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Grid Connected Photovoltaic Systems with SmartGrid functionality

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Abstract

This thesis work is part of the NTNU renewable energy laboratory project, "Grid Connected PV Systems with Smart grid functionality". It solves the problem of shading to the available NTNU PV modules which is sensitive to the exiting central inverter system topology by proposing a PV system which is more efficient and reliable. This thesis is focused on the design of the PV-grid connected inverter power stage that supports the proposed PV system under study. As part of the NTNU renewable energy laboratory project, a single phase 1kW, 230V, dual power stage inverter is designed. The important parameters required for inverter stage including input inductance and capacitance, DC –Link capacitance and LCL filter were designed.

In chapters 1 to 2, the PV system overview and grid connected inverter technology is discussed. Photovoltaic characteristics that help the development of a proposed PV system are pointed out. The real scenario of the available NTNU PV system and the challenges facing its poor efficient to generate electricity is explained in Chapter 2. Chapters 3 to 4, present different topologies that are possible in the design of the power stage inverter of which full bridge converter topology is chosen due to its numerous advantages. The significance of dual stage and galvanic isolation to PV-grid inverters is depicted in chapter 3.

The energy conversion efficiency, maximum power point tracking, anti-islanding, power quality and cost have been mentioned in Chapter 4 as the most important criteria to be considered when designing any power stage inverter. In chapter 5 the parameters for power stage inverters are estimated and proposed. The boost inductor and input capacitor which are important components to voltage source inverter (VSI) are calculated. Switching scheme and the L-C-L filter is proposed to give a clear sinusoidal output phase voltage of 230V from a DC capacitance bus estimated to handle 400V. The parameters are designed in Multism / NI LabView and the desired output simulation results are discussed in Chapter 6.

Lastly, the conclusion of this thesis is made and proposes the scope of the future work. This is the next part of the NTNU renewable energy laboratory project. The proposed control schemes would compromise with the inverter power stage and would results in the smart grid system. The proposed control shall be able to integrate the available renewable energy sources available in the laboratory and shall be implemented in NI LabView.

Declaration

I hereby declare that, the work in this thesis is my own and has not been submitted for any other degree or examination in any University. In cases where other people's ideas in the literatures have been used, acknowledgement and complete reference has been made.

…………………………..

Henry Massawe

25th June, 2013
NTNU-Trondheim

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Acronyms

NTNU	Norges teknisk-naturvitenskapelige universitet.
PV	Photovoltaic
DC	Direct Current
AC	Alternating Current
IEEE	Institute of Electrical and Electronics Engineers
IEC	Electro technical Commission
NEC	National Electrical Code
MPPT	Maximum Power Point Tracking
MCB	Miniature Circuit Breaker
STC	Standard Test Condition
PC	Personal Computer
DSP	Digital Signal Processor
CCM	Continuous Conduction Mode
NI	National Instruments
CSI	Current Source Inverter
VSI	Voltage Source Inverter
IGBT	Insulated Gate Bipolar Junction Transistor
MOSFET	Metal Oxide Semiconductor field Effect Transistor
FACTS	Flexible AC Transmission
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
HF	High Frequency
LF	Low Frequency
PCC	Point of Common Coupling
I T	Information Technology
RMS	Root Mean Square
THD	Total Harmonic Distortion

Chapter 1

Smart Grid connected Inverters and PV systems Overview

1.0 Introduction

This chapter gives an overview of grid connected inverters and the PV systems. Grid connected technologies have been discussed. The important solar characteristics in relations to temperature and irradiance and how the open circuit voltage is affected are depicted in the chapter. Standards to design and installation practices of PV-grid connected systems discussed in this chapter play the significant role at the point of common coupling. These standards helped in the development of the proposed PV system.

1.1 PV inverters and smart grid

Photovoltaic (PV) power supplied to the utility grid is gaining more and more visibility, while the world's power demand is increasing. Solid-state inverters have been shown to be the enabling technology for putting PV systems into the grid [1]. Integration of PV power generation systems in the grid plays an important role in securing the electric power supply in an environmentally-friendly manner [3].

Grid-connected PV System comprises of PV panel, a DC/AC converter that capably connected to the grid. This system is used for power generation in places or sites accessed by the electric utility grid. If the PV system AC power is greater than the owner's needs, the inverter sends the surplus to the utility grid for use by others.

The utility provides AC power to the owner at night and during times when the owner's requirements exceed the capability of the PV system [9]. Depending on the application and requirements PV system can either be a stand alone or hybrid system.

The concept of smart grid is introduced in PV systems [18] depend on different ways of power utilization in the future. A smart grid construction with more strength and higher efficiency in power utilization is on schedule worldwide.

Due to a large amount of new technologies and service will be raised, updated or replaced in smart grid from traditional power grid, a framework of the whole smart grid structure become necessary for the huge costly deployment, as well as the characteristics and functionalities. Smart Grid is a large and complicated concept which is still holding debate on its definition because of the expected emphasis addressed by each participant

1.2 Photovoltaic system overview and inverter sizing

Generally the PV system comprises of PV generator which is a set of series-parallel electrically interconnected solar panels. PV panels are delivered by the manufacturers and are given in terms of the nominal peak power of the panel at standard test conditions (STC). PV generator gives the total installed power which is the sum of nominal peak power of each solar panel present in the PV installation [15]. This PV generator is connected to an inverter which connected to an AC/DC load and/or grid.

The grid-connected inverter must be designed for the peak power and must obey conditions that deal with issues like power quality, detection of islanding operation, grounding; MPPT and long-life [14]. Inverter maximum power is exactly referred to the total installed power of the PV generator and has to optimize the energy injected to grid.

Since the expected irradiance in the physical location of the PV installation is lower than the nominal or standard one, a current practice is to select the inverter maximum power than the nominal peak power of the PV generator. This practice is what is known as under sizing of the Inverter and has been discussed in [14] [15]

The nominal power of the PV generator corresponds to standard irradiance conditions. However this irradiance is unusual. Under low irradiance, a PV array generates power at only a part of its nominal capacity and the inverter thus operates under part load conditions with lower system efficiency [14].

Despite of the irradiance level affecting the PV generator characteristics, it is also important to consider the effects of temperature when selecting inverters. The two factors contribute to inverters maximum power and efficiency at the time of design and sizing.

1.3 Photovoltaic characteristics

Voltage and Current outputs of the PV modules is affected by temperature and irradiance [5]. Power electronics components of a photovoltaic system, such as grid-direct inverters have maximum and minimum voltage inputs. During rating of power electronics equipment, these variations should be taken into account especially for the MPPT range of inverters.

1.3.1 Open Circuit Voltage and Temperature

A PV module's voltage output is actually a variable value that is primarily affected by temperature. The relationship between module voltage and temperature is actually an inverse one. As elaborated in Fig.1.1 the module's temperature increases, the voltage value decreases and vice versa. It is important to put into consideration the cold and hot temperatures during PV design as shown in PV calculations in [13] [24] [25]. If the temperature of the module is less than the STC value of 25°C, the module's open circuited voltage, V_{oc} value will actually be greater than the value listed on the module's listing label.

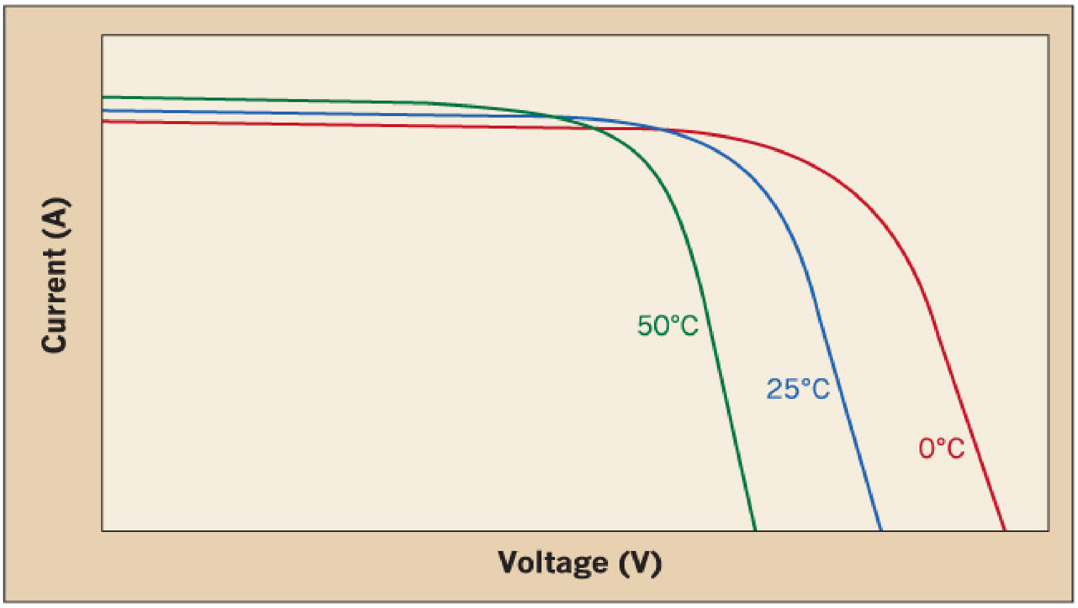


Fig.1.1: Current and Voltage characteristics of a PV module with temperature variation [13]

PV module manufacturers will report the amount of change their modules experience in the form of temperature coefficients, most often in terms of a percentage per degree Celsius. For example for BP solar modules at NTNU, the open circuited voltage temperature coefficient is $-0.086/^{o}C$. This means that for every degree change in temperature, the module's open circuited voltage, V_{oc} will change in the opposite direction by 8.6%. For example, if the PV module got colder by 1°C, the PV voltage would increase by 8.6%. [13], [24] [25]

To illustrate this phenomenon, let's consider the worst case of temperatures recorded in [44] it shows for the data recorded the average maximum temperature was 14.4°**C** with irradiance of 123W/m^2 h in the month of August. On the other hand the minimum average temperature was obtained in January and the data recorded was -3.4°C with irradiance of 18W/m^2 h.

The formula in [24] [25]can be used to determine the averaged maximum and minimum voltages of the modules at these temperatures. Since the string voltage in this design will have a voltage, V_{oc} is obtained to be 300 V. If we assume the working environment of the PV modules as recorded in [22], the working temperatures of the modules are assumed to be from -20°C to 40°C.

$$V_{oc} = V_{oc\_STC} - [\gamma * (T - T_{STC}) \qquad (1.1)$$

Therefore using equation 1.1 for the worst environment conditions we have the minimum and maximum open circuit voltage as 296.13V and 301.29V respectively. This gives the voltage change of approximately to $\Delta V = 5V$.

1.3.2 Module Current and Irradiance

The amount of current produced by a PV module is directly proportional to how bright the sun is. Higher levels of irradiance will cause more electrons to flow off the PV cells to the load attached. However the amount of voltage produced by the PV module is affected by the irradiance value, but the effect is very small.

As demonstrated in Fig. 1.2 the PV module's voltage changes very little with varying levels of irradiance. In the modules used in the NTNU façade system, the BP solar module has coefficient of current of +0.0025 A/ ^{o}C [22]

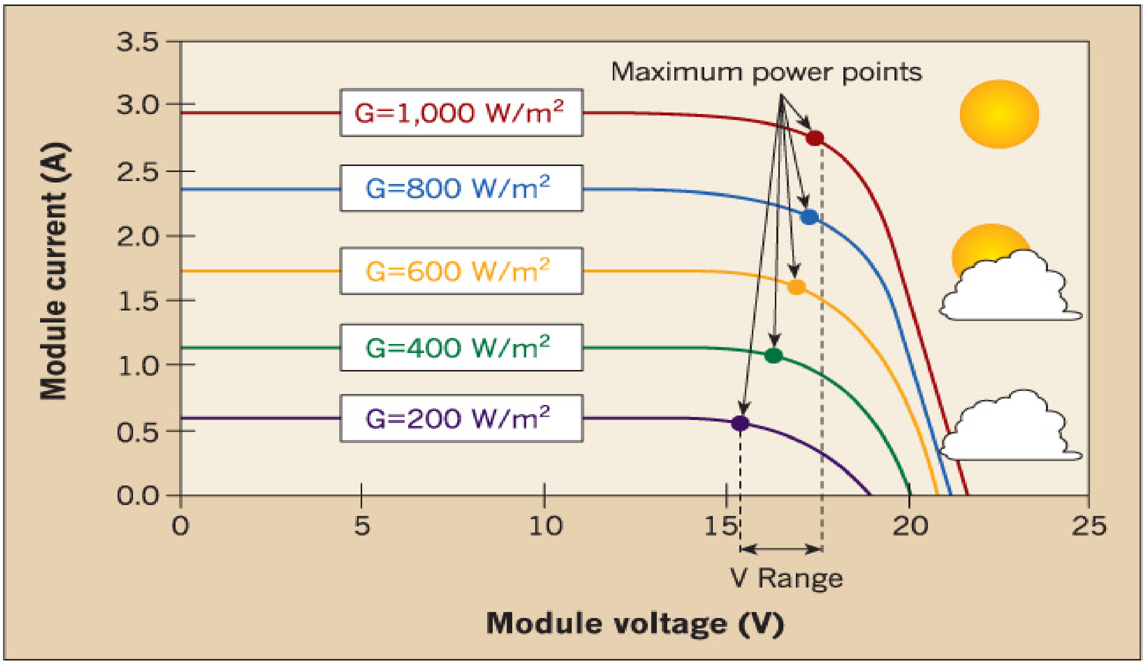


Fig.1.2: Current and Voltage characteristics of a PV module with irradiance variation [13]

1.3.3 Maximum Tracking Point (MPPT)

Many MPPT methods have been reported, such as perturb and observe, incremental conductance, neural network based and fuzzy logic control as it has been said in [7], [10] [12]. Together with the efficiency, each method has its advantage and disadvantage.

