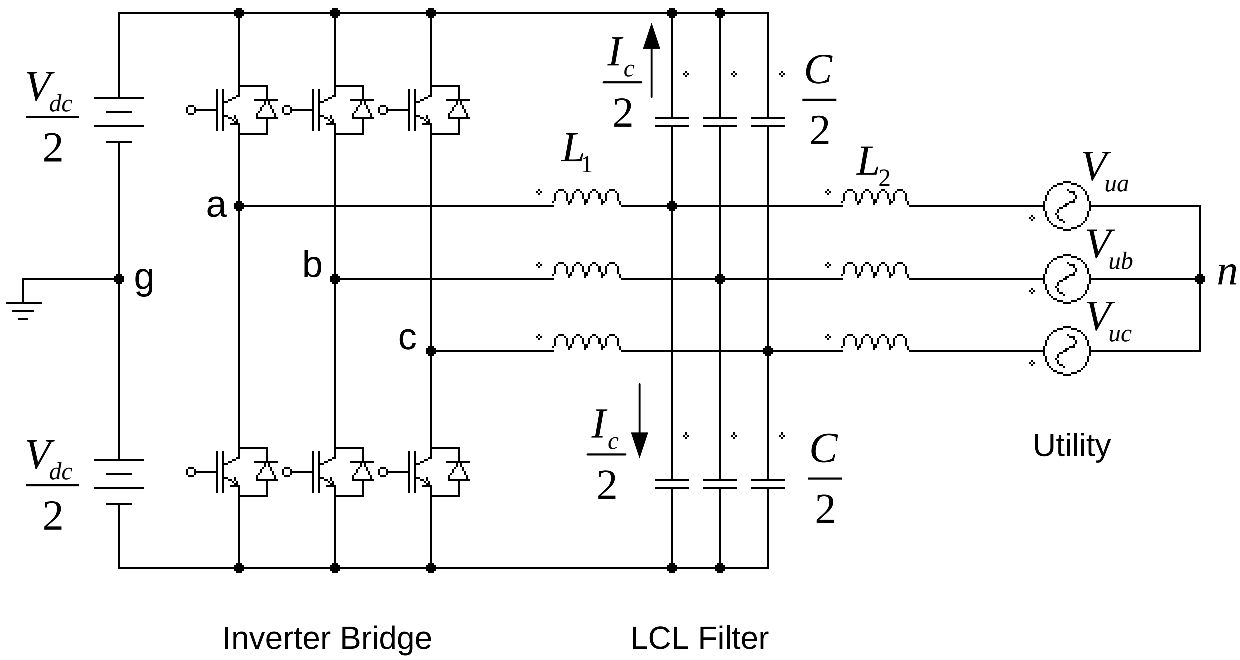

Fig 3.1 3-Φ GCI with LCL filter

As it is difficult to work on the Three-Phase model and derive its transfer function [47], we take the Single-Phase equivalent Fig 3.2 and derive its transfer function. The reason that there are two capacitors of capacitance C/2 in each leg of the LCL filter is that by connecting them to the DC link instead of connecting them in delta or star configuration, the DC link midpoint has virtually zero voltage with respect to the neutral [46]. Therefore, the inverter voltage produced in one phase is almost independent of the inverter voltages produced in the other phases. Also the steady state error is reduced by using this connection technique for the hysteresis current controller. By connecting the capacitors across the DC link, we get $V_{gn} = 0$ [66]. The three phase-to-neutral voltages are V_{an} , V_{bn}, V_{cn} respectively.

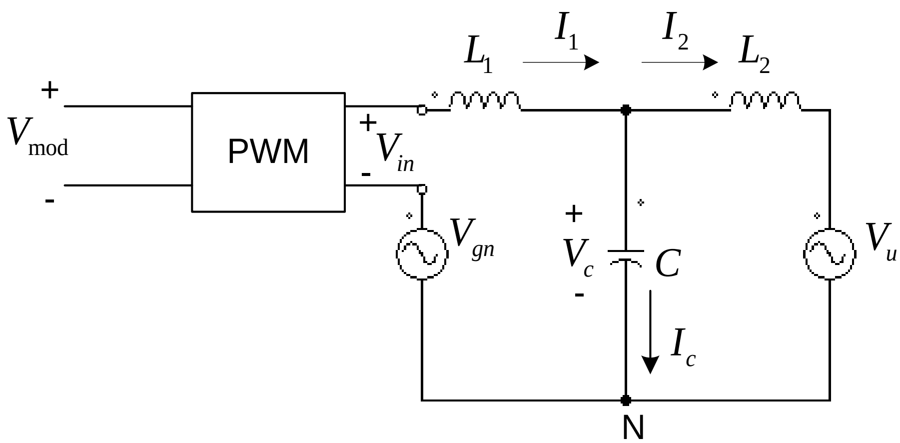

Fig 3.2 The 1-Φ model of the GCI

The application of Kirchhoff's Voltage Law and Current Law to Fig 3.2, results in

$$V_{in} = L_1 \frac{dI_1}{dt} + V_C \tag{2}$$

$$V_C = L_2 \frac{dI_2}{dt} + V_u \tag{3}$$

$$I_1 = I_C + I_2 \tag{4}$$

$$I_C = C \frac{dV_C}{dt} \tag{5}$$

Taking derivative on both sides of (3), we get

$$\frac{dI_1}{dt} = \frac{dI_C}{dt} + \frac{dI_2}{dt} \tag{6}$$

$$\frac{dI_1}{dt} = \frac{d}{dt}\left(C \frac{dV_C}{dt}\right) + \frac{dI_2}{dt} \tag{7}$$

$$\frac{dI_1}{dt} = C \frac{d^2 V_C}{dt^2} + \frac{dI_2}{dt} \tag{8}$$

Substituting dI_1/dt into

$$V_{in} = L_1\left(C\frac{d^2V_C}{dt^2} + \frac{dI_2}{dt}\right) + V_C \tag{9}$$

$$V_{in} = L_1C\frac{d^2}{dt^2}\left(L_2\frac{dI_2}{dt} + V_u\right) + L_1\frac{dI_2}{dt} + L_2\frac{dI_2}{dt} + V_u \tag{10}$$

$$V_{in} = L_1L_2C\frac{d^3I_2}{dt^3} + L_1C\frac{d^2V_u}{dt^2} + L_1\frac{dI_2}{dt} + L_2\frac{dI_2}{dt} + V_u \tag{11}$$

Taking the Laplace Transform of V_{in}, we get

$$V_{in}(s) = s^3L_1L_2CI_2(s) + s^2L_1CV_u(s) + sL_1I_2(s) + sL_2I_2(s) + V_u(s) \tag{12}$$

$$V_{in}(s) = I_2(s)(s^3L_1L_2C + s(L_1+L_2)) + V_u(s)(s^2L_1C + 1) \tag{13}$$

$$I_2(s)(s^3L_1L_2C + s(L_1+L_2)) = V_{in}(s) - V_u(s)(s^2L_1C + 1) \tag{14}$$

$$I_2(s) = \frac{V_{in}(s)}{s^3L_1L_2C + s(L_1 + L_2)} - \frac{V_u(s)(s^2L_1C + 1)}{s^3L_1L_2C + s(L_1 + L_2)} \tag{15}$$

The second part of (15) is the disturbance entering the system at the PCC i.e., the current entering the system from the grid side due to low impedance path provided by the LCL filter.

Taking Laplace Transform of equations 2-5, we get

$$I_1(s) = \frac{V_{in}(s) - V_C(s)}{sL_1} \tag{16}$$

$$I_2(s) = \frac{V_C(s) - V_u(s)}{sL_2} \tag{17}$$

$$I_C(s) = I_1(s) - I_2(s) \tag{18}$$

$$V_C = \frac{I_C}{sC} \tag{19}$$

Henceforth, we can derive the block diagram from the above set of equations as Fig 3.3.

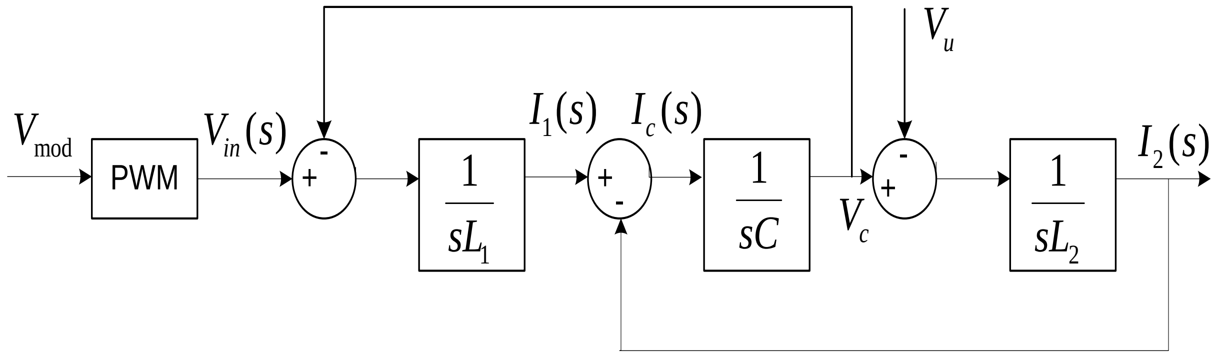

Fig 3.3 Control loop diagram of the 1-Φ GCI with LCL filter

Ignoring disturbance present in (15), we get G_{ol}, which comes out as

$$G(s) = \frac{I_2(s)}{V_{in}(s)} = \frac{1}{s^3 L_1 L_2 C + s(L_1 + L_2)} \tag{20}$$

For our system the values of the LCL filter parameters are $L_1 = 350\mu H, L_2 = 50\mu H, C = 22.5\mu F$. Substituting these values into (20), we get the open-loop transfer function of the system as

$$G(s) = \frac{1}{3.938 \times 10^{-13} s^3 + 4 \times 10^{-4} s} \tag{21}$$

One pole lies at zero, whereas the other two poles lie at ±31783j respectively. The open-loop response of the system to an applied sinusoidal signal of amplitude 100 amperes and frequency

50 Hz comes out to be as Fig 3.4

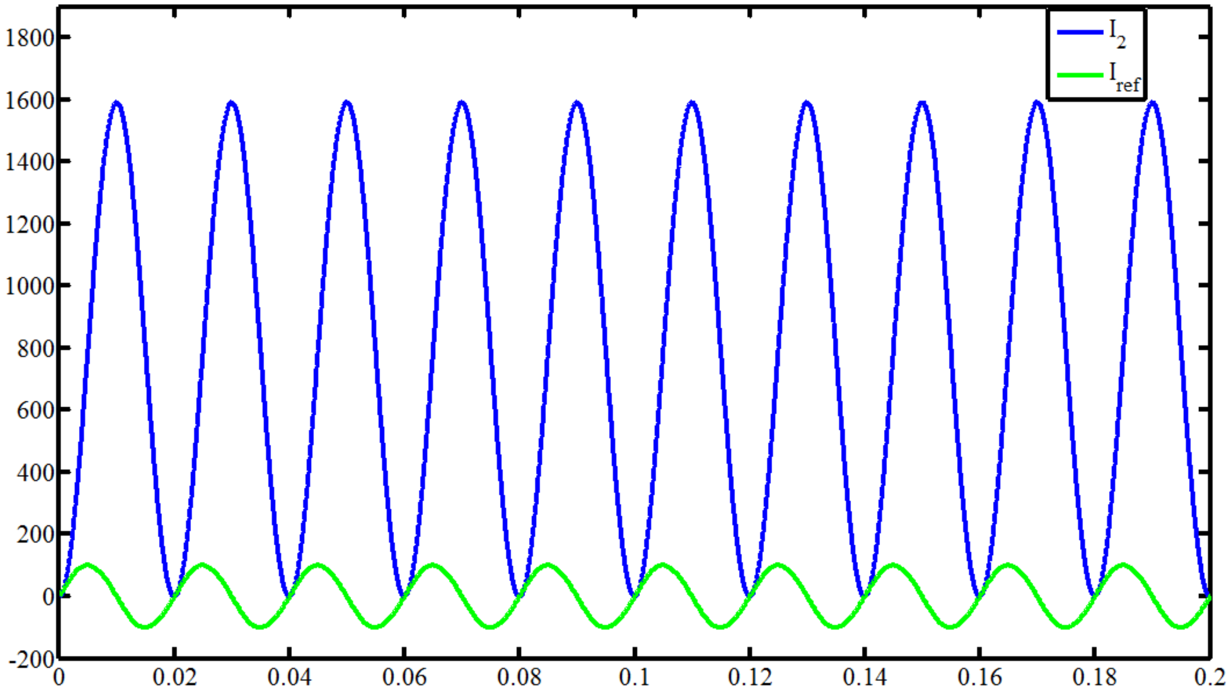

Fig 3.4 The open-loop response of the system

It is obvious from Fig. 3.4 that the output signal is much larger than the desired signal, so we will have to resort to closed-loop system and introduce a controller in the loop. Also, a technique that has been explored in literature and also is effective is to provide an inner-loop feedback gain from I_C back to the summer [67]. This capacitive damping helps in stabilizing the system and we have explored different values of K_C to discover the optimal value of 3.