These approaches have been effectively used in standalone and grid-connected PV solar energy systems and work well under reasonably slow and smoothly changing illumination conditions mainly caused by weather fluctuations, seen also in [5] [10].

In order to utilize the maximum power produced by the PV modules, the power conversion equipment has to be equipped with a maximum power point tracker (MPPT). This is a device which tracks the voltage at where the maximum power is utilized at all times.

It is usually implemented in the DC-DC converter, but in systems without a DC-DC converter the MPPT is included in the DC-AC inverter control [7]. MPPT will ensure that, PV modules operate in such away maximum voltage, V_{mp} and maximum current, I_{mp} of the modules will be attained and produce maximum power, P_{mp} point.

However these values together with short-circuit current, I_{sc} and open circuit voltages, V_{oc} as illustrated on the Fig.1.3 are specified in the PV module data sheet of attached to it. The values are at standard test condition (STC) and they are called PV performance parameters.

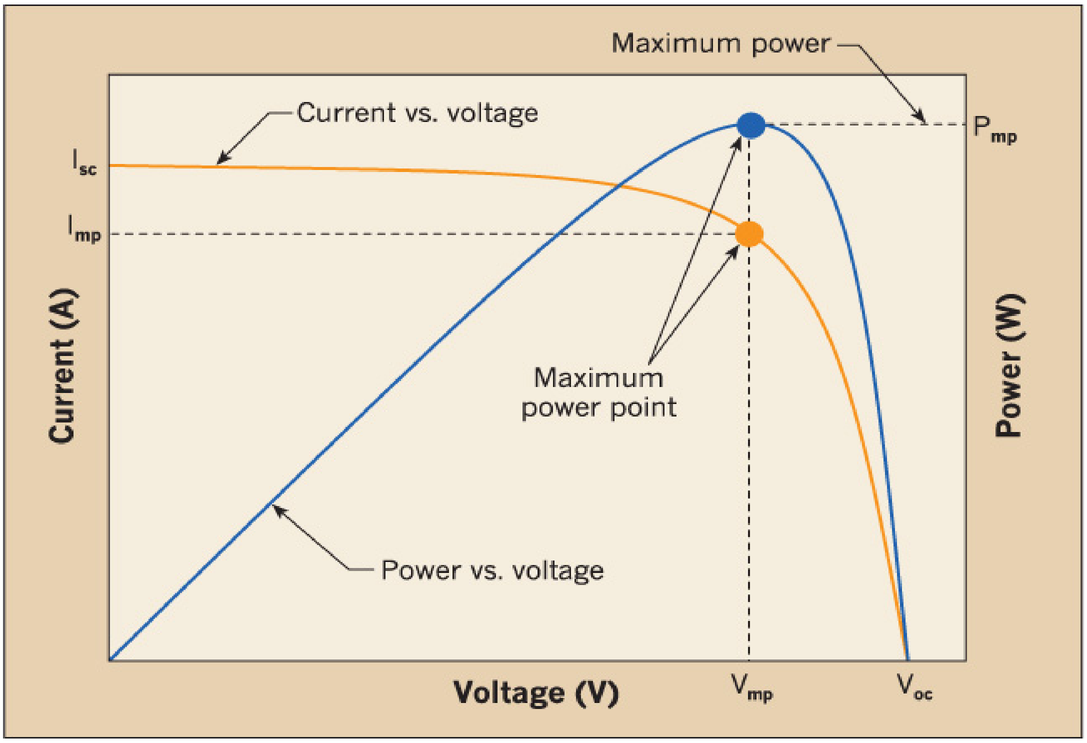


Fig.1.3: Current, Voltage and Power characteristics of a PV module [13]

1.3 Topologies of Grid Connected PV systems

Inverters are very important power electronics equipment in grid connected PV systems. Their major role is to convert DC power into AC power. Furthermore inverter interfacing PV module(s) with the grid ensures that the PV module(s) is operated at the maximum power point (MPPT) [1].

Based on the photovoltaic arrays output voltage, output power level and applications, the photovoltaic grid-connected system can adopt different topologies. These configurations describe the evolution of grid-connected inverters as from past, present and future technologies.

1.4 Grid –Connected Inverters Technology

There are different technologies and topologies available for grid connected PV systems which are categorized based on the number of power stages. In PV plants applications, various technological concepts are used for connecting the PV array to the utility grid. Each technology has its advantage and/or disadvantages compared to other, interns of efficiency and maximum power point tracking.

1.4.1 Centralized inverters

This is the past technology as illustrated in Fig. 1.4(a) was based on centralized inverters that interfaced a large number of PV modules to the grid. The PV modules were divided into a string, each generating a sufficiently high voltage to avoid further amplification. These series connections were then connected in parallel, through string diodes, in order to reach high power levels [1]. For this architecture, the PV arrays are connected in parallel to one central inverter.

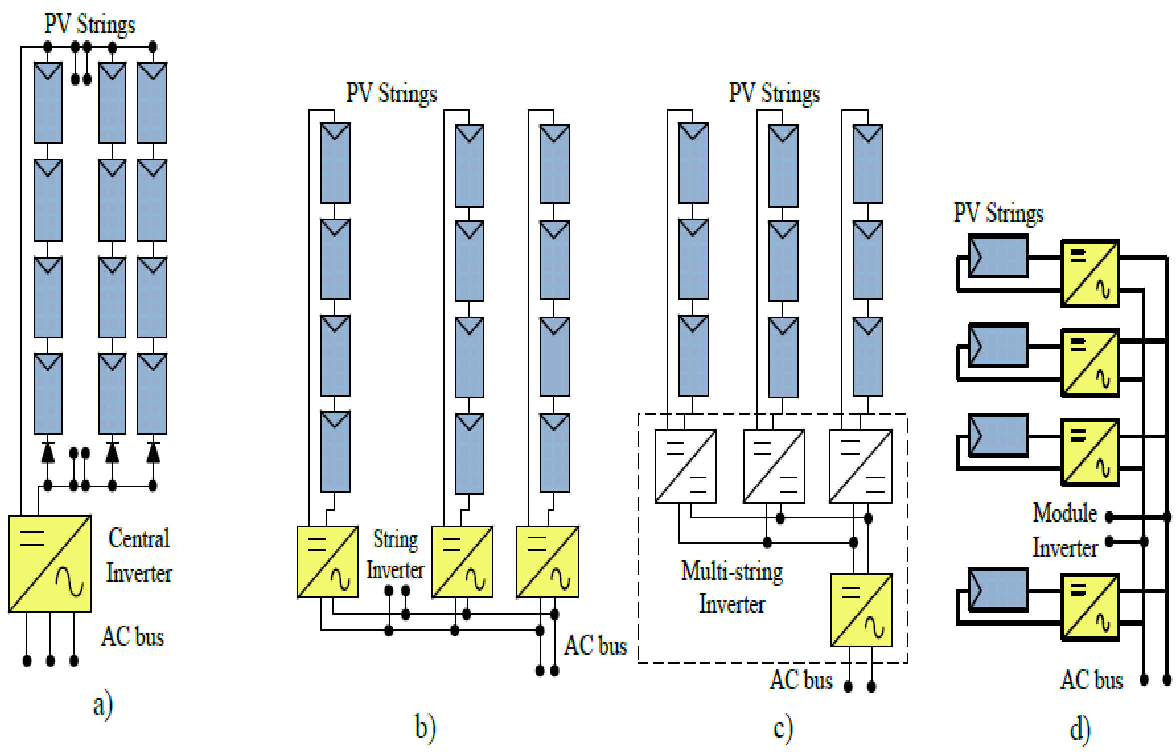


Fig.1.4: PV grid connected systems configurations a).Central Inverters; b). String Inverters; c).Multi-String Inverters; d). Module inverters [3]

The configuration is used for three-phase power plants, with power ranges between 10-1000 kW. The main advantage of central inverters is the high efficiency (low losses in the power conversion stage) and low cost due to usage of only one inverter. The drawbacks of this topology are the long DC cables required to connect the PV modules to the inverter and the losses caused by string diodes, mismatches between PV modules, and centralized maximum power point tracking [3] [7].

1.4.2 String Inverters

The present technology consists of the string inverters and the ac module. The string inverter, shown in Fig.1.4 (b), is a reduced version of the centralized inverter, where a single string of PV modules is connected to the inverter. The input voltage may be high enough to avoid voltage amplification [1]. This configuration emerged on the PV market in 1995 with the purpose of improving the drawbacks of central inverters.

Compared to central inverters, in this topology the PV strings are connected to separate inverters. If the voltage level before the inverter is too low, a DC-DC converter can be used to boost it. For this topology, each string has its own inverter and therefore the need for string diodes is eliminated leading to total loss reduction of the system.

The configuration allows individual MPPT for each string; hence the reliability of the system is improved due to the fact that the system is no longer dependent on only one inverter compared to the central inverter topology [3]. The mismatch losses are also reduced, but not eliminated.

This configuration increases the overall efficiency when compared to the centralized converter, and it will reduce the price, due to possibility for mass production [1] [7]. The photovoltaic modules in the given topology are linked in a structure whereby they end up forming a string; the voltage from the PV array ranges between 150-450 V [12].

1.4.3 Multi-String inverters

As this present and future topology, multi-string inverter configuration became available on the PV market in 2002 being a mixture of the string and module inverters [3]. The multi-string inverter depicted in Fig. 1.4(c) is the further development of the string inverter, where several strings are interfaced with their own dc–dc converter to a common dc–ac inverter. This is beneficial, compared with the centralized system, since every string can be controlled individually [1] [7].

The power ranges of this configuration are maximum 5 kW and the strings use an individual DC-DC converter before the connection to a common inverter. The topology allows the connection of inverters with different power ratings and PV modules with different current-voltage (I-V) characteristics. MPPT is implemented for each string, thus improved power efficiency can be obtained [3]. This gives a flexible design with high efficiency, and will probably become standard where centralized and string converters are used today [7].

1.4.4 Module Inverters

Module Inverters shown in Fig.1.4 (d) is the present and future technology consists of single solar panels connected to the grid through an inverter. A better efficiency is obtained compared to string inverters as MPPT is implemented for every each panel [3]. By incorporating the PV module and the converter into one device, the possibilities of creating a module based “plug and play” device arises, and it can then be used by persons without any knowledge of electrical installations.

In this configuration the mismatch losses between the PV modules is removed and it is possible to optimize the converter to the PV module, and thus also allowing individual MPPT of each module. Since there will be need for more devices then with the previous mentioned configurations, it will give the benefit of large scale production, and thus lower prices. On the other hand the input voltage will become low, requiring high voltage amplification, which may reduce the overall efficiency [1].

1.5 Standards and Codes for Grid Connected Photovoltaic system

There are several standards on the market dealing with the interconnection of distributed resources with the grid [7]. In this context PV system is of importance where all practice for wiring, design and installation has been explained. This thesis is limited to International Electro technical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE) and National Electrical Code (NEC).

Standards and codes governing the design of the proposed PV system at NTNU electro building is based on PV electrical installations practices and interfacing with grid. In the standard [13] IEEE 929-2000: Recommended Practice for Utility Interface of Photovoltaic (PV) Systems which gives the guidance to PV system practices. These practices include power quality and protection functions [26]. The IEEE 929 standard also containing UL 1741 standard which has been used as the key to select inverters used in this design.

The IEC standard has been discussed in [7] and they show to give out the characteristics of PV system and grid interface at the point of common coupling (PCC). National Electrical Code in article 690 Photovoltaic power systems [23] as well as explain in literatures [16] and [17] shows the necessity and important information for proper installation of PV system.

The 690 code explain most of the important information in both design aspects and installation. Some of this important information includes;

- PV system conductors and coding.
- Grounding system and Module connection
- PV source circuits, PV Inverter output circuits and circuit routing.
- Identification of equipment used and system circuit requirements i.e. Open Circuit voltage and short-circuit current.

Chapter 2

Existing Scenario of the PV System at NTNU Renewable Energy Laboratory

2.0 Introduction

In this chapter the statement of the problem and objectives of this work is pointed out. The methods to meet the objectives are outlined in this chapter. The significant and importance of this work is stated. NTNU PV system description and the desired system that suit the design of the inverter power stage is proposed later in the chapter.

2.1 Project description

At NTNU a laboratory for renewable energy is under construction. This lab emulates several different renewable energy sources connected together. The power from the PV panels mounted outside on the building will be available for connection in the laboratory. A survey of control structures for the inverter when used as a grid connected PV inverter will be made. Based on this a suitable control will be chosen, which will include methods for grid synchronization, maximum power utilization, anti-islanding and current/voltage control.

System models must be developed, which shall form a basis for controller parameter estimation. In the project the instrumentation system for collection of operation information of the PV plant into a database will be designed based on EtherCAT network. The purpose of this database is to collect and archive performance, reliability and operating cost data for this PV based distributed power systems.

This thesis focused on the design of the single phase converter power stage. Important parameters for the inverter stage will be proposed. The converter is designed in Multism and implemented in LabView for the control of the output and user interface. The remaining task to accomplish the whole NTNU project in this laboratory will be the proposal of the control system.

The control shall meet the system requirement and meet the proposed inverter power stage in this thesis. When required the prototype will be built after being satisfied with the performance on NI LabView after implementation. As an interesting idea, this thesis provides the room for using LabView to integrate with other renewable sources available in the basis of the suitable control systems that can be easy implemented in the software.

2.3 NTNU Photovoltaic System

The installed PV system is located at O.S. Bragstads plass 2, Trondheim on the wall of electro- building in a vertical façade south oriented at the Norwegian University of Science and Technology. The system is 15kWp installed power and the modules are integrated in the double façade that follows the architectural criteria which covers an area of 455 square meters. Sixteen PV strings of five PV modules with sixty cells and ninety cells connected in series. The PV system that covers an area of 192 square meters is a result of these sixteen strings connected in parallel to a central inverter. [7] and [22].

Fig.2.1: O.S. Bragstads plass 2, with BP solar modules in a double façade [20]

The PV cells and the conduits are embedded in a resin layer in laminated glass modules. These modules are located outside the façade sections without windows. The cells used are of the high efficiency that maximizes the output power, mono-crystalline BP Saturn type, with an efficiency of about 16%. The PV cells generate low voltage direct current that is coupled to the building’s electricity supply via an inverter and a transformer [20]

2.4 NTNU Photovoltaic System Description

In the literatures [7]; and [22] at given standard test conditions (STC), with irradiance of $1kW/m^{2,}$ air mass (AM) of 1.5, and cell temperature of $25^{o}C$, PV string has the following electrical data.

Open circuit voltage	300V
Short circuit current	5A
Maximum power	910W
Voltage at maximum power	210V
Current at maximum power	4.3A

The NTNU photovoltaic uses a three phase 12kW central inverter connected to sixteen parallel PV arrays. This inverter is then connected to a 400VAC transformer to have isolation to the grid. The inverter is controlled by a digital signal processor (DSP). The inverter assembly is available for variety control, protection and data acquisition functions. In this system the user interface of the DSP and PC is done though the V.32 system. In addition the RS-232 is used to provide additional user interface for purposes of changing control and protective set points.

2.5 Problem Formulation and Identification

NTNU PV system is among the centralized inverter system topologies connected from single PV array resulted from parallel connected strings. This is Norway's largest solar wall and the only one of its kind. Although the solar façade is south facing, effects of occasional shading have had to be minimized to maximize electricity generation [19].

Plant-oriented configuration has observed to be one of the most popular PV grid-connected system's architectures due to its simplicity and low cost per peak kilowatt, and assumes a single PV array formed by parallel connection of strings which is linked to the grid through a single central inverter. The DC power extraction is carried out by the inverter input stage which is generally driven by a maximum power point tracking (MPPT) algorithm in charge to ensure the PV array operates at its maximum power point regardless of the environmental (irradiance and temperature) conditions explained in [4] [10].

Partially shaded of the PV array by clouds or by surrounding obstacles such as nearby buildings and trees, has been the major source of power losses in such architecture. These losses are mainly due to PV module failure or the electrical configuration of the PV array, in particular to the hardwired series connection of PV modules in each string since a partially shaded module limits the string current where it is connected, thus reducing the maximum available dc power of the PV array .

It is also stated in the literatures [4] [10], one of the strategies to improve DC power from a partially shaded solar array is to modify the power processing architecture. This approach improves the energy efficiency and the reliability of the PV system. The strategy is based on a previous association of the available PV modules in several independent PV arrays.

Each PV array is formed by the PV modules operating under similar environmental conditions to reduce the current limitation on the strings. In addition, the dc power is improved by a modified power processing architecture which shares out the maximum DC power extraction task among as many power processors as independent PV arrays.

Depending on the number of PV arrays as discussed in section 1.4; string inverters, module inverters and multi-string inverters are commonly available technologies of power processing architectures topologies supporting this strategy.

2.6 Thesis Objectives

2.6.1 Main Objective

This thesis work is based on the design of a high efficient and reliable grid-connected PV system from the façade structure in the NTNU laboratory. The aim is to study and design an inverter power stage that will be connected to the proposed PV system. This system is suitable for power supply and academic research purposes when integrated with other renewable energy sources available in the laboratory.

2.6.2 Specific Objectives

Specifically this thesis work aimed at:

- Propose the best and reliable grid connected PV system topology.
- Propose a grid connected inverter with high efficiency and availability.
- Design of 1kW single phase power stage inverter in Multism and LabView.

2.6.3 Significance of the thesis work

A conscientious thesis should have positive impact on society as an outcome. This work is going to benefit directly and indirectly in the NTNU academic society in the following areas:

i. The system will be applicable for power supply in the NTNU lab.
ii. Proposed topology will be used for academic research purposes.
iii. Explore the importance of NI Multism and NI LabView in PV systems design, control and implementation.
iv. Encourage the use of PV system as the best alternative energy source of electricity.

2.6.4 Methodology

To accomplish the objectives in this thesis the following methods are important;

i. Develop a suitable PV system that will meet the requirements of the designed inverter power stage.
ii. Design of the important parameters of the inverter power stage. These parameters include the design of boost inductor, input PV capacitor, DC link capacitor and the output filter.
iii. Design the suitable switching strategies that will give the desired voltage and current outputs.
iv. Analyze the power stage inverter in both Multism and LabView.

2.7 Proposed PV system Topology

In order to meet the objectives, the PV system deploys the string inverters topology due to its advantages over the central inverter technology as discussed in section 1.4. Based on the codes and standards, the proposed PV system consists of four inverter systems, three inverters will be tied to the grid and one inverter system is used for research purposes.

This inverter under researched PV string, which later its power stage inverter is designed, will also be used in distributed generation with others sources available in the laboratory and the resulted hybrid system will have smart grid characteristics. Each inverter proposed has independent MPPT for each PV string.

2.7.1 Strings electrical characteristics.

Proposed system has eight strings connected in parallel as shown in Fig. 2.2; each string consists of ten modules connected in series to give a nominal operating voltage of 420 VDC. A maximum current flow to each string is 5 Ampere. Therefore the total current flowing into the inverter will be the total from the parallel connected strings Voltage and current variation due irradiance and temperature have been taken into account in this design.

The open circuit voltage has chosen not to exceed 600 VDC under any conditions. As discussed earlier the voltage generated by PV modules is inversely proportional to the temperature at lower temperatures the PV voltage increases from the nameplate rating and at higher temperatures the PV voltage decreases from the nameplate rating. This voltage rating will help in safety to personal and protect the insulations of the equipments.

This proposed PV system configuration is important in the design of the power stage of the inverter. The output power rated will be assumed to be 1kW. This value is assumed as the worst case; hence the actual rated power from the string is 4.2kW for ideal PV system. Considering factors affecting power conversion from PV system this power would drop further to a value lower than the ideal rated power.

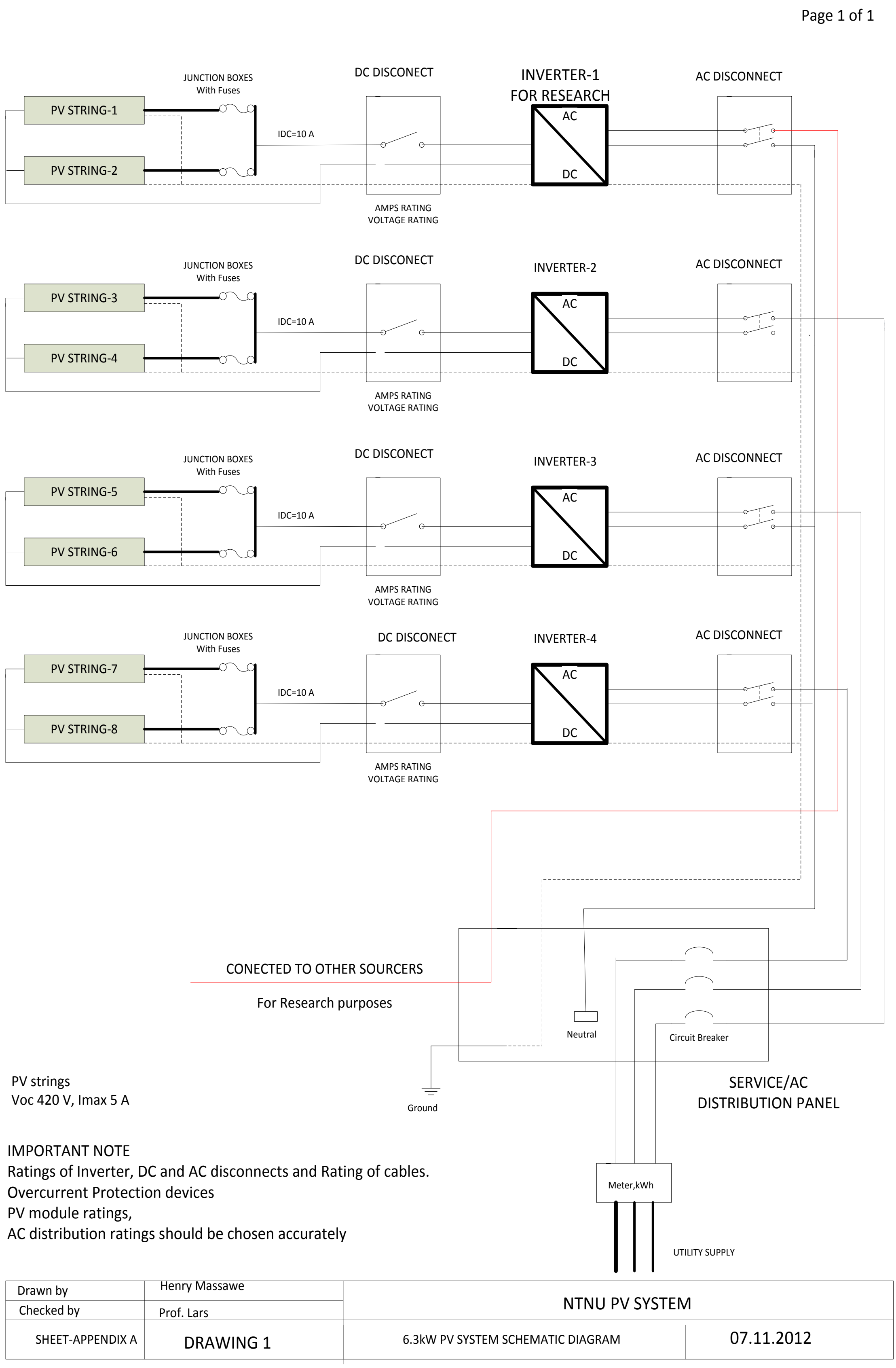


Fig.2.2: NTNU Proposed PV System

Chapter 3

Inverter Power Stage Topologies and Design Considerations

3.0 Inverter design considerations

There are many design considerations for one to develop inverters for grid connected photovoltaic systems. The design trade-off decisions are the key to implementing a successful system as well as achieving customer satisfaction. These key design considerations discussed in [8] and examined in more details in [27] includes circuit topology, conversion efficiency, maximum power point tracking, anti-islanding, power quality and cost. Similarly, for single phase grid connected inverters these considerations are essential and important to follow to achieve the best design.

Topology as being the first significant decision that an inverter designer must make is the choice of an overall circuit topology. The PV array voltage and utility grid interconnect voltage drive the topology selection. There can be wide DC input voltage variations resulting from various combinations of array power, temperature and module configurations. The primary topology consideration is whether or not to use a single stage or two stage single phase PV inverter topology [29].

Conversion efficiency of an inverter is a very important function of the DC operating point in any inverter. High efficiency is advantageous for all inverters utilized in photovoltaic systems. Every watt that is lost in the inverter is power that is not delivered to the utility grid. These losses affects on the efficiency of inverters. The primary method of increasing efficiency is through the selection of inverter components with a focus on their efficiencies.

As mentioned in [27] the key components for efficiency optimization includes transistor devices, magnetic, and parasitic loads. The selection of switching frequency is based on trade-offs between losses, magnetic component costs, power quality, cooling system requirements, audible noise, and equipment size and weight. Careful selection of components that present parasitic loads can significantly increase efficiency.