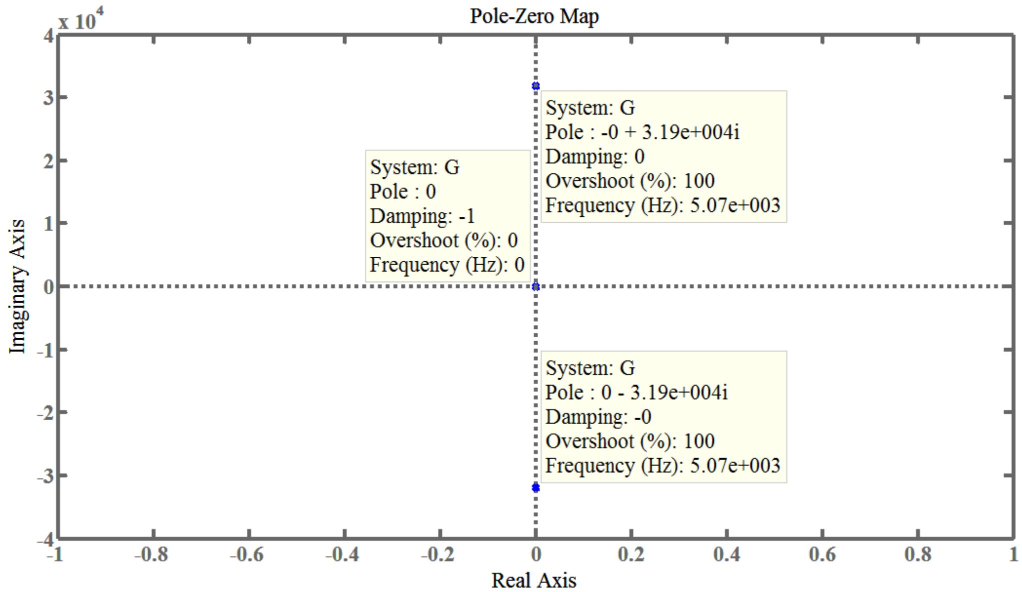

Fig 3.5 Pole-Zero map of G(s)

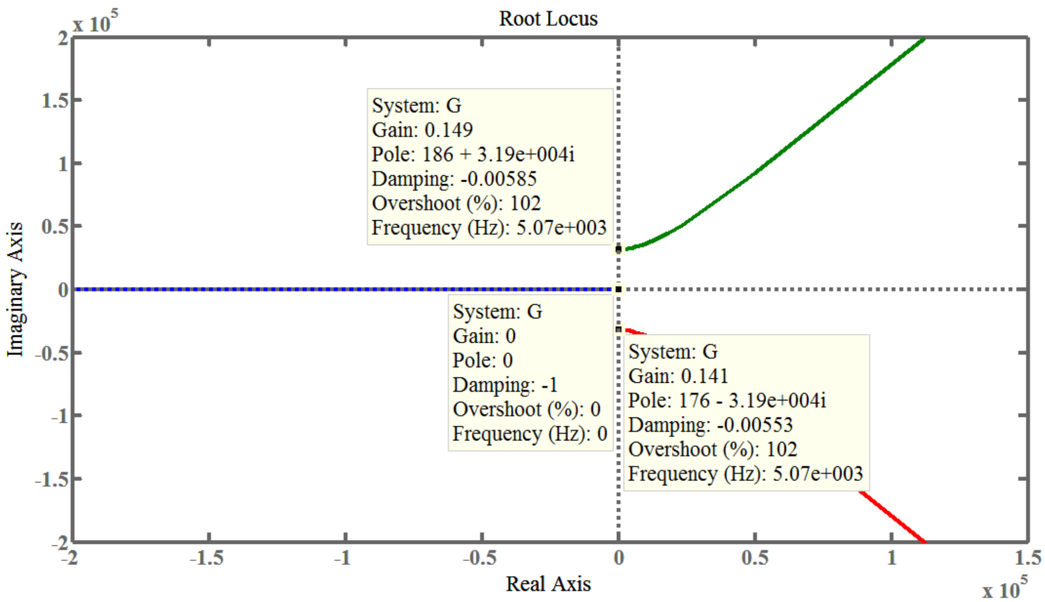

Fig 3.6 Root locus diagram of G(s)

From the root locus plot of our system, it is obvious that with the increase in the gain values two of our poles are going towards the unstable region and therefore the system as a whole will become unstable even when a small gain is applied to the system. Also the damping provided by the system at the poles is very less and the overshoot of the critical poles is very high, so the performance of the system as a whole is not very satisfactory.

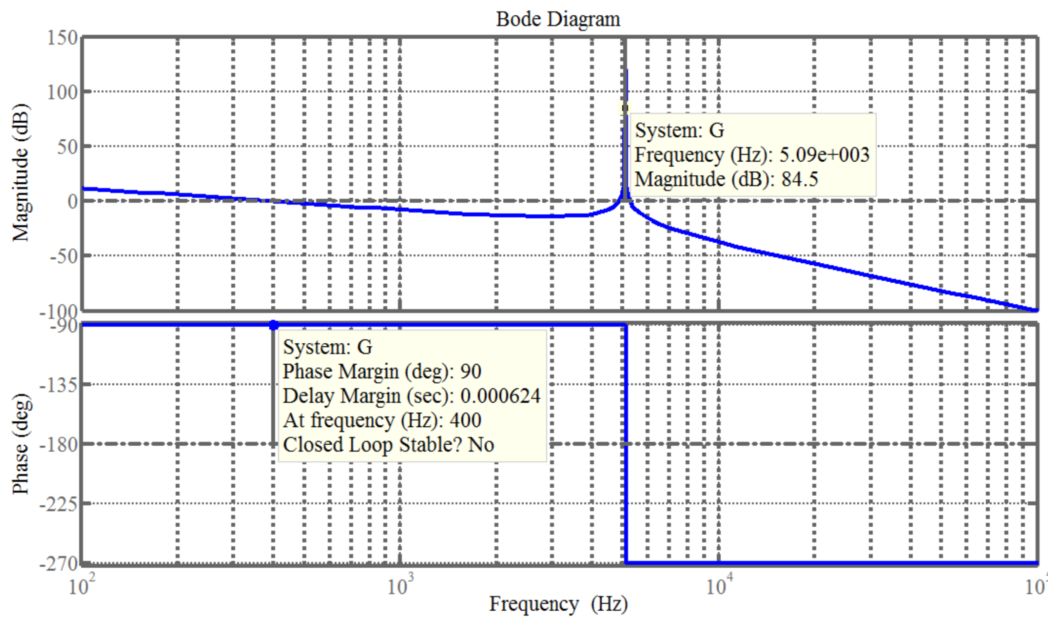

Fig 3.7 Bode plot of G(s)

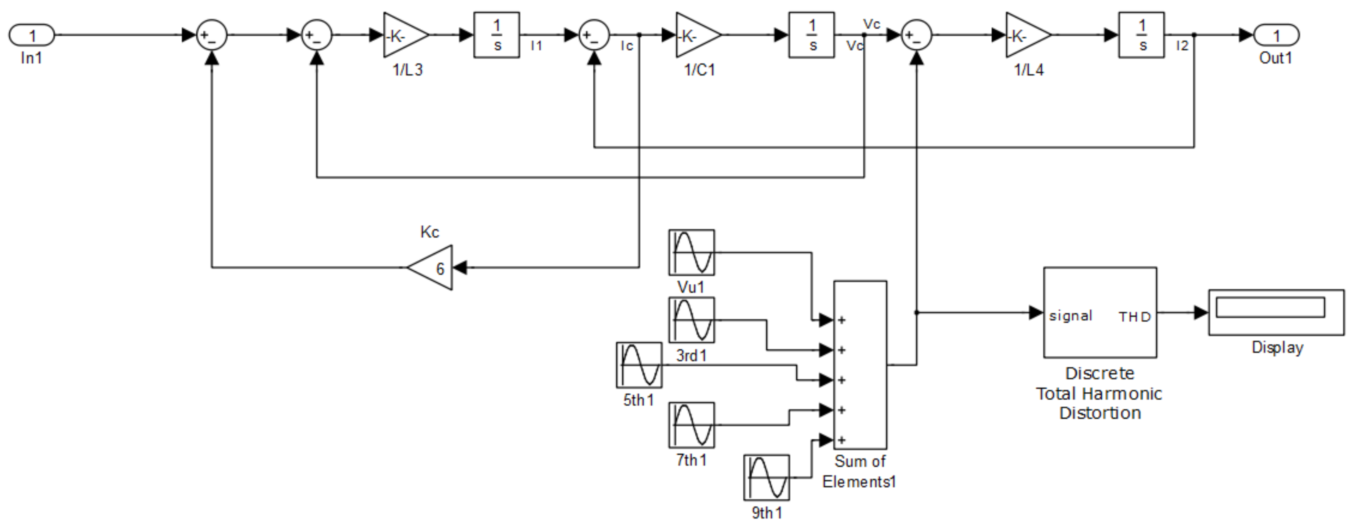

Fig 3.8 Matlab/Simulink diagram of the GCI with LCL filter

The system stability is improved by the addition of an inner-loop [47].