A key function that is integrated into the inverter system for photovoltaic applications is maximum power point tracking (MPPT). This algorithm operates to keep the system on the peak power point of the voltage versus current relationship of the connected PV array based on the array characteristics available irradiance and module temperature.

As pointed out in section 1.3.3 various algorithms for achieving this have been proposed and/or implemented including those in references [7] [10] [12]. Due to the nonlinearity of the solar cells with temperature and radiation, MPPT in the design of the PV system is essential to get as much as the power from solar cells. [29]

As explained in [27], another key aspect in the performance of grid connected PV systems is that the power injected into the grid must meet utility power quality requirements. These requirements are specified in the IEEE 929-2000 [21]**.** The primary trade-offs that drive power quality, once a topology has been selected, are the transistor switching frequency used and the output filter components. Higher switching frequencies result in higher power quality as measured by total harmonic distortion, total demand distortion and the levels of individual harmonics, for a given filter configuration. This is at the expense of higher switching losses.

The size of filter components is driven by the magnitude of the ripple current at the switching frequency. This ripple current decreases as the switching frequency increases. The quality of the power provided by the PV system for the on-site loads and the power delivered to the utility is governed by practices and standards addressing voltage, DC injection, flicker, frequency, distortion/harmonics and power factor. These parameters must, unless otherwise is specified, be measured at the point of common coupling [7].

Anti-islanding as being another considerably factor for designing of inverter as defined in [21] and [7] as an inverter that ceases to operate within a certain time after the islanding occurs. Islanding that happens when the grid line is in failure but the node of grid-connected photovoltaic system is still in operation, is hazardous to personnel and equipment and is required to be detected and prevented.

This is further explained in [27] the requirements given in the IEEE Std. 929-2000 [21] and UL 1741 Standards 151 define the inverter response to potential local islanding conditions when the utility is lost.

To meet these interconnect standards, an active method of anti-islanding must be employed. A number of methods have been described where a perturbation of power, current, or phase angle is employed to cause unstable operation in the absence of the grid.

All of the preceding design considerations are traded off with the cost of the equipment. In addition, ease of manufacture, production test costs and reliability considerations must be addressed. Any inverter must be designed for ease of assembly and testing. Low component costs alone will not insure a competitively priced end product. The manufacturing and test methodology must be considered at the beginning of the design process, not as an afterthought, in order to achieve the highest overall product value.

An inverter with a better reliability rating should theoretically be able to command a higher price than one with lower reliability. Under current market conditions it is unclear if an inverter with twice the guaranteed lifetime would be able to sell at anywhere near twice the price. As the inverter market matures and the total long-term system costs became more of a system design driver, high-reliability equipment should come of age. [27]

3.1 Dual and single stage PV inverter circuit topology

PV inverter circuit topology with DC-DC converter is termed as dual stage, and in this topology the DC-DC converter will handle the MPPT and some voltage amplification if needed [7]. As discussed in reference [29] to date, the single-phase grid-tied PV inverter has been constructed using either single-stage or two-stage topology as illustrated in Fig.3.1.

Single-stage topology Fig.3.1 (a) presents the most reliable and cost effective solution but with the operational limitation of minimum PV voltage being larger than the peak ac grid voltage in order to avoid the over-modulation operation resulting in the large series connection of PV panels which is unwanted from the optimal operation point of view and can be attenuated by connecting to a line frequency transformer. However this topology is bulky and less efficient.

Meanwhile the AC output power ripple which has double fundamental frequency oscillation unavoidably introduces the double-line-frequency voltage ripple unlike the balanced operation of maximum power point tracking as discussed in section 1.3.3. To minimize the DC voltage ripple and then enhance the solar energy transfer efficiency, a large value DC-link capacitor is normally employed, which however cannot fully eliminate this problem and leads to the increase of system size and cost.

Alternatively, a two-stage solution as shown in Fig.3.1 (b) consisting of DC-DC boost converter and DC-AC inverter can operate in a large range of PV voltage ensuring the proper PV energy conversion under wide operational range. Moreover, the inserted DC-DC converter decouples the direct connection of PV panel and ac output so that the ac output power ripple will not induce the double-line-frequency ripple of PV voltage.

The MPPT efficiency can then be enhanced by using a relatively small input capacitor to just attenuate the high frequency input voltage ripple in the DC-DC voltage conversion. Using a DC-DC converter in front, the efficiency of whole inverter would decrease since more passive and active components are involved in the energy processing when compared to the single-stage topology but when considering the improved MPPT efficiency and wide operation range the two-stage solution is superior to the single-stage inverter [27]. The concepts of single stage and two stage single phase inverters is also summarized in [1] and [32]

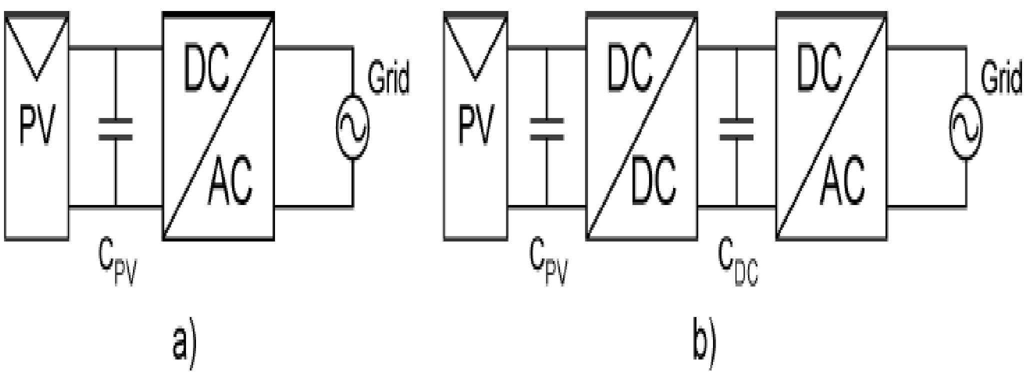


Fig.3.1: Single and dual stage inverter topology with coupling capacitances [1]

3.2 Galvanic isolated and transformerless PV inverters

Transformerless photovoltaic (PV) inverters are the major functional units of modern grid connected PV energy production systems. Transformerless topologies for PV inverters are the upcoming technology and there is more freedom in control [30] [31]. By comparing this type of topology with the grid-connected PV inverters with galvanic isolation, Transformerless PV inverters have the advantages of lower cost, higher efficiency, smaller size and lower weight.

Whenever galvanic isolation is not important, transformerless PV-inverters get more interesting [30] [31]. However in [31] transformerless inverter topology shows to have constraints due to system ground and ground leakage currents. Since this topology is the direct connection of the PV array to the grid without galvanic isolation, this may cause fluctuations of the potential between the PV array and ground [8] [32].

In this thesis, I will focus on galvanic isolation inverter topology. The available PV arrays at NTNU, needs voltage amplification and there is a need to have system grounding either at the PV array side or in the grid side. This galvanic isolation between input and output can be achieved by the use of transformers. According to [7] the transformer used in galvanic isolation circuit topology has two major functions in the circuit, to amplify the voltage and to gain galvanic isolation between the PV modules and the grid.

Transformers which are normally used in this topology operated at 50Hz or 60Hz grid frequency as applied in USA or Europe electricity systems respectively. This way of using transformer as galvanic isolation is described in [7] as low frequency (LF) transformer on the grid side. The problems of using this topology is high weight, high cost, additional losses and a non-unity factor under low load situation [31].

However to get rid of this problems the use of high frequency (HF) transformers is taking into account by embedded it in the DC-DC converter. The use of HF transformer as galvanic isolation makes the design simpler than when LF is used which is expensive, large and heavy.

3.4 DC- DC converter topologies

DC-DC converters have a wide range of uses today and are becoming increasingly more important in everyday use. DC power supplies are probably the largest use of the converters and are much more compact and efficient. There are three basic types of DC/DC converters [47] from which Cuk converters and Full bridge converters are derived from these converters. The inverters include;

i. The boost converter as a step-up converter is used for cases in which a higher output voltage than input is required;
ii. A buck converter as a step-down converter is used for cases in which a lower output voltage than input is required; and
iii. A buck-boost converter, which reduces or increases the voltage ratio with a unit gain for a duty ratio of 50%.

The power stage of grid connected PV inverter presented in this thesis uses full bridge switch mode DC- DC converter. The boost converter is the basic structure and the choice is made for worst case scenario when the PV array voltages will be very low, and therefore voltage amplification is important. The boost converter will also be important for MPPT control. The operations, application and characteristics of boost converter have been discussed in [47] as the fixed DC output voltage is always greater than the varying input DC voltage.

There are many topologies available for the DC/DC converter as in [47] and they can be used in single stage inverter circuit topology with no isolation. Each topology has its advantage and disadvantages when used. As explained in [47] duty ratio, switching frequency, voltage handling capabilities and switching power losses has been pointed out as challenges to each of the circuit configuration.

For single stages topologies and with low output voltages [7], fly-back converters, boost converters and Cuk converters have shown some challenges when used alone as converters. To handle 400DC which will give approximately 230 V AC voltage as an output to these converters, poor efficiency, switches to be on all the time, high current, large inductor is used and switching power losses are among the factors affecting the performance of these topologies.

On the other hand, when high voltage and galvanic isolation is needed there are other topologies that can be used to provide higher power. As discussed in [47] these topologies have a multistage operation. The multistage converter first inverts the signal to AC for use with a transformer, and then it converts back to DC voltage.

By using a high-frequency transformer it provides an efficient way to step up the voltage. The transformer uses different grounds, which allows both sides of the system to be electrically isolated. This line isolation provides continuous noise filtering from the noisy primary side signal. This noise filtering allows the reduction in the electrical noise emitted in high frequency circuits.

Topologies that handling high power as in the book [47] include push-pull converter, half-bridge converter and full bridge converters which will be discussed latter and is the key design circuit topology in the discussion. Push-pull converter has a configuration similar to the Full-Bridge but has two switches instead of four to cause a low switching loss. The transformer has an input and output center tap, which makes it a more difficult design to implement and hence, results in a higher cost.

Furthermore, in push-pull configuration the transformer will need larger windings on the primary side, which will increase the physical size and weight. The output inductance would need to be very large, which is not practical to implement into the design. Another disadvantage is that to other power electronics switches it may cause all switches to conduct at the same time.

This problem occurs when MOSFETs are used as switches in this design they may conduct simultaneously causing a short circuit in the control circuit. According to performance analysis conducted on this topology, the push-pull converter is highly efficient and has fewer switches, however the transient response would be poor and the transformer would be hard to manufacture in the design.

Another configuration to provide high voltages as pointed out in [47] is the Half-Bridge Converter. It has a higher efficiency and a simpler structure with only two switches. Furthermore, the output voltage of the Half- Bridge converter is half that of the Push-Pull Converter. The main disadvantage with this design is the sensitivity to the load variations.

This converter will need a more complex control circuit to accommodate the rapid change of the voltage ratio. The regulated output voltage would be very difficult to control within desired constraints. Switching losses and large current changes have been also pointed out to be the main problems to this topology. Circuit symmetric is difficult to achieve which causes a more complex control circuit design.

3.5 Full bridge DC-DC converter

Full bridge DC-DC converter is chosen in the design among the different converter topologies discussed above. This converter is used in the DC- DC input stage, in which it will convert the low and varying voltage from the PV array through the input capacitor C_{PV} to a constant 400V DC voltage at the capacitor link, C_{DC}. The topology has numerous advantages as discussed in [32] [47]. The primary benefit of using a Full-Bridge DC/DC converter in the DC to DC stage is its power handling capabilities, stability, and symmetry.

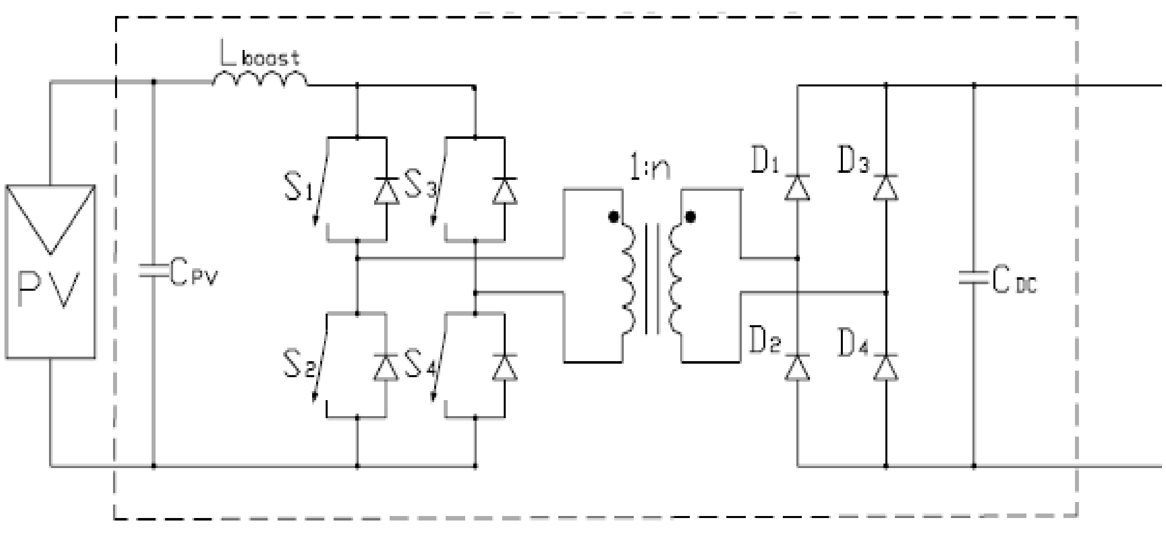


Fig.3.2: Full Bridge DC-DC Converter Topology [7]

Moreover, the use of high frequency transformer plays a very big role in choosing the type of the converter to be used. As pointed out in [7], the choice of DC-DC converter depends mainly on the use of high frequency transformer, and amplification range. When there is no transformer, a buck, boost, buck-boost or variants of these can be used, and if a high frequency transformer is used, a forward, push-pull, fly back, half-bride, full-bridge or other variants can be applied.

With this reason the full bridge is essential and because there is usually a need for galvanic isolation especially for the power stage designed in this thesis. Furthermore, the full-bridge isolated DC-DC converter is advantageous as it uses the same power stage as the grid inverter and it is more suitable for applications with higher input voltages from the PV system array.

The Full-Bridge DC-DC converter will have to maintain a constant 400V DC output with a varying DC input range from the combination of series and parallel connected PV arrays. This is accomplished by using Pulse Width Modulation (PWM) control. By increasing or decreasing the duty cycle (D) of the square-wave pulses to the switches S1-S4, the output voltage can be held constant with a varying input voltage.

The choice of switch to be used is one of the challenges. The switching power devices possibly used in the converter topology can be either IGBTs or MOSFETs. For high power applications and output voltage rating higher than 150V, the IGBT can be used as power device. In spite of its lower on-state voltage drop, higher power density and lower cost respect to the MOSFET, the IGBT has higher switching losses and limited switching frequency. In particular, the turn-off switching loss is very high because of the IGBT current-tail phenomena [34] [47].

The size and weight of DC–DC converter reactive elements can be reduced by increasing the switching frequency, but the switching power losses will proportionally increase with the frequency [34]. These reactive elements are high frequency transformer, the input capacitor and boost inductors that can be seen as L–C filter.

As mentioned earlier high frequency transformer is used in this design in order to provide isolation between the common or ground of the input supply and the output load or grid. In addition it isolates the common returns from different parts of the electronic system.

This helps to eliminate ground loops between circuitries. It facilitates to have multiple outputs with the same or different voltages for different load requirements. Provide voltage scaling and reduce component stresses that result when input output conversion ratio is far from unity.

3.6 Full bridge DC-AC Inverter

In this thesis single phase full bridge inverter is used. This is the DC-AC stage that converts DC power into AC power at desired output voltage and frequency. The power stage designed in this thesis converts the 400V DC output voltage of the full bridge converter to the grid voltage of 230V AC – 240V AC at 50 Hz/60 Hz frequency. The full-bridge inverter can produce an output power twice that of the half-bridge inverter with the same input voltage. As this being one of the distinct features it is used at high power levels since it requires less paralleling devices [11] [37] and [47].

The single phase full bridge topology is shown in Fig. 3.3 which consists of four switching devices, two of them on each leg. Single-phase converters are used where transformation between DC and AC voltage is required; more precisely where converters transfer power back and forth between DC and AC. Unfiltered output voltage is created by switching the full-bridge in an appropriate sequence. The output voltage of the bridge, V_{ab} can be either be $+V_d$, $-V_d$ or 0 voltage depending on how the switches are controlled.

The input voltage V_d at the DC link or bus link capacitor C is a fixed-magnitude voltage and the output voltage is V_{ab} which can be controlled in both polarity and magnitude. Similarly the output current and direction of this converter can be controlled. Therefore the full-bridge converter can operate in four quadrants of its current-voltage characteristics plane, and the power flow through the converter can be in either direction.

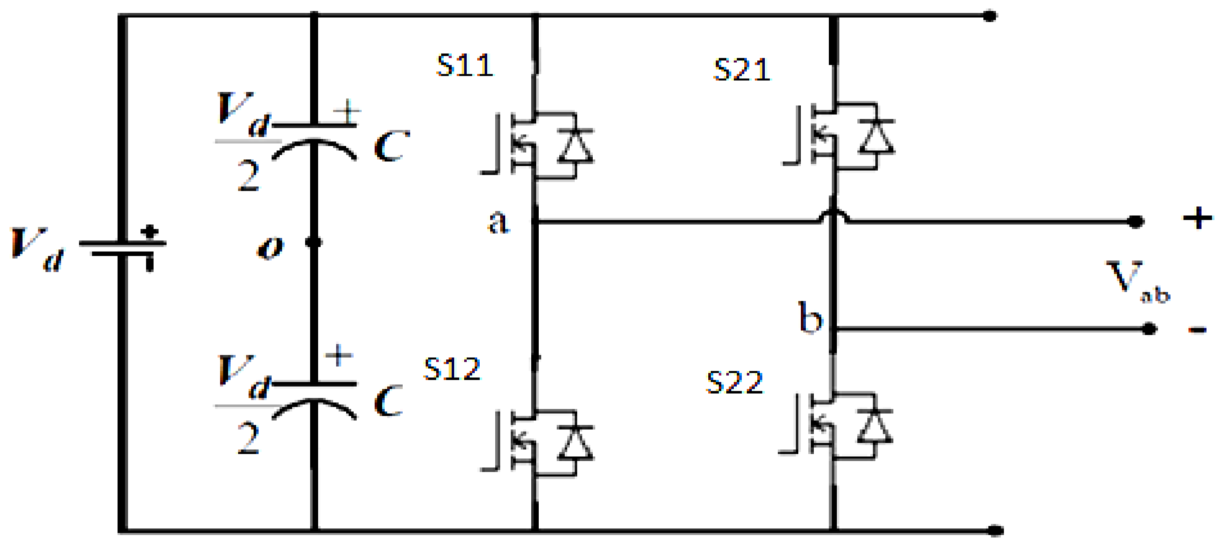


Fig.3.3: Single phase full bridge Inverter [11]

The switches S11 – S22 will be controlled by PWM scheme to produce unfiltered output. The PWM switching schemes which will be discussed later will improve the characteristics of the overall inverter. It should be noted that the switches of the converter in each leg are switched in such a way that both the switches in a leg are not off simultaneously and therefore the output current will flow continuously.

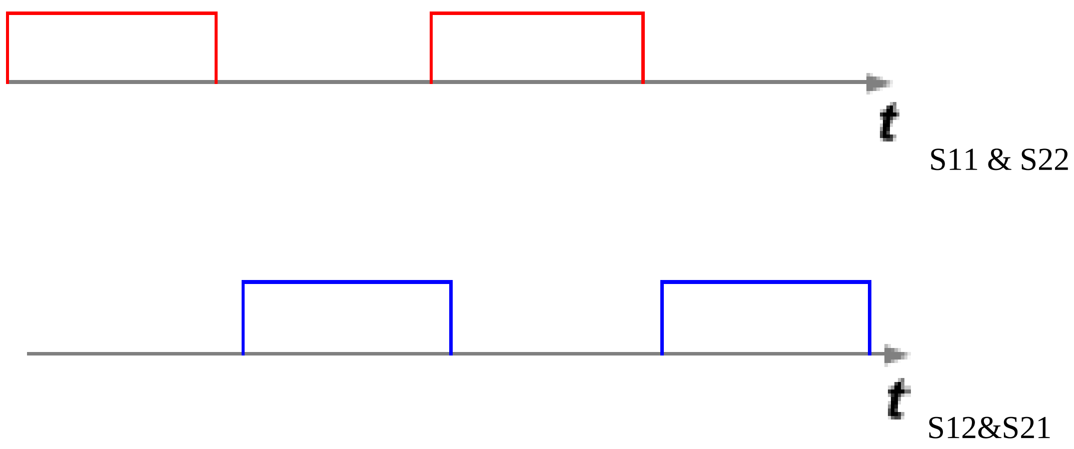
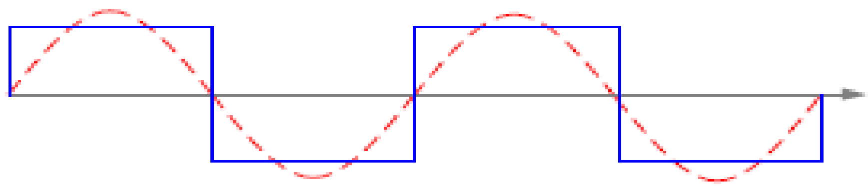
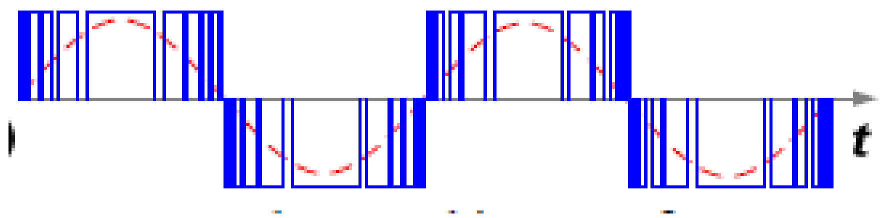


Fig. 3.4: Switching schemes of the Full bridge inverters [38]

The simultaneously switching would cause a short circuit across the DC source, which would destroy the switches or the converter itself. Switching is done diagonally, S11 & S22 pair to give $+V_d$ output voltage and S12&S21 pair to give $-V_d$ output voltage. The combination of the two switching gives the unfiltered output voltage V_{ab}. When the output voltage is 0, this is when the freewheeling diodes conduct. [38] [47]



a) V_{ab} - Waveform



b) V_{ab} & PWM -waveforms

Fig.3.5: Output voltage of a Single phase Full bridge Inverter **[**38]

It is also important to note the on state and conducting state of the switches in full bridge inverters as explain in [47] during switching operation. In full bridge converter in which the diodes are connected in antiparallel with the switches, a distinction must be made between the on-state versus the conducting state of the switch.

Because of the diodes in antiparallel with the switches, when the switch is turned on, it may conduct or not conduct a current, depending on the direction of the output current. If the switch conducts a current, then it is in conducting state. No such distinction is required when the switch is turned off.

3.7 Voltage source and Current source inverters

Inverters can be broadly classified into two types based on their operation as Voltage Source Inverters (VSI) and Current Source Inverters (CSI). In [11] and [39] explains Voltage Source Inverters as one in which the DC source has small or negligible impedance.

In addition, Voltage Source Inverter is the type of inverter where the independently controlled ac output is a voltage waveform. The output voltage waveform is mostly remaining unaffected by the load. Due to this property, the VSI have many industrial applications such as adjustable speed drives and also in Power system for FACTS.

On the other hand, Current Source Inverter is the type of inverter where the independently controlled ac output is a current waveform. The output current waveform is mostly remaining unaffected by the load. These are widely used in medium voltage industrial applications, where high quality waveform is required. In Other words VSI has stiff DC voltage source at its input terminals. A current source inverter is fed with adjustable current from a DC source of high impedance. In a CSI fed with stiff current source, output current waves are not affected by the load. [11] [39]

Similarly to [2], [11] and [39] this thesis focus on the VSI design of the DC/AC inverter which is commonly used in the dual stage PV inverter systems. When voltage amplification from the PV arrays at the input capacitor is essential, then DC/AC inverter is then a voltage sourced inverter (VSI) which handles the output current regulation and DC bus voltage regulation. The voltage source inverter usually uses a self commutating half bridge or full bridge configuration as its switching circuit.

Chapter 4

Grid Connected PV Inverter Power Stage Parameters Sizing and Design

4.0 Introduction

In designing the power stage of the inverter there are important parameters needed to be considered in the design process. In the input stage, the input voltage range, nominal output voltage and maximum output current. In the output stage the filter is essential. In the design some of the assumptions are needed to compromise the design. This chapter discusses the important parameters for the power stage of the inverter.

4.1 Input and DC-link capacitors

The DC link capacitor sometimes called power decoupling is normally achieved by means of electrolytic capacitor [1]. For years design engineers have chosen electrolytic capacitor technology for use as the bus link capacitor on inverter designs. Electrolytic capacitors have been the workhorse technology for hard switched inverter bus link capacitors for many years.

Electrolytic capacitor technology has also remained virtually unchanged over the years. The main attraction has always been the low cost per farad associated with electrolytic capacitors. [35]. The DC link capacitor is very important in the life time of the converter, and it should be kept as small as possible and preferably substituted with film capacitors [1] [32] [36].

A lot of work has been invested into reducing the DC-link capacitance of inverters in order to replace electrolytic capacitors with the more reliable, but also more expensive and larger film capacitors [36]. The comparison of electrolytic capacitor and film capacitor has been explained in [2]. Temperature has been the effect to electrolytic capacitor to its life time. Film capacitors are a clear the alternative given their long life expectancy and wide operating temperature range.