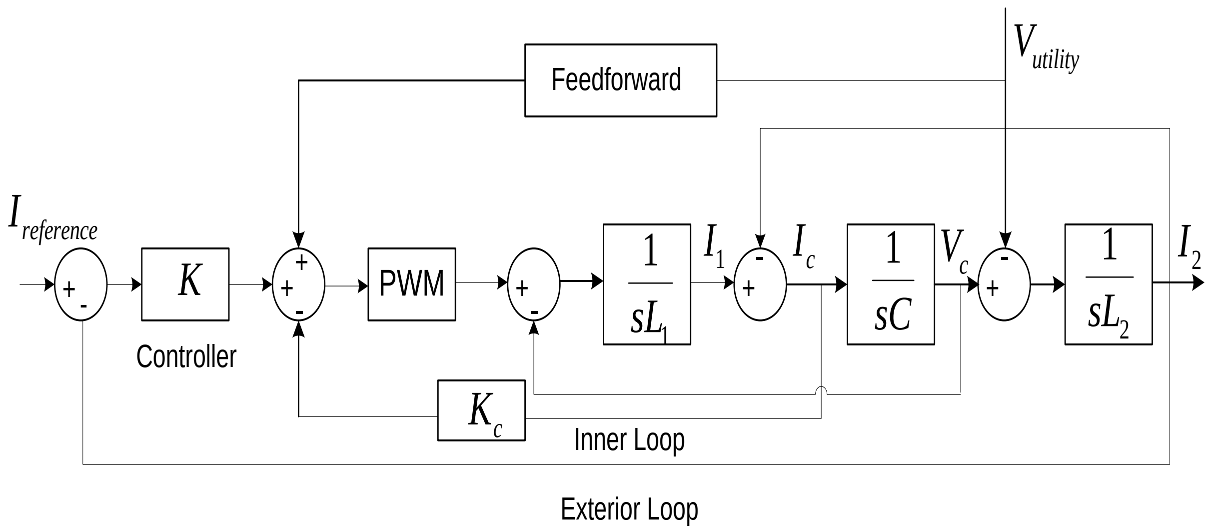

Fig 3.9 Control loop diagram having both inner and exterior loop

Using block diagram reduction techniques on Fig 3.9 gives us,

$$I_2 = \frac{V_{in}(s)}{L_1L_2Cs^3 + K_CL_2s^2 + (L_1 + L_2)s} - \frac{(L_1Cs^2 + K_CCs + 1)V_u(s)}{L_1L_2Cs^3 + K_CL_2s^2 + (L_1 + L_2)s} \tag{22}$$

The transfer function of $G_1(s)$ is

$$G_1(s) = \frac{1}{L_1L_2Cs^3 + K_CL_2s^2 + (L_1 + L_2)s} \tag{23}$$

Normally we consider K_C to be 3.2. So our modified transfer function comes out to be

$$G_1(s) = \frac{1}{3.938 \times 10^{-13}s^3 + 1.6 \times 10^{-4}s^2 + 4 \times 10^{-4}s} \tag{24}$$

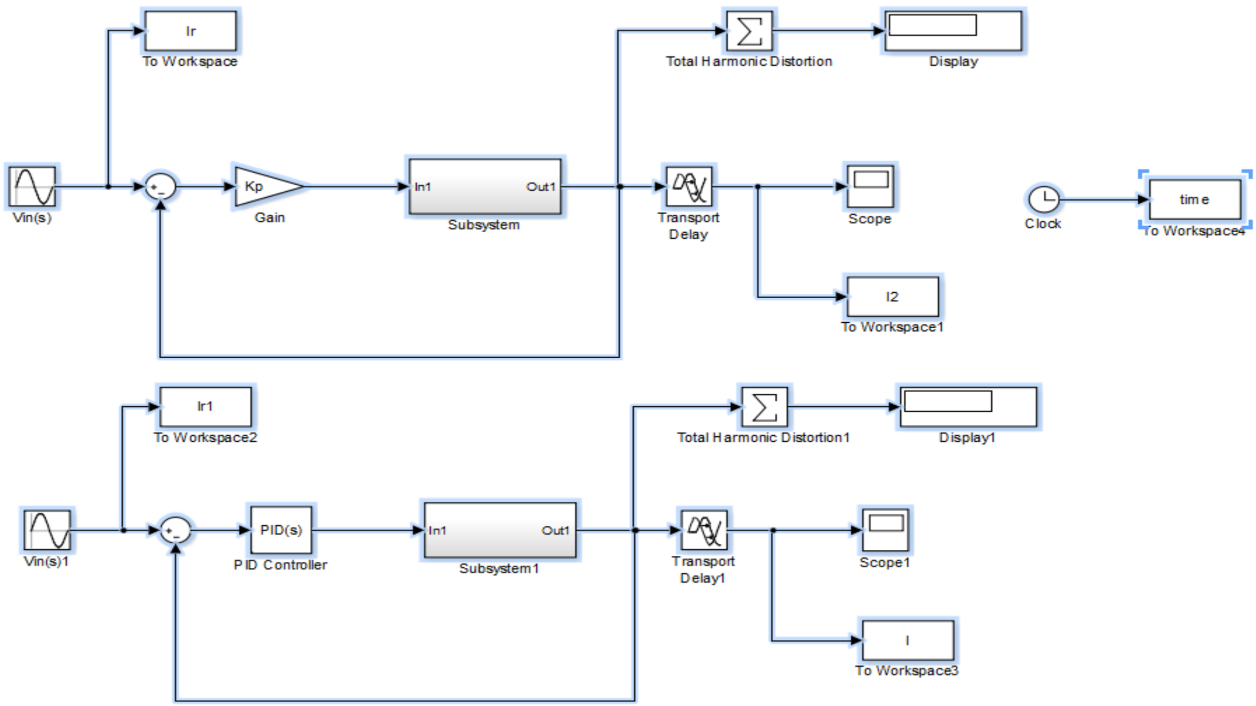

Fig 3.10 Matlab/Simulink block diagram showing the mechanism we have used to implement the proportional (P) and proportional integral (PI) controller

Two poles of the modified transfer function lie at zero, while the third one lies at -4.0635×10^{8} respectively.

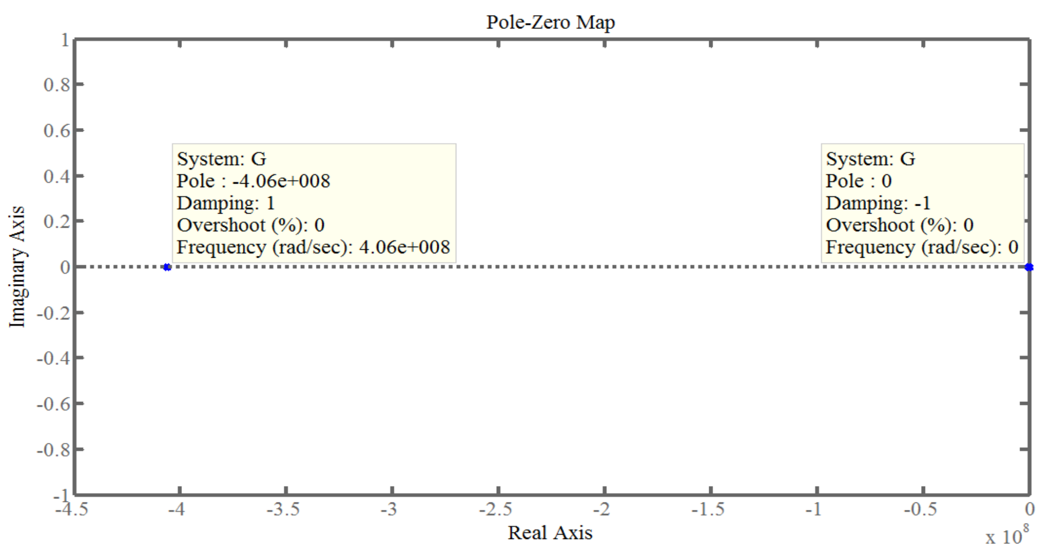

Fig 3.11 Pole-Zero map of the modified transfer function $G_1(s)$ with inner-loop gain $K_c = 3.2$

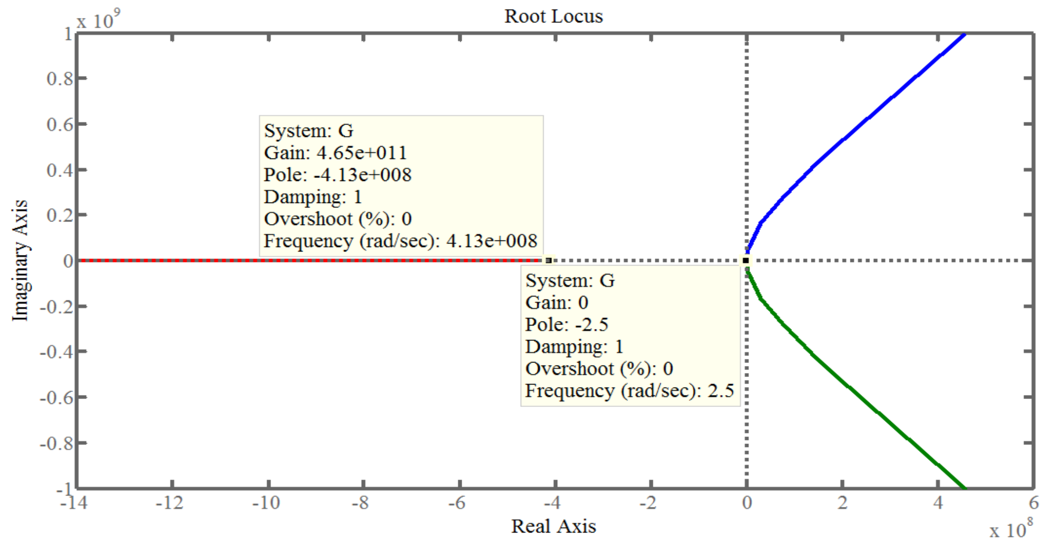

Fig 3.12 Root locus of the modified transfer function $G_1(s)$ with inner-loop gain $K_c = 3.2$.

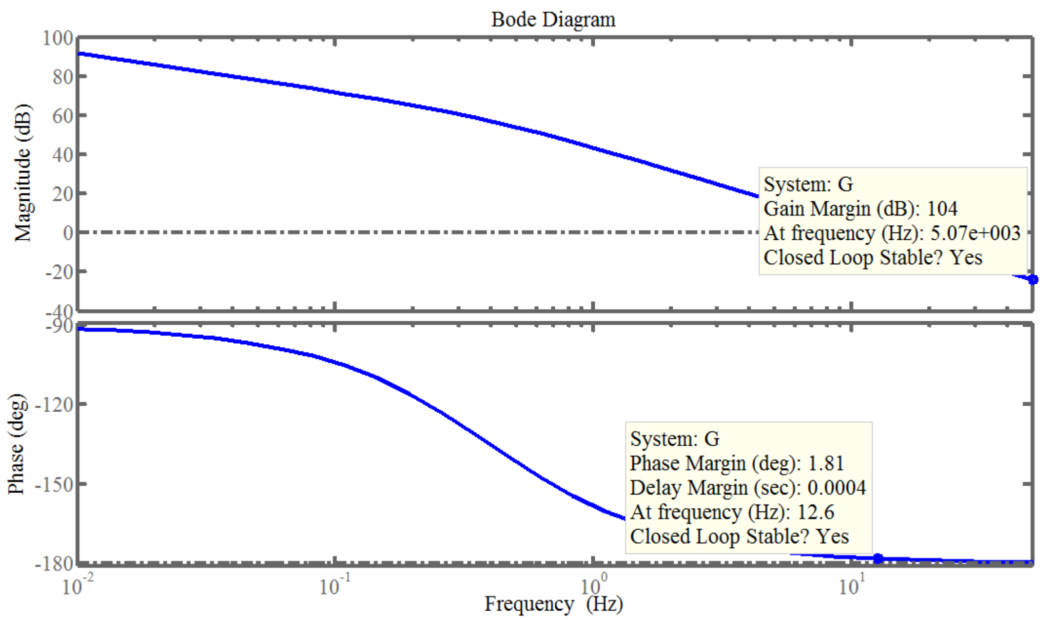

Fig 3.13 Bode plot of the modified transfer function $G_1(s)$ with inner-loop gain $K_c = 3.2$.

From the bode plot it is clear that due to the capacitive damping provided by the inner-loop gain K_C the system has become stable.