Unfortunately, film capacitors are far more expensive than the electrolytic ones in term of cost per farad and hence the size of the capacitance has to be smaller to keep the price of the capacitor acceptable. However, smaller capacitance would weaken the power decoupling ability of the DC-link capacitor which may cause DC-link voltage fluctuations that lead to distortion of the inverter output current to the grid.

References [1] [2] [29] [35] [36] explain the importance and challenges facing the DC link capacitor. The transient DC fluctuation is caused by the rapid increase/decrease of the input power flowing into the DC-link capacitor. This can be removed by very fast current controller. The DC fluctuation is not a major concern when designing a VSI for PV application.

The second factor, which can be referred to as the AC fluctuation of the DC-link voltage is caused by the double-line frequency ripple power generated from the grid side. This double-line frequency ripple component can couple through the DC voltage control loop to cause a significant amount of distortion on the current reference signal.

The bus link capacitor is used in DC to AC inverters to decouple the effects of the inductance from the DC voltage source to the power bridge. The bus link capacitor also plays a role in reducing the leakage inductance of the inverter power bridge.

Leakage inductance in an inverter power bridge leads to inefficiencies due to the voltage spikes they produce when the power devices are switched on and off at a high rate of rise of current. This can damage the devices because when the inductance becomes too large the switching time is increased and hence increasing switching loss. Having a low impedance DC bus is fundamental for an efficient inverter design.

The bus link capacitor provides a low impedance path for the ripple currents associated with a hard switched inverter. The ripple currents are a result of the output inductance of the load, the bus voltage and the PWM frequency of the inverter. Unfortunately the ripple currents have been the primary factor in sizing the electrolytic bus link capacitor. [29] [35]

On the other hand, since the PV modules are current sources, a capacitor has to be added in parallel when using a voltage source inverter (VSI), in this way the inverter sees a voltage source. The input capacitance or input filter capacitance as illustrated in [29] is inserted to reduce the power oscillation by keeping the PV voltage constant in theory.

In practice, the large current ripple of DC inductor or boost inductor will lead to the significant voltage oscillation in PV panel when input capacitance filter is not connected. This inductor is small normally assumed in high frequency switching converter to reduce the system cost and size. With a small filter or input capacitor added, the voltage ripple across PV panel can be reduced significantly. The input capacitance is very much depends on the I-V characteristics of the PV array at MPPT. The capacitors are placed in parallel with the PV array or in the DC link between the inverters stages as seen in Fig 3.1.

It is also discussed in reference [2], In order to improve the energy harvesting capabilities and design flexibility, dedicated DC/DC converters, which perform MPPT for each PV string present in the PV system array can be connected in the middle between the PV modules and the DC/AC inverter through the DC Link capacitor.

The output from the DC/DC converter at the capacitor link can be either a low ripple DC voltage, or a modulated current that follows a rectified sine wave. In dual stage converters, the DC/DC converter handles MPPT and output current regulation while the DC/AC inverter switches at the grid frequency to unfold the rectified sine wave. In the case that the output is a low ripple DC voltage, the DC/DC converter performs MPPT and voltage amplification if necessary [2]. This is the basic feature of the design of the DC-DC input stage in this thesis.

4.2 Input inductance and capacitance

The necessity and importance of the input parameters as applied to the input voltage from the PV array have been explain in previous sections. These parameters are boost inductor or DC inductor L_{PV} and input capacitor. C_{PV}. There are direct formulae that have been used by various literatures to estimate these parameters as summarized in [7] [29] [45] [46].

In this design the proposed PV system discussed in section 2.7 and drawn in Fig.2.2 shall be used. The system has two strings which are connected in series to have a nominal voltage of 420 V. The two series combination is then connected in parallel to give a current of 10A. Irradiance and temperature affects the V-I characteristics of the NTNU PV array as discussed in chapter 2. Though the changes are minimal but should be kept in mind during design hence it affects the MPPT performance.

It is very difficult to achieve nominal voltage of 420V from the available PV array at NTNU. As explained in [42] the PV cells convert about 15% of the solar radiation to electricity. Due to this reason and for the benefit of this thesis the minimum worst case of voltage that is assumed to be available all the time shall be taken as 100V.

As shown in [7] [46] the minimum voltage is used to estimate the duty ratio, D of the boost converter. The minimum voltage is used because it gives the maximum switching current. Using the equations for the boost converter power stage derived from [7] [46] the duty ratio D is obtained in equation 4.1. The efficiency of the converter in worst case is assumed to be 85%, to give the derided output voltage of 312.5 V. This duty ratio D=0.68 is significant to the full bridge converter.

$$D = 1 - \frac{V_{IN\_min} * \eta}{V_{out}} \tag{4.1}$$

$$\therefore D = 1 - \frac{150 * 0.85}{400} = 0.68$$

For the boost converter stage, the equation 4.2 is necessary to find the desired output voltage before step it up by a transformer.

$$V_{out} = \frac{1}{1-D} V_{in} = 312.5V \tag{4.2}$$

4.2.1 Input Inductance, L_{PV}

In most designs, the inductor is always given in a certain range provided in the data sheet. However it is wise to estimate the boost inductor directly if no data sheet available. The estimation is calculated using equation 4.2 [46].

$$L_{PV} = \frac{V_{IN} * (V_{out} - V_{IN})}{\Delta I_L * V_{out} * f_s} \tag{4.3}$$

Where: ΔI_L = Estimated inductor ripple current

f_s = Switching frequency

V_{out} = Desired output voltage

L_{pv} = Boost or PV input inductor

V_{IN} = Typical input voltage

The inductor ripple current can be estimated by 20% to 40% of the output maximum current. This can be found by using equation 4.3 [46]. In this design input voltage is assumed to be $V_{pv} = 100V$ and the switching frequency is $f_s = 10kHzV$. The PV string available for research has the nominal voltage of $V_{pv\_n} = 420V$ (which is difficult to achieve this) and the maximum current that the two parallel strings will produce is $I_{pv} = 10A$. Using equation 4.3, the value of estimated inductor ripple current can be found.

$$\Delta I_L = 0.2 * I_{OUT\_\max} * \frac{V_{OUT}}{V_{IN}} \tag{4.4}$$

$$\therefore \Delta I_L = 0.2 * 10A * \frac{312.5}{100} = 6.25A$$

Therefore the boost inductor is then calculated using equation 4.3 by assuming the factor of 20% approximation and is found to be, $L_{PV} = 0.2mH$ by assuming the continuous conduction mode, (CCM) of the boost converter stage.

4.2.2 Input capacitance, C_{PV}

After obtaining the boost inductor, then the input capacitance can be obtained easily by using the analysis done in [29]. The analysis also assumes the continuous conduction mode (CCM) of the boost converter.

In the variation of temperature and irradiance discussed in section 1.3.1 of this thesis, the capacitance will see the voltage ripple from the PV array MPP as ΔV_{pv}. As temperature changes from -20^{0} C to 40 ^{0}C the open circuit voltages also sees these changes and the open circuit of the PV string voltage change is by, $\Delta V_{pv} = 5V$.

Therefore, by using equation 4.4 [29] the PV input capacitance that is important to voltage source inverters (VSI). This converts the model of the PV modules and seen as voltage source by the inverter. It is also keeps the voltage constant and reduces power oscillation at the input.

$$\Delta P_{PV} = \frac{D * V_{PV}}{4 * f_s^{\,2} * L_{PV} * C_{PV}} \qquad (4.5)$$

Therefore, the input capacitance is then estimated as;

$$\therefore C_{PV} = \frac{D * V_{PV}}{4 * f_s^{\,2} * L_{PV} * \Delta C_{PV}} = \frac{0.68 * 100}{4 * (10.10^{3})^{2} * 0.2.10^{-3} * 5} = 170 \mu F$$

4.3 DC- Link design

The output AC voltage of the inverter is specified to 230 V as VSI single phase. This value will give the estimated voltage value of 400 V at the DC bus. This voltage is seen at the DC link capacitance which sometimes is called power coupling capacitor. The DC link voltage is estimated using equation 4.5 as the bus voltage, V_{bus}. In this design the ripple voltage is taken as 10% of the specified bus voltage or link voltage.

$$V_{bus} = \sqrt{2} * 230 + 10\% * 230 = 358V \Rightarrow 400V \qquad (4.6)$$

It is difficult to control the grid current if the DC –link voltage is lower than the peak grid voltage plus the voltage drop across the semiconductor devices and filter voltage. This is the reason to which the 10% is added and gives an approximated DC bus voltage of 400V.

In addition to the advantages discussed in previous sections, the most important function of the DC link capacitor is to limit the magnitude of the double-line frequency ripple voltage to the specified level. The DC link capacitor C_{DC} is sized according to the equation 4.6 similar to the equation derived in [2], [28], [29], [45].

$$C_{DC} = \frac{P_{PV}}{2 * \omega * V_{DC} * \Delta V} \tag{4.7}$$

Assuming the net nominal power from the strings is $P_{PV} = 1kW$ at the input voltage $V_{pv} = 220V$ is to be delivered to the DC bus. By substituting the grid frequency of 50Hz the value of DC link capacitor $C_{DC} = 100\mu F$ is approximated.

The calculated values are summarized in Table 4.1. In design methodologies, standard values for these parameters at certain rated voltages are being selected. In this thesis the standardization of parameters will not be taken into account. The actual calculated values will be used in the design.

Parameter	**Value**
Duty ratio	0.68
Switching frequency	10kHz
Input inductance, L_{pv}	0.2mH
Input capacitance, C_{pv}	170µF
DC-Link capacitance, C_{DC}	100 µF
Ripple voltage, ΔV	40V

Table 4.1: Calculated parameters for converter input stage

4.4 Grid connected filter topologies

In order to supply the grid with a sinusoidal line current without harmonic distortion, the inverter is connected to the supply network via filter. The filter is an important part of every semiconductor converter. The filter reduces the effects caused by switching semiconductor devices on other devices. [40].

According to [42] parameters like efficiency, weight and volume have to be considered when choosing an optimal filter topology. Regarding efficiency, filter topologies with reduced losses are required, though those are relatively small when compared to losses in the inverter. Weight and volume of filters are considered as critical due to difficulties with inverter transportation, installation and maintenance.

The filter cost depends basically on the amount of components and materials used, for example the magnetic material for the core of inductors. In addition the filter shall be able to perform its task within a certain degree of independence of the grid parameters, like resonance susceptibility and dynamic performance are of major importance.

References [28], [39] [42] [43] [44] analyses different topologies of grid connected filters. The filters include L-filter, L-C filter and L-C-L filter as shown in Fig. 4.1. Advantages and disadvantages are pointed out based on the most important features for designing and performance of filters. Harmonic attenuation, better decoupling between filter and grid impedance and system dynamics of these types of filters are among the performance features discussed in these literatures

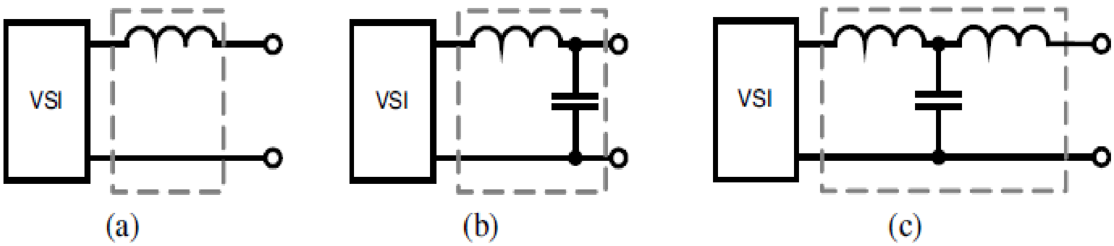


Fig.4.1: Filter Topologies (a) L-Filter (b) L-C Filter (d) L-C-L Filter [43]

4.4.1 L-C-L Filter

The main functions of filter [28] includes convert the voltages from switch devices to current, to reduce high frequency (HF) switching noises and protect the switching devices from transients.. As explain in [28] [43] [44] the L-filter and L-C filters has excellent performance in terms of voltage to current conversion but the damping of the HF noise is rather poor. The capacitor to these filters may be exposed to line voltage harmonics that results in large currents. The L-C-L filter has good current ripple attenuation even with small inductance values. [40]

In addition to good voltage-current conversion L-C-L filter damps the HF noises due to its extra inductance. Unlike L and L-C filters, the capacitor in L-C-L filter is not exposed to line voltage distortion [28]. Low grid current distortion and reactive power production and possibility of using a relatively low switching frequency for a given harmonic attenuation are among the advantages of L-C-L filter [44]. L-C-L filter is a third order filter and has attenuation of -60 dB/decade for frequencies in excess of the resonance frequency [40] [42] [44].

Though the LCL filter can sometimes cost more than other more simple topologies depicted in Fig. 4.1, its small dependence on the grid parameters is of major importance at high power applications, in order to guarantee a stable power quality level. Furthermore, it provides better attenuation than other filters with the same size and by having an inductive output; it is capable of limiting current inrush problems [42].

On the other side, L-C-L is unstable may cause both dynamic and steady state input current distortion due to resonance [44]. In order to reduce oscillations and unstable states of the L-C-L filter, the damping resistor is added. This solution is sometimes called “passive damping”.

Damping technique is simple and reliable, but it increases the heat losses in the system and it greatly decreases the efficiency of the filter. In general there are four possible places where the resistor can be placed series/parallel to the inverter side inductor or series/parallel to filter capacitor.

The characteristics and advantages of L-C-L filter, over other filter topologies are among the reasons made this thesis to use L-C-L filter. The filter will have a damping resistor in series with the filter capacitor. The filter is common to voltage source inverters (VSI). The design of the filter for PV-Grid connection is discussed in later chapter.

4.4.2 L-C-L Filter Design

Analysis and estimation approach of the L-C-L filter with damping resistance as seen in Fig.4.2 have been discussed in [2] [40] [42] [30]. The simplified formulae to estimate the parameters of the filter has stipulated in these literatures. The same approach will be used in this thesis to determine inverter side inductance, L_i , grid side inductance, L_g, filter capacitance, C_f and the damping resistance R_d.

Equations 4.7 to 4.14 have been derived in [40] [41] [42] and used to estimate the filter parameters. The main function of the LCL filter is to reduce high-order harmonics on the output side; however poor design may cause a distortion increase. Therefore, the filter must be designed correctly and reasonably [41].

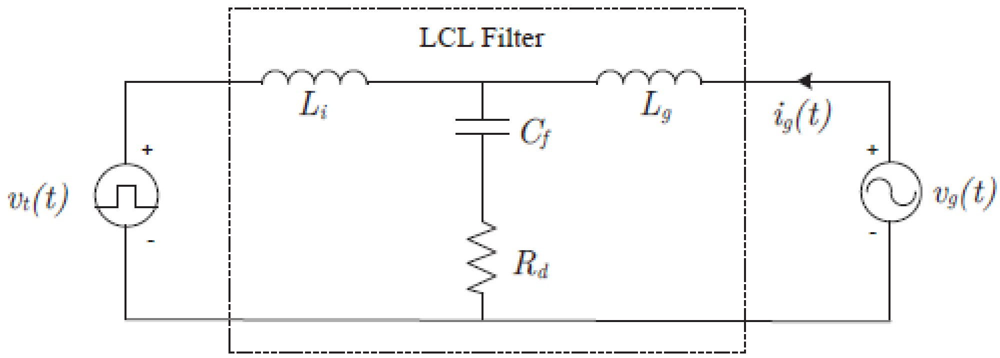


Fig.4.2: L-C-L filter and components [2]

Table 4.2 summarizes parameters for calculating filter components. The data provided are important and are the rating of the power stage of the inviter designed in this thesis. These parameters are designed to handle an approximate power of 1kVA. The most important assumption made is the use of unity power factor.

Parameter	Value
Grid Voltage	230 V
Output Power of the Inverter	1kVA
DC-Link voltage	400 V
Grid frequency	50 Hz
Switching frequency	10kHz
Power factor	1

Table 4.2: Filter design specifications

During design of L-C-L filter it is important to take care of some necessary factors. This factor includes inverter output ripple current, inverter to grid inductor ratios and filter capacitance maximum power variations. Typically [40] [41] [42] current ripple is usually limited to 10%-25%, inverter to grid ratio is between 0-1, the capacitor value is limited to less than 5% of the decrease of the rated power and ripple attenuation must be less than 20%.

The inverter to grid side inductance ratio is derived in [41] [42] and the relation is plotted in Fig.4.3 based on the equation 4.8. This factor is obtained from the ratio between the filter impedance and the difference between resonant frequency and switching frequency. Thus, this ratio is the key factor for the desired ripple attenuation of the filter which is given as the ratio of $\frac{i_g(h)}{i(h_{sw})}$

$$\frac{i_g(h)}{i(h_{sw})} = \frac{1}{\{1 + r * [1 - (C_b * L * w_{sw}{}^2) * x\}} \tag{4.8}$$

Whereas, r , C_b and x are the relation factor between inductances, base capacitance and the filter capacitance factor.

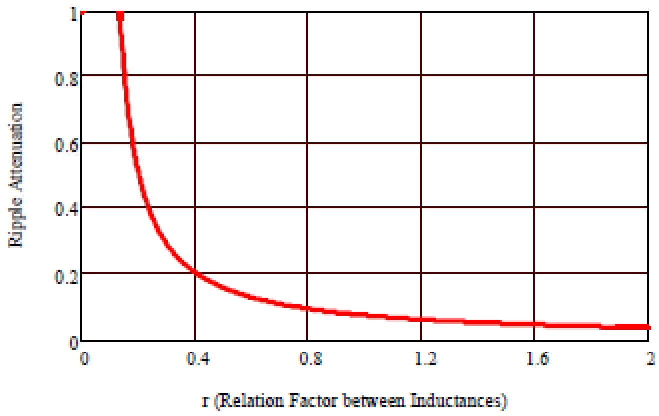


Fig 4.3: Ripple attenuation as a function of the relation factor between inductances [42]

Therefore based on the important factors in estimating L-C-L filter, this thesis uses output ripple current of 10% of the rated output current.

$$\Delta I_L = 10\% * \frac{\sqrt{2} * P_N}{V_{phase\_grid}} \qquad (4.9)$$

$$\therefore \Delta I_L = 10\% * \frac{\sqrt{2} * 1kW}{230V} = 0.615A$$

The value of the ripple output current is used in estimating the value of the inverter side inductance, L_i [40] [41] [42]

$$L_i = \frac{V_{DC}}{16 * f_s * \Delta I_L} \qquad (4.10)$$

$$\therefore L_i = \frac{400V}{16 * 10kHz * 0.615A} = 4mH$$

Inverter inductance L_i and grid inductance L_g are related with r in equation 4.10. If 5% is taken as attenuation factor of the filter, then the approximated value of $r = 0.6$ as seen in Fig 4.3;

$$L_g = r * L_i \qquad (4.11)$$

$$\therefore L_g = 0.6 * 4mH = 2.4mH$$

The filter capacitance C_f of the L-C-L filter in this thesis is limited to 5% of the rated output power. Usually is taken as the fraction of the base capacitance, C_b

$$C_f = 5\% * C_b = 0.05 * \frac{P_N}{\omega_{grid} * U^2_{phase\_grid}} \tag{4.12}$$

$$C_f = 0.05 * \frac{1kW}{2 * \pi * 50Hz * 230^2} = 3\mu F$$

Literatures [40] [41] [42] explain the importance of the damping resistance to L-C-L filter as discussed in previous section of this thesis. The passive damping resistor, R_d , is obtained at the resonance frequency, f_0 of the L-C-L filter. The values of damping resistance and resonance frequency are given in the equations 4.13 and 4.14 respectively.

$$R_d = \frac{1}{3 * \omega_o * C_f} \tag{4.13}$$

$$f_o = \frac{1}{2\pi} * \sqrt{\frac{L_i + L_g}{L_i * L_g * C_f}} \tag{4.14}$$

$$\therefore f_o = \frac{1}{2\pi} * \sqrt{\frac{4mH + 2.4mH}{4mH * 2.4mH * 3\mu F}} = 23.4kHz$$

Resonance frequency is then calculated by using the filters components in equation 4.13. Then the damping resistance R_d is found to be 0.755Ω .Filter components are summarized in Table 4.3

Components	**Value**
Inverter side inductor L_i	4mH
Filter capacitor, C_f	3μF
Grid side inductor, L_g	2.4mH
Damping resistance, R_d	0.755Ω
Resonance frequency, f_0	23.4kHz

Table 4.3: L-C-L filter components

Chapter 5

Control of the Power Stage of a Single Phase Voltage Source Inverter

5.0 Introduction

This chapter discusses different techniques of switching and control of the inverter power stage. Methods to switch voltage sources inverter (VSI) have been studied and presented. The generation of SPWM with unipolar voltage switching schemes which is the key switching technique in this thesis is explained in details. Later, SPWM with unipolar voltage switching generation from Lab View IP Cores for power stage switching control is chosen to control the output voltage of the inverter.

5.1 Control strategies of the inverter power stage

Different techniques have been mentioned in [2] to control voltage source, VSI power stage. There are three major output current control techniques for the single phase VSI which includes hysteresis band, predictive, and sinusoidal pulse width modulation (SPWM) control. This thesis will explore various techniques of PWM and concentrate on the one that will seem to be the best in the control of the inverter power stage under discussion.

The DC-AC inverters usually operate on Pulse Width Modulation (PWM) technique. The PWM is a very advance and useful technique in which width of the gate pulses are controlled by various mechanisms. PWM inverter is used to keep the output voltage of the inverter at the rated voltage irrespective of the output load. With PWM, inverters usually switch between different circuit topologies, which mean that inverter is a nonlinear, specifically piecewise smooth system.

In addition to this, the control strategies used in the inverters are also similar to those in DC-DC converters. Both current-mode control and voltage-mode control are employed in practical applications [39]. Pulse Width Modulation (PWM) is a technique which is characterized by the generation of constant amplitude pulse by modulating the pulse duration by modulating the duty cycle [11] [39] [47].

Analog PWM control requires the generation of both reference and carrier signals that are feed into the comparator and based on some logical output, the final output is generated. The reference signal is the desired signal output maybe sinusoidal or square wave, while the carrier signal is either a saw tooth or triangular wave at a frequency significantly greater than the reference signal.

Inverters that use PWM switching techniques have a DC input voltage that is usually constant in magnitude. The inverters job is to take this input voltage and convert to the output AC where the magnitude and frequency can be controlled. There are many different ways that pulse-width modulation can be implemented to shape the output to be AC power.

These different types of PWM switching techniques have been discussed so far in [2] [11] [39] [47]. This technique for switching power stage inverters includes; Single Pulse Width Modulation, Multiple Pulse Width Modulation and Sinusoidal Pulse Width Modulation. Generating concepts, principles and applications have been mentioned.

Each PWM switching technique is comparable to one another with important features which signify the applicability of the switching scheme. Important features for different PWM techniques are based on switching losses and utilization of DC power supply that is to deliver a higher output voltage with the same DC supply. In addition linearity in voltage and current control and harmonics contents in the voltage and current are the important features to be considered when selecting the switching technique.

The pulse width modulation inverter has been the main choice in power electronic for decades, because of its circuit simplicity and strong control scheme [11]. Depending on the switching performance and good characteristic features, Sinusoidal Pulse Width Modulation (SPWM) will be used.

As mentioned in [39], the advantages of using SPWM include low power consumption, high energy efficient up to 90%, high power handling capability, no temperature variation-and ageing-caused drifting or degradation in linearity and SPWM is easy to implement and control. SPWM techniques are characterized by constant amplitude pulses with different duty cycle for each period.

5.1.1 Sinusoidal pulse width modulation (SPWM)

In this modulation technique there are multiple numbers of output pulses per half cycle and pulses are of different width. The width of each pulse is varying in proportion to the amplitude of a sine wave evaluated at the centre of the same pulse. The gating signals are generated by comparing a sinusoidal reference signal with a high frequency triangular signal [11] [39]. The reference signal frequency determines the frequency of the inverter output voltage.

SPWM generating techniques have discussed in [11] [39] [47]. The triangle waveform V_{tri} is at switching frequency f_s; this frequency controls the speed at which the inverter switches are turned off and on. The control signal $V_{control}$ is used to modulate the switch duty ratio and has a frequency f_1. This is the fundamental frequency of the inverter output voltage. Since the output of the inverter is affected by the switching frequency it will contain harmonics at the switching frequency. This comparison of waveforms produces the SPWM signals to turn on/off switches.