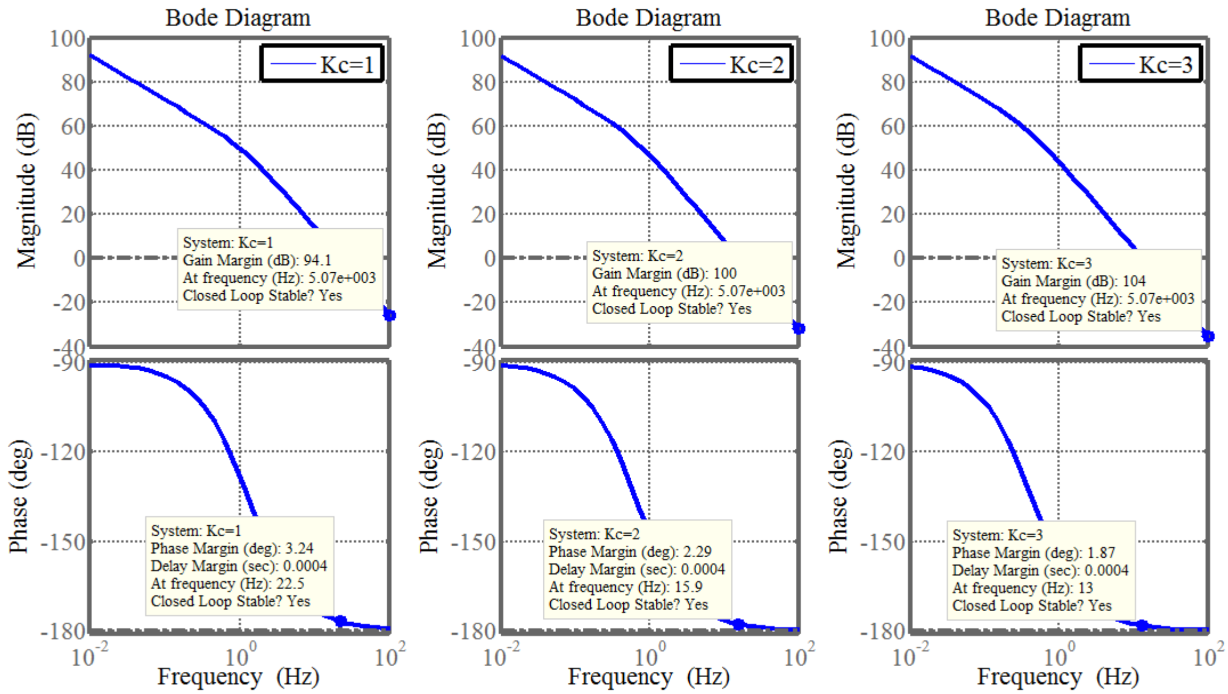

Fig 3.14 The effect of variation of the inner-loop gain K_c on the open-loop system performance while ignoring harmonics

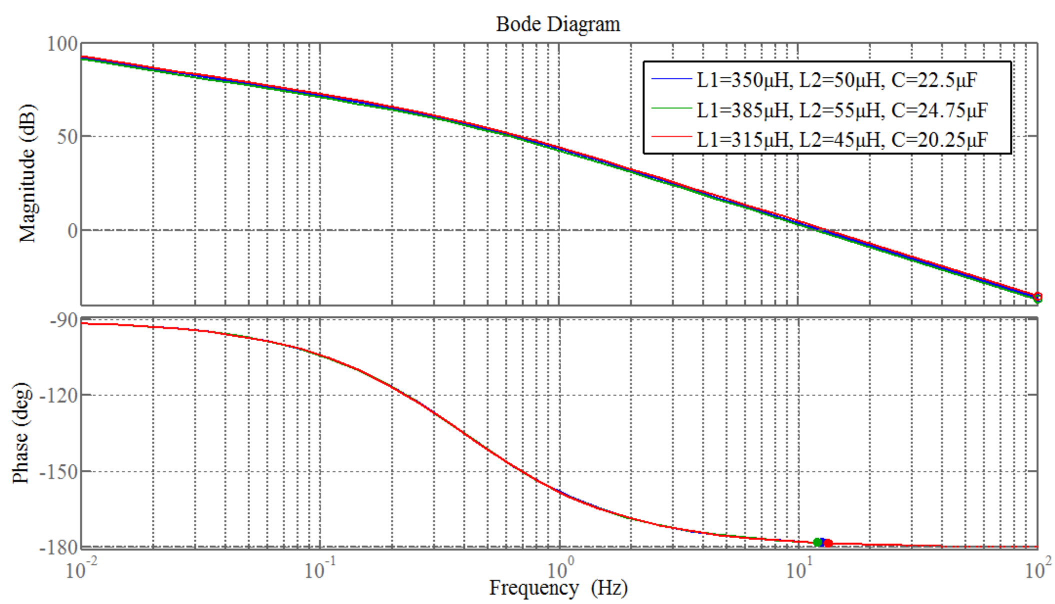

Fig 3.15 The effect of variation of the LCL filter parameters on the system performance

Table 3.2 Effect of variation of LCL filter parameters on system performance

	Case 1	Case 2	Case 3
Filter Parameter Values	L_1 = 350μH, L_2 = 50 μH, C = 22.5μH	L_1 = 385μH, L_2 = 55 μH, C = 24.75μH	L_1 = 315μH, L_2 = 45 μH, C = 20.25μH
Gain Margins (dB)	-6.8	-6.8	-6.8
Frequency (kHZ)	1.79	1.63	1.99
Phase Margins (°)	-35.7	-35.7	-35.7
Frequency (kHz)	2.39	2.17	2.66
Delay Margin (sec)	0.000377	0.000415	0.000339
Stable	No	No	No

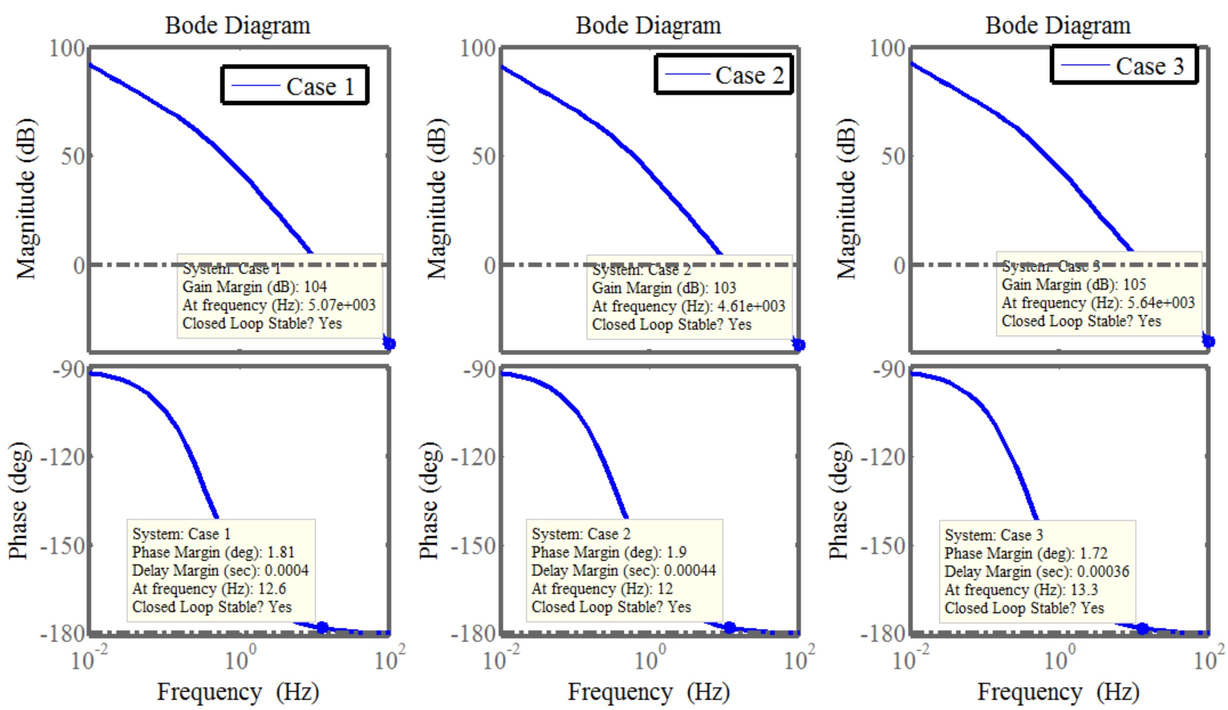

Fig 3.16 The effect of variation of the LCL filter parameters on the system performance

As we are varying the LCL filter parameters by +10 % and -10 % of the original values, the change in gain margins is -0.962 % and 0.962 %, while the change in phase margins is 4.972 % and -4.972 % respectively. As the effect on the system performance is less than 5 % for a 10 % variation in the filter parameters we can safely say that our controller is adaptive and change in parameters of the filter in real-time system would not lead to the system becoming unstable. If we vary the filter parameters and apply a proportional controller for inner-loop gain K_C = 3.2 and K_p = 1.63, we get the following graph which supports the premise stated above that there is little or no difference on the system performance due to parameter variations. The gain margin for the three cases is 7.02 dB and the phase margin is 87.8°. Only minor difference in frequency at which these gains are reported is observed which does not in any way affect system stability or robustness.

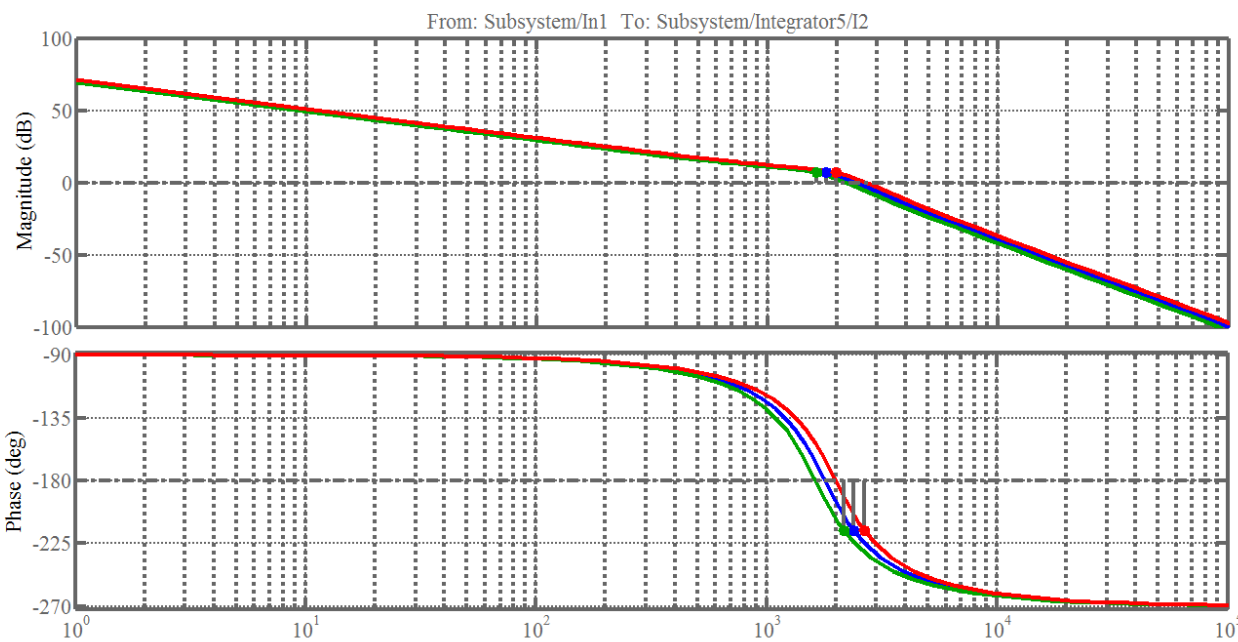

Fig 3.17 The effect of variation of filter values on performance for a proportional controller with K_p = 1.63 and K_c = 3.2.

3.2 Proportional (P) Controller

We use Matlab / Simulink for the modeling (Fig 3.8) and simulation of the system (Fig 3.9). For inner-loop gain K_C = 0 our system is unstable. For inner-loop gain K_C = 1.4, the system is stable but after 0.04 seconds, it starts getting unstable and THD in the signal increases. From Table 1 at inner-loop gain $K_C = 1.6$ we have reached our optimal performance as far as reference tracking is concerned.

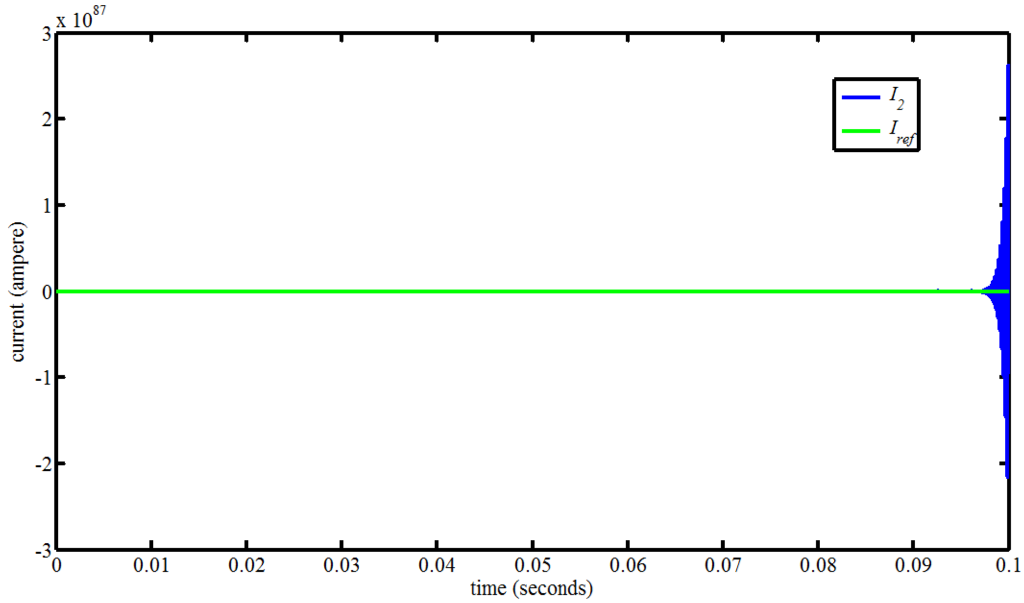

Fig 3.18 Plot of *I(t)* vs t, inner-loop gain $K_c = 0$

Fig 3.18 shows that for this value of inner-loop gain K_c, our system is unstable and we should increase the value more until we reach some results that show that the system is responding positively to that value.

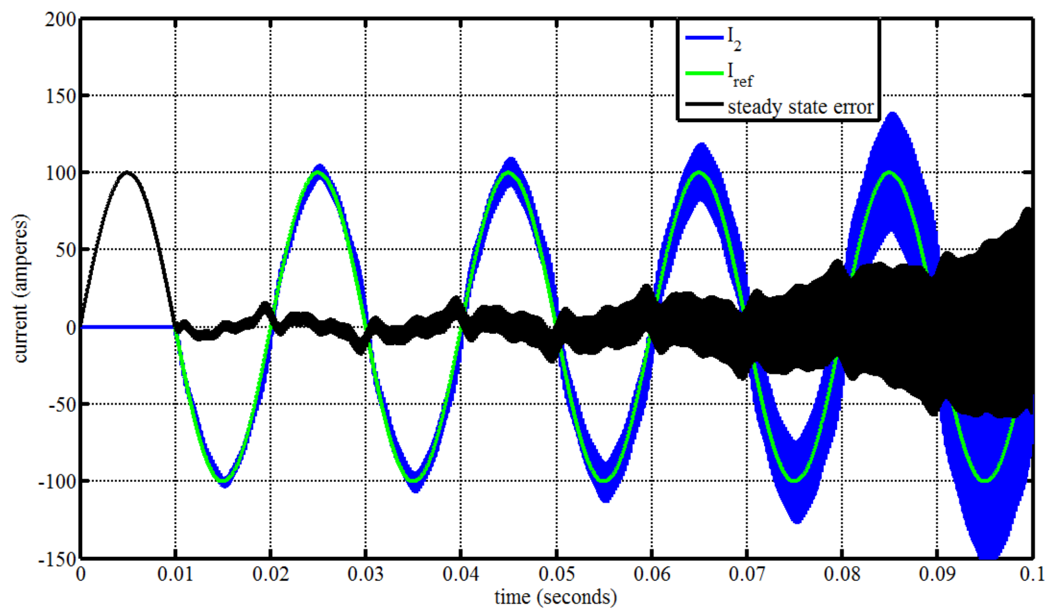

Fig 3.19 Plot of *I(t)* vs t, inner-loop gain $K_c = 1.4$

Fig 3.19 shows that the system is much more stable as compared to the previous value but after 0.04 seconds, it starts getting unstable and the amount of THD in the signal is increasing. From Table 1, at inner-loop gain K_c equal to 1.6 we have reached our optimal performance as far as reference tracking is concerned, but there is still a little room for improvement as far as controller gain is concerned.

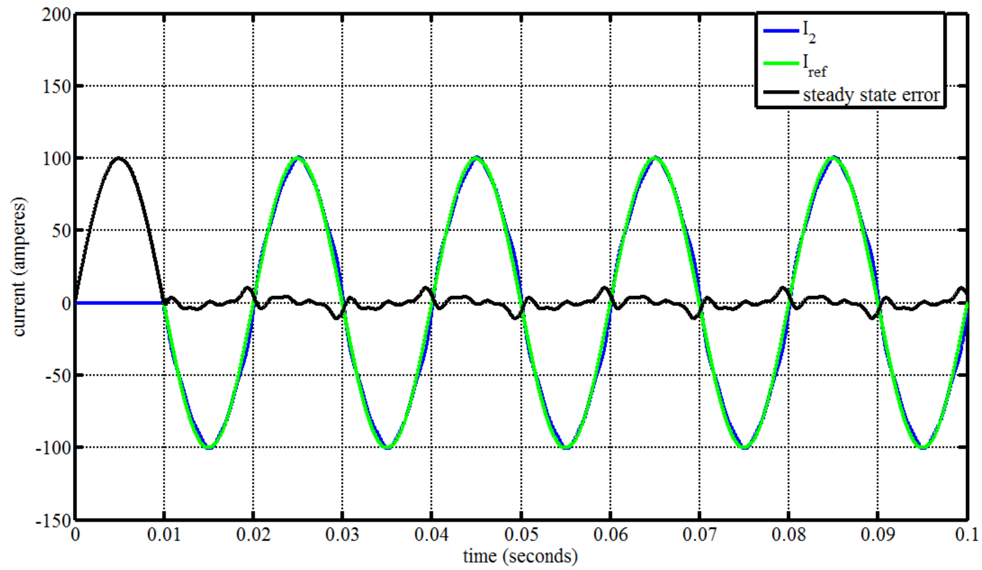

Fig 3.20 Plot of *I(t)* vs t, inner-loop gain $K_C = 3$

At the value of inner-loop gain K_C equal to 3, we are getting the optimal phase and gain margins along with a reduced value of THD.

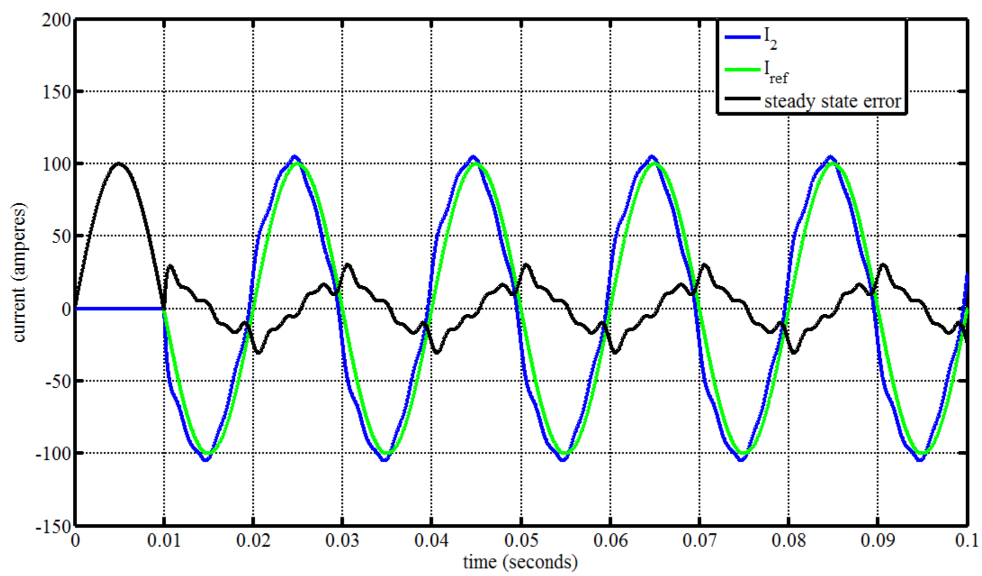

Fig 3.21 Plot of *I(t)* vs t, inner-loop gain $K_C = 20$

Fig 3.21 shows that although the gain margin at this value of inner-loop gain (K_C is high, but there is THD in the output signal which is visible from Table 1. We can also state that beyond a certain value, increasing the gain margin will be ineffective, because it will lead to system instability and such high gain margins are not practically realizable. Best controllers are those which give minimum gain to overcome the transients, but this is dependent on the designers' understanding of the behavior and the mathematical model of the system itself which has to be controlled.

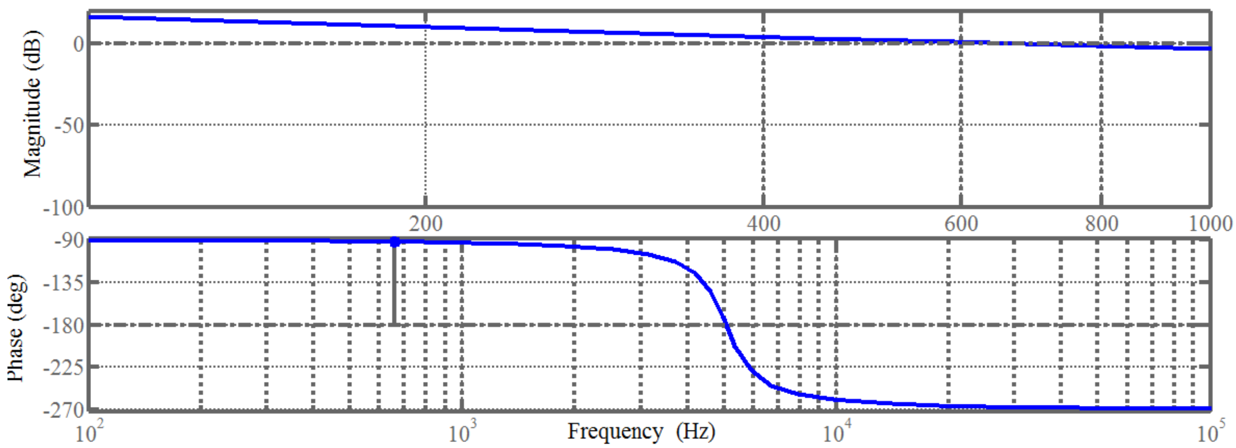

Fig 3.22 Bode Plot of I_2 w.r.t I_{ref} for optimal gain i.e., inner-loop gain $K_C = 3$.

Fig 3.22 is the bode plot of I_2 with respect to the reference current for the optimal controller gain at which the gain and phase margins are maximum resulting in accurate reference tracking and better disturbance rejection. The results of our findings have been mentioned in Table.1

Table. 3.3 Effect of variation of inner-loop gain k_c on system performance

S. No	K_c	THD	Gain Margin (dB)	Phase Margin (°)	Stable
1	0	3804	undefined	-90	No
2	1.4	69.43	-0.161	-5.96	No
3	1.6	4.512	0.998	88.9	Yes
4	3	4.544	6.46	88	Yes
5	20	5.815	22.9	77	Yes

Fig 3.18 shows an unstable system, while Fig 3.19 shows a critically stable system.

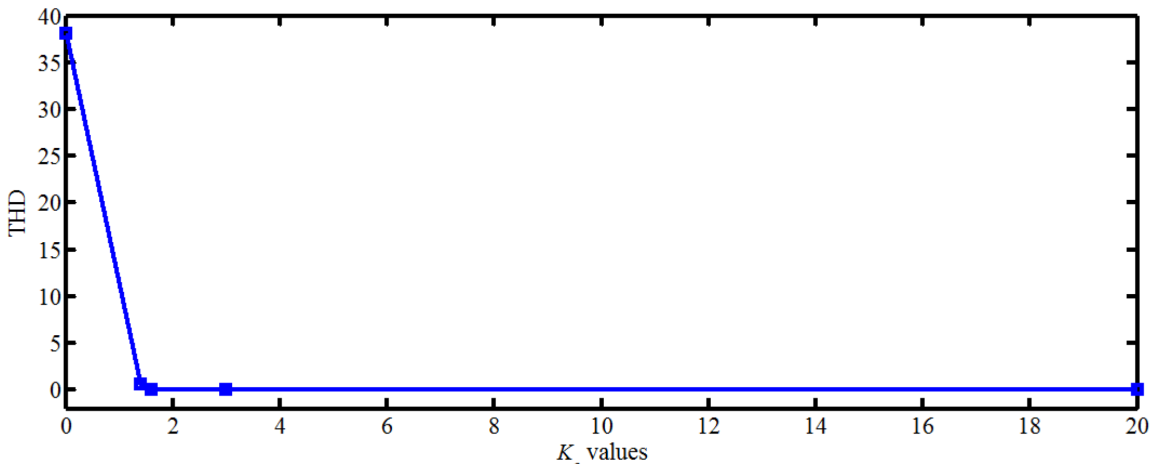

Fig 3.23 Variation of THD with inner-loop gain K_C for the values in Table. 3.2

With the increase in the inner-loop gain $K_{C,}$ the THD starts reducing until we reach a value of 1.4. From thereon, the THD is more or less constant with minute increase beyond 3.

3.2.1 Effect of Variation of THD Level on the Performance of P Controller

In this section we are going to investigate the effect of variation of the THD on the disturbance reference tracking capabilities of the P controller. We shall select our most optimal gain i.e., K_p =

1.63 and K_C = 3.2 and then choose different values of grid THDs to try to understand the behavior of the THD on our controller.

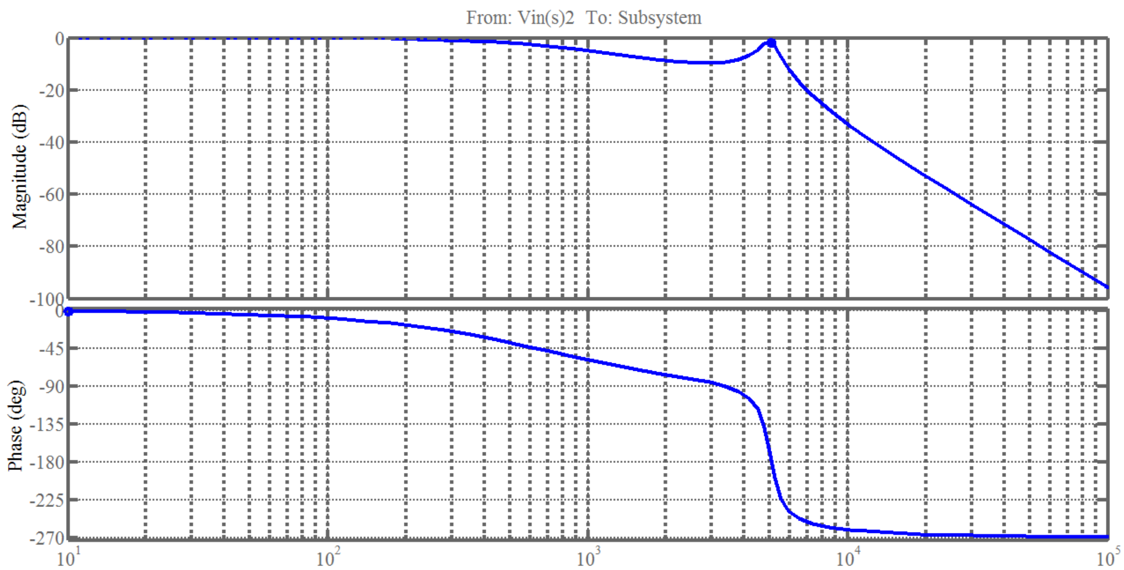

Fig 3.24 The reference tracking capability of the controller for input THD=0.5 % with inner-loop gain K_C = 3.2 and K_p = 1.63

The above graph gives a G.M of 1.9 dB and P.M of -180° and system is stable.

3.3 Proportional Integral (PI) Controller

The proportional gain K_p and integral gains are being varied. With the increase in K_p and K_i beyond the value of 1, the gain margins and phase margins are diminishing. The best performance of the controller is found at the value of 1.65. So, basically the range between 1-1.65 is a suitable range for our system with the parameters we are using.

Table. 3.4 Effect of variation of proportional K_P and integral K_i gains on THD

S.No	K_p	K_I	Gain Margin (dB)	Phase Margin (°)	THD	Stable
1	1	1	10.7	88.8	2.965	Yes
2	2	2	4.68	87.4	6.027	Yes
3	3	3	1.16	85.9	29.65	Yes
4	3.4	4	0.0726	1.92	45.81	Yes
5	3.5	4	-0.179	-3.9	18150	No
6	2.8	2.8	1.76	86.2	16.95	Yes
7	1.65	1.65	6.35	87.9	4.606	Yes

This table should also be seen in the perspective that we are trying to prove that the classical controllers lack the ability to control the sinusoidal signal. So Table 3.2 only proves what has been said and therefore this lack of robustness in simulation means that it would be totally unfeasible for it to work in a practical environment with mechanical disturbances as well which have not been considered along with environmental and other types. For $K_p = K_i = 1$, the output is under-damped and so the value of I_2 is over-exceeding the value of the reference current. The value of THD is less so the disturbance rejection is good. For $K_p = K_i = 2$, the output signal is over-damped and also the THD has increased. For $K_p = K_i = 3$, the controller is only able to follow the reference for the first cycle and when a higher order disturbance enters the system at the beginning of the second cycle, the controller totally fails and adopts a sort of brute-force suppression that makes the output useless. For $K_p = 3.4$, $K_i = 3$, we have reached the upper limit for the gains and we should try to work within this range rather than trying to go beyond. The most optimal gains give a good reference tracking, but the gain margin offered is very less and also THD in the output should also ideally be non-zero.

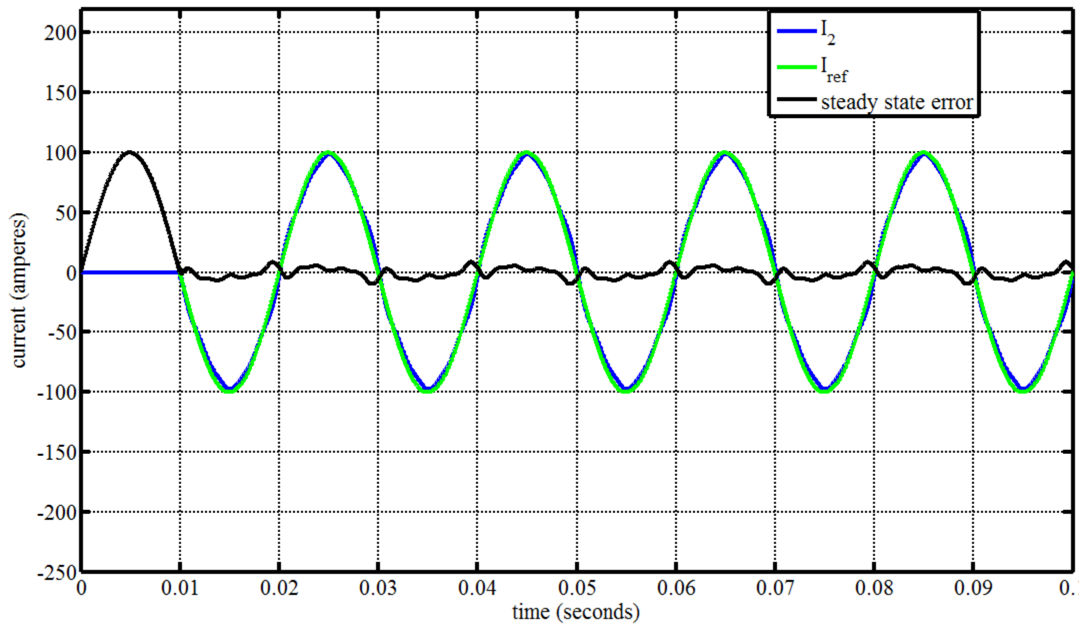

Fig 3.25 Output current w.r.t reference current for optimal gains

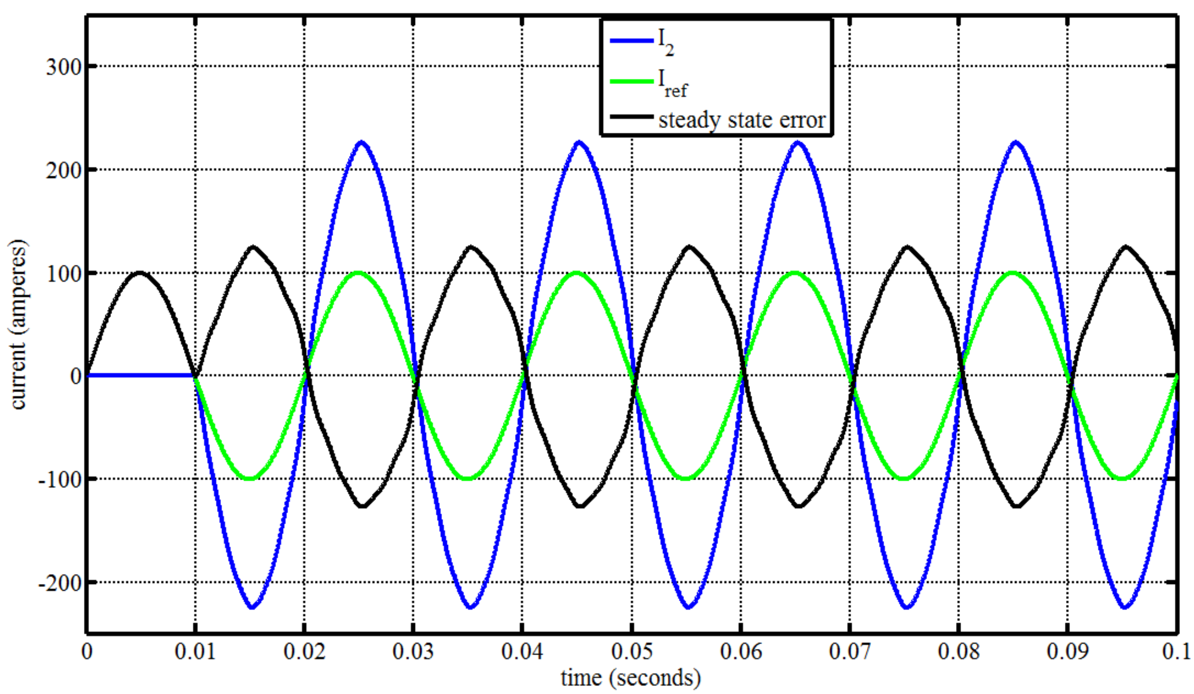

Fig 3.26 Output current w.r.t reference current for $K_p = K_i = 1$

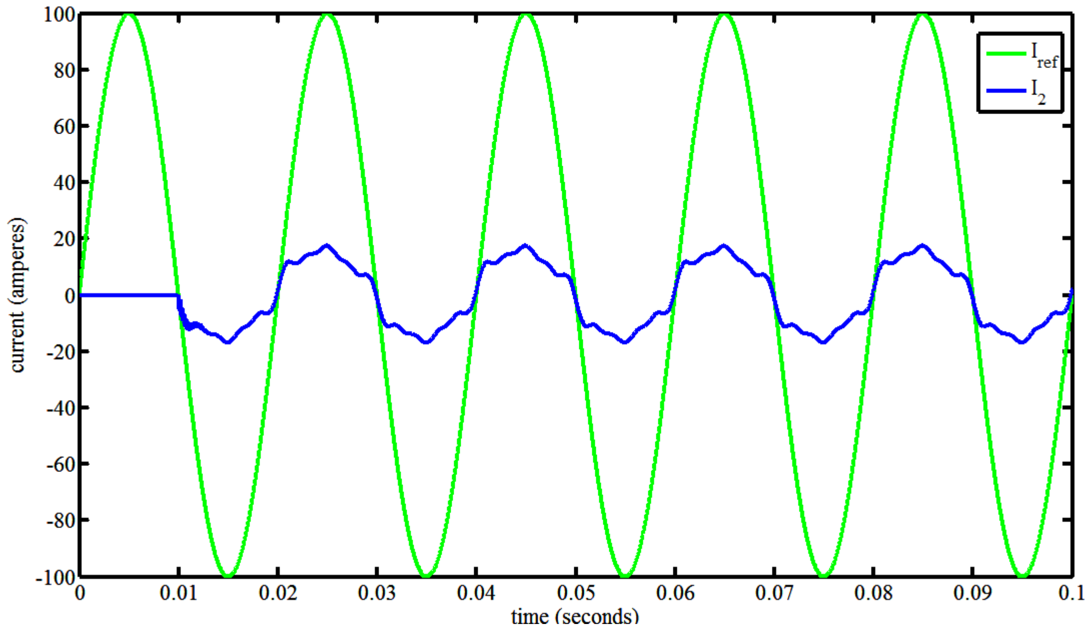

Fig 3.27 Output current w.r.t reference current for $K_p = K_i = 2.8$

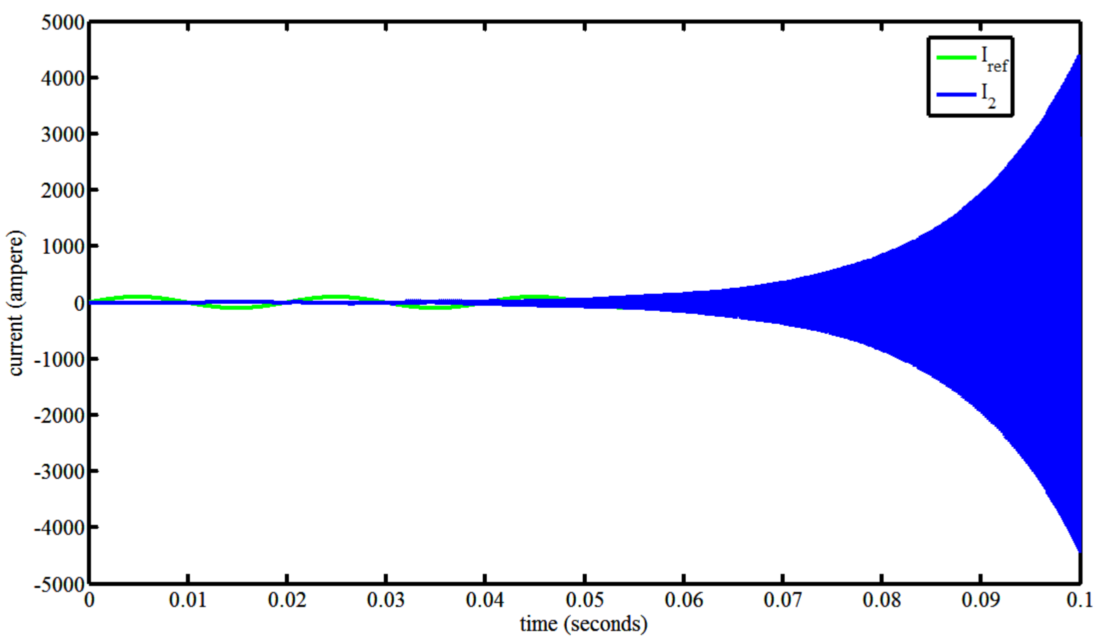

Fig 3.28 Output current w.r.t reference current for $K_p = 3.5$, $K_i = 4$.

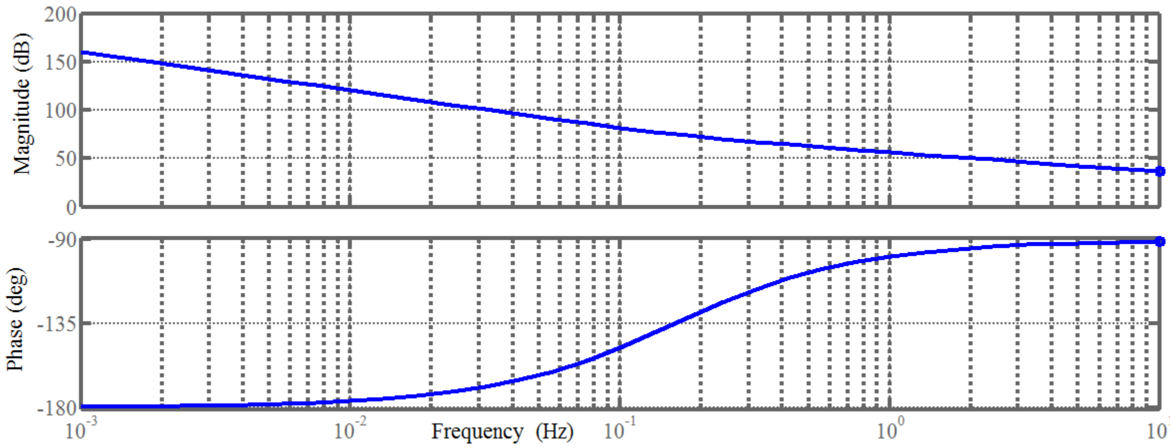

Fig 3.29 Bode plot showing the response of I_2 w.r.t I_{ref} for the optimal gains $K_p = K_i$ =1.65.

Chapter 4: LQR Controller

4.1 LQR Controller

A linear quadratic problem is one involving a set of ordinary differential equations (ODEs) used to represent a dynamic system and a quadratic cost function to optimize the solution. In this technique we want to reduce the value of the cost function based on some control law, whereas the weights of the cost function are selected by the user. The cost function is the mean square error (MSE) of the different values of the estimated values of the system. LQR involves repeated iterations and can be done effectively involving a computer. The engineer has to select the weighting factors and observe the performance against those weights to select optimal weights. This technique involves repeating the same steps again with slight modification of weights so that user can identify some optimality bounds keeping in view some desired constraints. In a layman language LQR is iterative application of a state-feedback method to find the best possible gains. We have also implemented the Linear Quadratic Gaussian controller and attempted to compare its performance with the controllers that have already been implemented. LQR is an optimization controller and is based on the optimization of the cost function.

State-Space Representation $\dot{x} = Ax + Bu \text{ and } y = Cx$ (25)

Cost Function $J = \frac{1}{2}\int_0^\infty (x^T Q x + u^T R u) dt$ (26)

Control input $u = -Kx = -R^{-1}B^T P x$ (27)

Modified State Matrix $A' = A - BK$ (28)

Algebraic Riccati Equation (ARE) $A^T P + PA + Q = PBR^{-1}B^T P$ (29)

The basic flow diagram of the LQR technique is as given in Fig 4.1

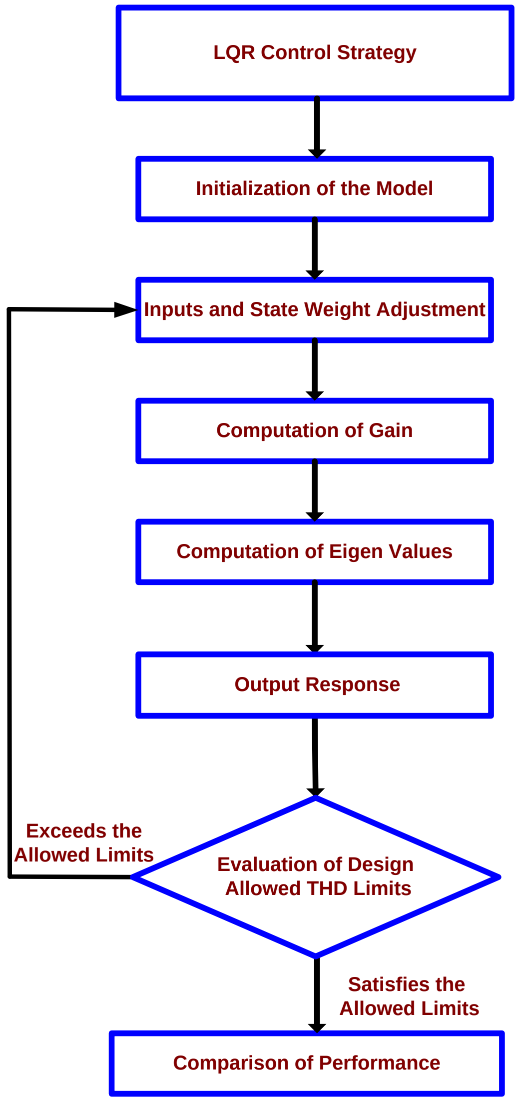

Fig 4.1 Flow diagram of LQR Technique

We are modifying the Q and R matrices to modify the behavior of the original system. For LQR we are taking the input THD to be 4.51%. The gain value of $Q = [0.5\ 0\ 0; 0\ 135\ 0; 0\ 0\ 1e6]$ has found to be the most optimal. Q defines the weight on the state and R defines the weight on the control input. Q is positive semi-definite while R is positive definite. LQR is also useful for assessing performance in terms of user-defined criterion. To implement it, we have to write the state-space representation of the system and to define the states.

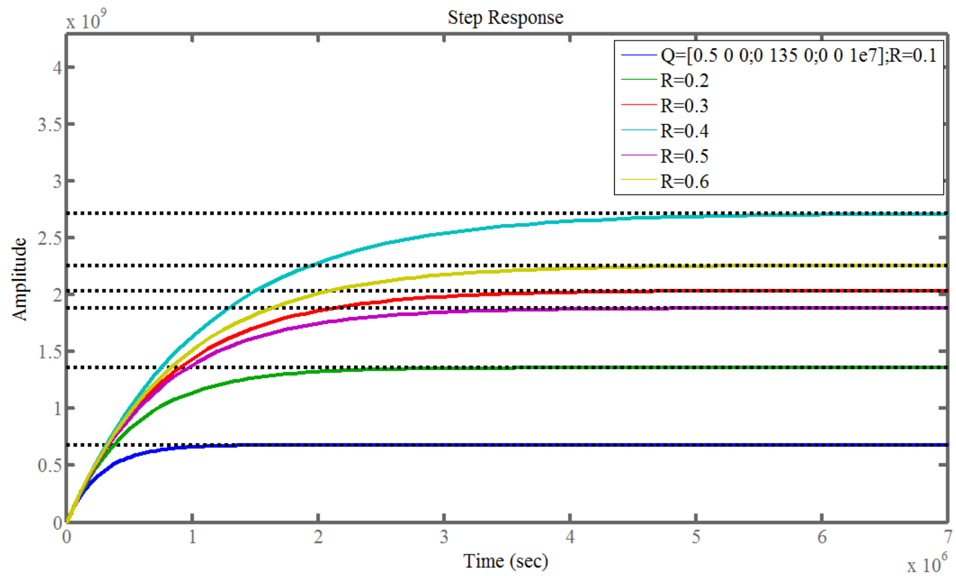

Fig 4.2 Effect of variation of R factor on system performance

Table. 4.1 Effect of variation of LCL parameters on system performance

R	Rise Time (seconds)	Settling Time (seconds)	Peak Response
0.1	$5.97x10^5$	$1.06x10^6$	$6.79x10^8$
0.2	$1.19x10^6$	$2.13x10^6$	$1.36x10^9$
0.3	$1.79x10^6$	$3.19x10^6$	$2.04x10^9$
0.4	$2.39x10^6$	$4.25x10^6$	$2.71x10^9$
0.5	$1.66x10^6$	$2.95x10^6$	$1.88x10^9$
0.6	$1.99x10^6$	$3.54x10^6$	$2.26x10^9$

We have seen that conventional controllers have some limitations when it comes to disturbance rejection at odd multiples of the fundamental frequency. In order to reject the harmonics, LQR has proved to be a better choice. We can easily convert the transfer function into state space by using tf2ss command in matlab.

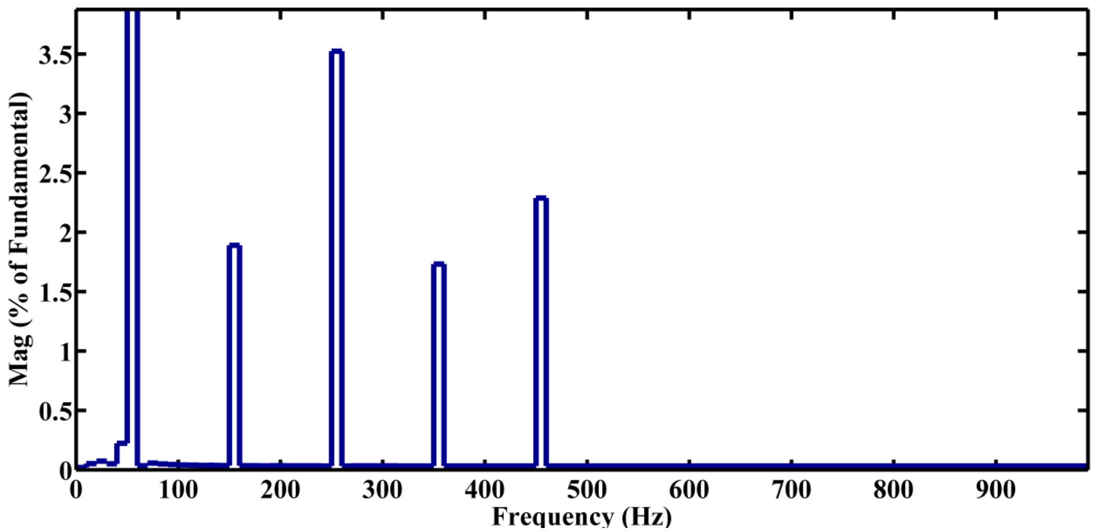

Fig 4.3 Frequency spectrum of LQR having grid THD 4.51%

From Fig. 4.3, we can see that the LQR has reduced the THD to 4.51 % by iterative operation. The point to keep in mind is that gain selection of LQR is a trial and error process and there is no shortcut to finding the optimal gains. We can achieve better disturbance rejection beyond 4.51%, but this will result in higher gains, which can lead to system instability.

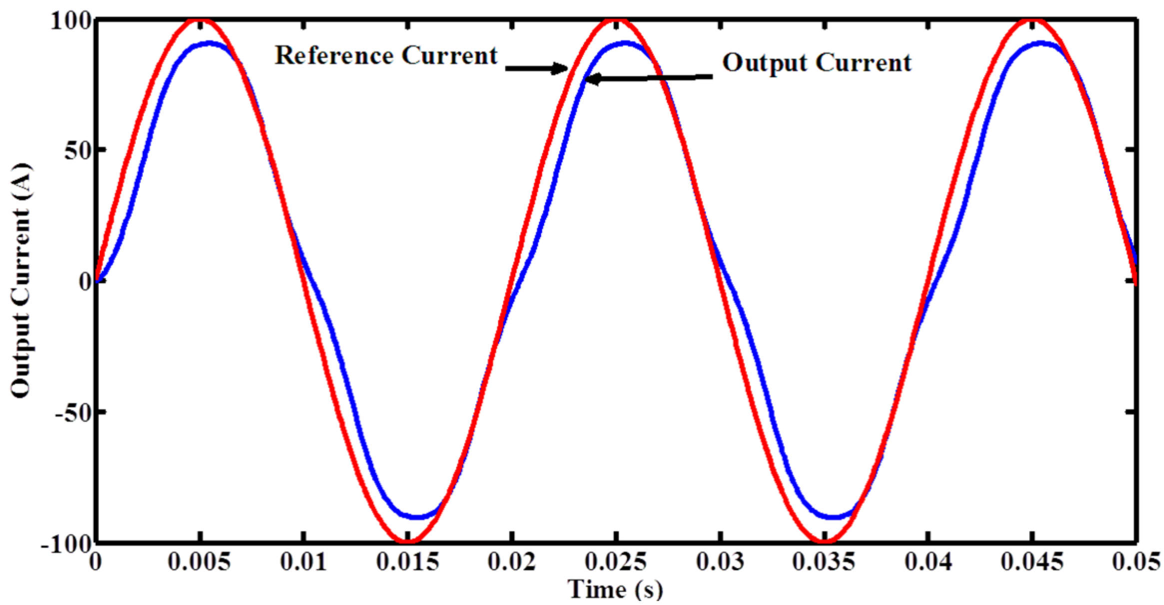

Fig 4.4 Output current of system having HD of 4% at 50 Hz.

4.2 CONCLUSIONS

We can use the proportional and proportional integral controllers under utility THD below 5% for certain gains. But even in the range of gains that has been explored in this text, the controller performance is limited. In practice for residential roof installed PV systems the PCC is considered to be the customer-side distribution panel [47]. This activity has been performed for the investigation into the performance of the current-controlled two-level grid connected converter. The frequency response of LQR showed that its performance was better than classical controllers in terms of timely disturbance rejection.

Chapter 5: Conclusions and Future Recommendations

5.1 Summary of the Thesis

The objective of this research has been to investigate the limitations of the classical controllers with a special focus on Proportional (P), Proportional Integral (PI) and Linear Quadratic Regulator (LQR) controllers. The work done can be distributed into two parts (i) analysis of performance of P/PI controller for LCL filter based two-level gird-connected converters (chapter 3) (ii) analysis of performance of LQr controller for LCL filter based two-level grid-connected converters (chapter 4) controller. Chapter 1 gives an idea about the background and scenario in which the importance of two-level grid-connected converters has been highlighted and the shortcomings and existing work that has been done and is an area on ongoing research. Chapter 2 is a literature review which covers the existing standards in detail and the factors that are of importance in ensuring quality grid-connectivity. Also a few control techniques that are followed by the existing converters have been mentioned. The concept of smart grid has been explained and what are advantages/disadvantages and the technological aspects required for the implementation of this technology has been discussed. Chapter 3 delves into the mathematical modeling, system modeling and control techniques that are applied to our system and comparative analysis of the different techniques and their optimal range of performance. The effect of LCL filter parameter variation on system stability has also been touched on. Chapter 4 deals with the performance of the LQR controller and its performance w.r.t proportional and proportional integral controllers. Chapter 5 gives future recommendations and concludes the thesis.

5.2 Future Work and Recommendations

Also the controller which can be used for future endeavors and has been greatly mentioned in literature is the repetitive controller, which employs a causal filter and some clever mathematics to track and reject a periodic steady state error. The performance of harmonics and disturbances has been seen to greatly reduce within a few cycles of the controller performance, until the error converges to zero. Also interleaved controller is an interesting topology that can be used instead of the two-level strategy. Another idea which can be explored and is very novel is the effect of ensuring maximum power transfer by matching the LCL filter impedance with the grid impedance. The grid has fixed impedance owing to inductive reactance of the transmission lines. The effect of THD due to variation in the reactance could be studied as to find a certain range of optimality in terms of grid impedance to be used as a standard. LQR controller has also been applied and has proved to be sufficient for controlling the system, but has not any significant advantage over the previously mentioned techniques. The application of controllers in the presence of variations in the input frequency is also another angle which can be explored as the repetitive controller in general has found to give degraded performance in the presence of this phenomenon. I have also personally experienced this with UPS systems that if they are being supplied by a generator and if the supply varies from 50 Hz by 5% the UPS will shift to battery mode. This problem has been addressed on a theoretical level but still some issues exist when it comes to the practical implementation. The selection of other filters apart from LCL such as LCCL, active filters using operational amplifiers could also be explored to check for performance gains that can be had.

5.3 Conclusion

We studied the effect of gain on the open-loop root locus plot and also the effect of the inner-loop gains on system stability. The classical controllers like P/PI were simulated and simulation results showed that it is difficult to produce output current satisfying IEEE standards when the input THD is high. To control the output current of the GCI in the presence of grid harmonics is a challenging task as the harmonics are present at the multiples of the fundamental frequency and they have different magnitudes at them. A smart controller is therefore required that can firstly detect the harmonics present in the output current and then also mitigate these harmonics within the required time. As nyquist’s criteria states that to accurately sample a signal, the sampling frequency must be at least two times greater than the highest frequency component that exists within the signal. In our case we must not only detect the harmonic but also compensate it, because if we delay one cycle the overall system will be delayed and this will cause the system to be very slow and inefficient. Since the control being achieved by the proportional P and proportional integral PI controllers are highly dependent on the gain values being chosen, we have attempted to find the optimal gains. The optimal gain for proportional controller is 3 which give a gain margin of 6.46 dB along with a phase margin of 88°. Higher gain margins were observed by increasing the gain beyond the optimal value, but the phase margins were reduced and also the output signal was lagging the reference sinusoid. The inner-loop gain also provided damping to the system and was instrumental in achieving more negative poles, thereby ensuring system stability. Here we have greatly simplified the system by approximating the linear model, but for a more real estimate the three-phase non-linear model should be used. When we used PI controller, we found that the optimal gains were found at 1.65, where we are getting a gain margin of 6.35 dB and a phase margin of 87.9 °. When we used the Linear Quadratic Regulator (LQR) technique, we achieved an output current having a THD less than 4 % in the presence of grid harmonics.

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Appendix

Positive Definite Matrices:

A symmetric matrix A is positive definite if for all vector x, $x^T Ax \geq 0$, and $x^T Ax = 0 \rightarrow x = 0$ or for all $x \neq 0, x^T Ax > 0$.

Note: $x = 0 \rightarrow \mathrm{x}_1 = \mathrm{x}_2 = \cdots \mathrm{x}_\mathrm{n} = 0$

Test 1: A is positive definite iff

$$a_{11} > 0, det \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} > 0, det \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{23} & a_{33} \end{bmatrix} > 0, \ldots \quad \text{(A.1)}$$

Test 2: The eigenvalues of A are all (strictly) positive.

Semi-Positive Definite Matrices:

A symmetric matrix A is semi-positive definite iff for all vector x, $x^T Ax \geq 0$.

Test 1: A is positive definite iff

$$a_{11} \geq 0, det \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \geq 0, det \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{23} & a_{33} \end{bmatrix} \geq 0, \ldots \quad \text{(A.2)}$$

Test 2: The eigenvalues of A are non-negative.