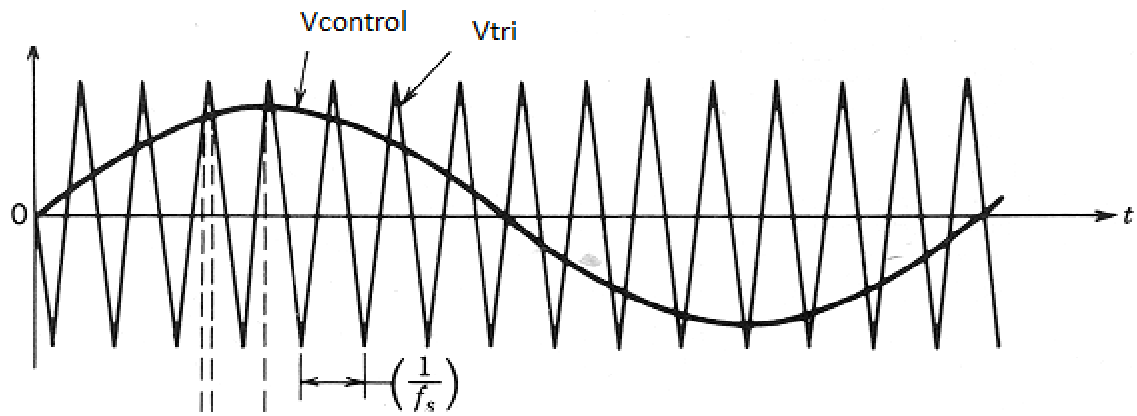


Fig. 5.1: Comparison of desired frequency and triangular waveform [11] [47]

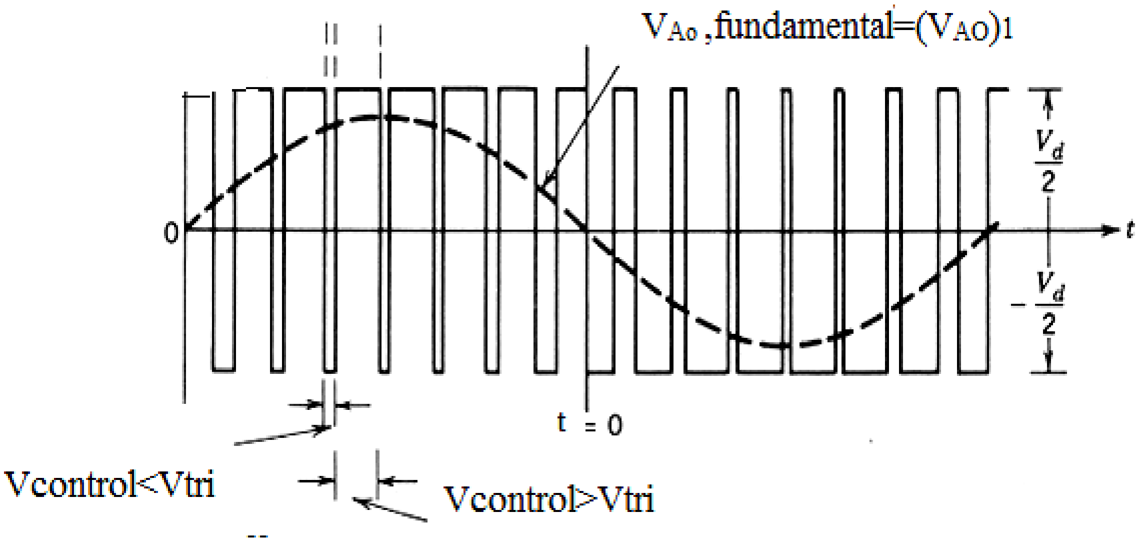


Fig 5.2: Pulse width modulation **[11] [47]**

Significance of modulation ratio or modulation index as explained in [11] [47] as the ratio of the amplitudes of the control voltage and triangle voltage. The modulation can also be in terms of frequencies ratios, termed as frequency modulation ratio.

Modulation index controls the amplitude of the output voltage. Over modulation can cause large AC magnitude voltage even though the spectral content of the voltage is poor. In addition to that, in over modulation the output voltage has more harmonic contents.

5.1.2 SPWM with bipolar voltage switching

In this type the switches are treated as two switch pairs [11] [47]. Switches in each pair are turned on and off simultaneously. As shown in Fig 3.3, the pairs can be S11&S22 and S12&S21.

The basic idea is explain in [11] as the comparator is used to compare between the reference voltage waveform with the triangular carrier signal and produces the bipolar switching signal. When this signal applied to the switches of a single phase full bridge DC-DC the output in the two legs are equal but differ in polarity [11] [47].

The output voltage is determined by comparing the control signal and the triangular signal as shown in Fig 5.2 to get the switching pulses for the switching devices. The resulting switching signal is seen in Fig 5.3. The output of the switching patterns containing the fundamental frequency voltage. The detailed analysis of harmonics contents is explained in details in [47].

In Fig 5.3 is observed the output voltage, V_o switches between V_d and $-V_d$ voltage levels. This is the main reason why this type is called SPWM with bipolar switching. This type of switching is not suitable in this design because the haronic contents problem containing in the current drawn in the DC side. This harmonic current componetnts results in a ripple in the lcapacitor voltage [47].

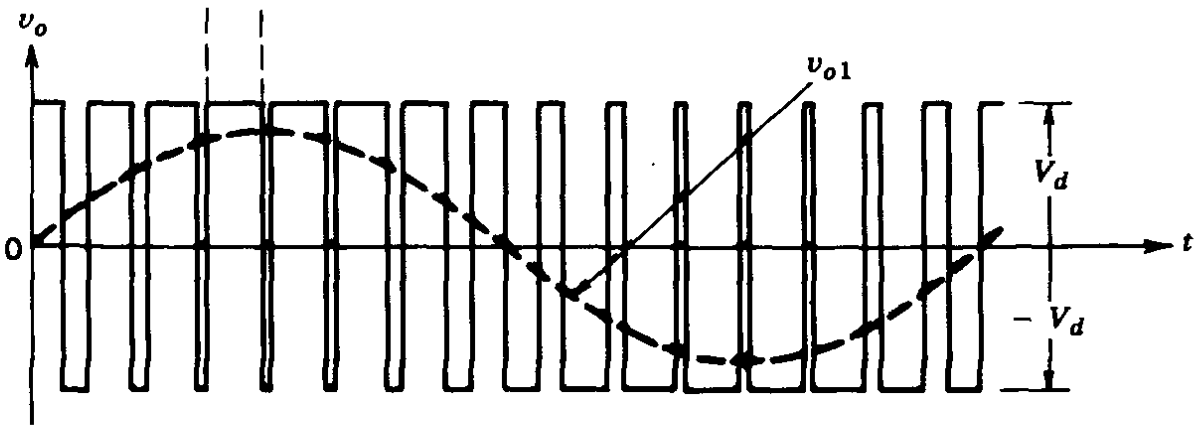


Fig.5.3: Bipolar SPWM switching [47]

5.1.3 SPWM with unipolar voltage switching

This type of switching is used in the inverter power stage designed in this thesis. As opposed to the SPWM bipolar scheme, the switches in the two legs of the full-bridge inverter presented in Fig 3.3 are not switched simultaneously. In this case each leg is controlled separately by comparing V_{tr} with $V_{control}$ and $-V_{control}$ respectively.

The basic idea to produce SPWM with unipolar voltage switching is shown in Fig. 5.4. The different between the SPWM with bipolar voltage switching generators is that the generator uses another comparator to compare between the inverse reference waveform with the triangle voltage [11].

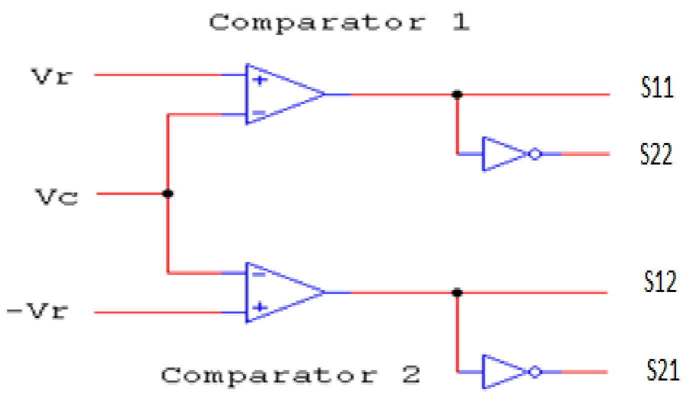


Fig.5.4: SPWM with Unipolar Voltage switching Generation **[11]**

As pointed out in [47] it is similar that when the upper switches S11&S21 or S12 & S22 are on the output voltage is zero. The switching scheme is shown in Fig 5.5, when the switching occurs the output voltage changes between zero and V_d or zero and $-V_d$ voltage levels. This is why it is called SPWM with unipolar voltage switching.

In SPWM [11] the effective switching frequency is seen by the load is doubled and the voltage pulse amplitude is halved. Due to this, the harmonic content of the output voltage waveform is reduced compared to bipolar switching. In unipolar voltage switching scheme the amplitude of the significant harmonics and its sidebands is much lower for all modulation indices thus making filtering easier, and with its size being significantly smaller.

The SPWM unipolar voltage switching has the advantage of effectively doubling the switching frequency as far as output harmonics are concerned, comparing to bipolar voltage switching scheme. Also the voltage jumps in the output voltage at each switching are reduced to V_d, as compared to twice V_d in bipolar voltage switching. [11] [32] [47].

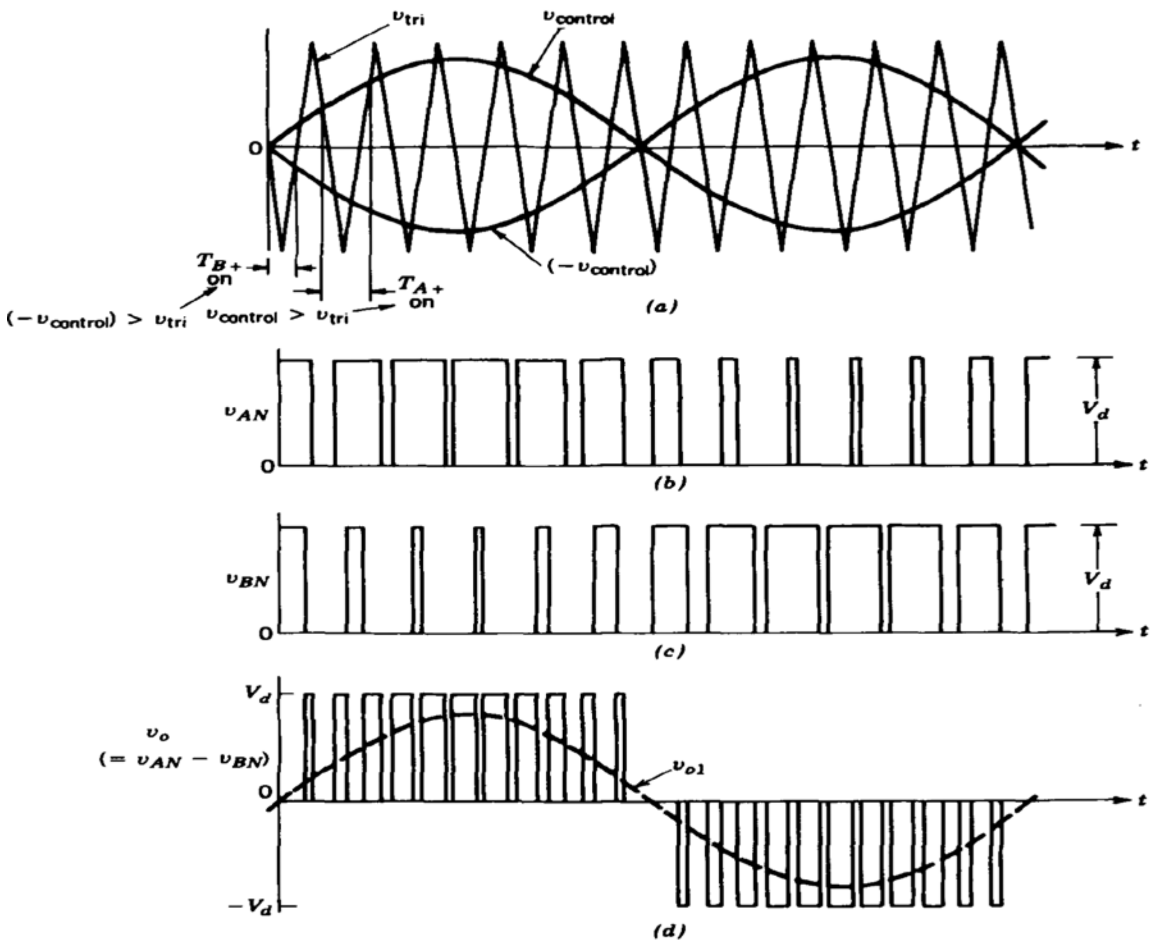


Fig. 5.5: SPWM with unipolar switching scheme **[47]**

With advantages of SPWM with unipolar voltage switching mentioned in [2] [11] [47] made the power stage in this thesis to use this type of switching scheme. When used in full bridge converter the minimum DC link voltage will be seen to the output AC grid voltage. Thus, power MOSFETs, instead of higher voltage IGBTs, can be used as the switching device which enables use of a high switching frequency without introduction of excessive switching loss.

For the harmonic analysis related to the switching scheme, sinusoidal pulse width modulation (SPWM) with unipolar switching scheme, changes the order of the major harmonic of the output voltage. Furthermore the technique is very much commonly used in voltage sources inverters, VSI. [2]

5.2 Switching of the inverter power stage

The IP Cores shown in Apendix from NI LabView is used to control and switch the power stage inverter. FPGA DDS TriangleGen IP.vi is used to generate 10 kHz switching frequency. The pulses are obtained by the comparison to the phase sine wave signal from the grid. The output of this comparison is fed back into the inverter power stage in the Multisim detailed in Fig 6.1 to control the opening and closure of the switches.

The switches signals SW1 to SW4 of the DC to DC stage open/close switches TSW1 to TSW4 and switches signals s1 to s4 of the DC to AC stage open/ close switches TS1 to TS4 and are controlled by SPWM with unipolar voltage switching. Each leg is controlled independently of the other. The duty ratio is set to 0.68 to maintain the ratios of the pulses to these switches. The pulses that opens and closes the switch SW3 and SW4 is shown in Fig 5.6 as an example for more demonstration of the switching process. .The amplitude switches from 0 to 1.

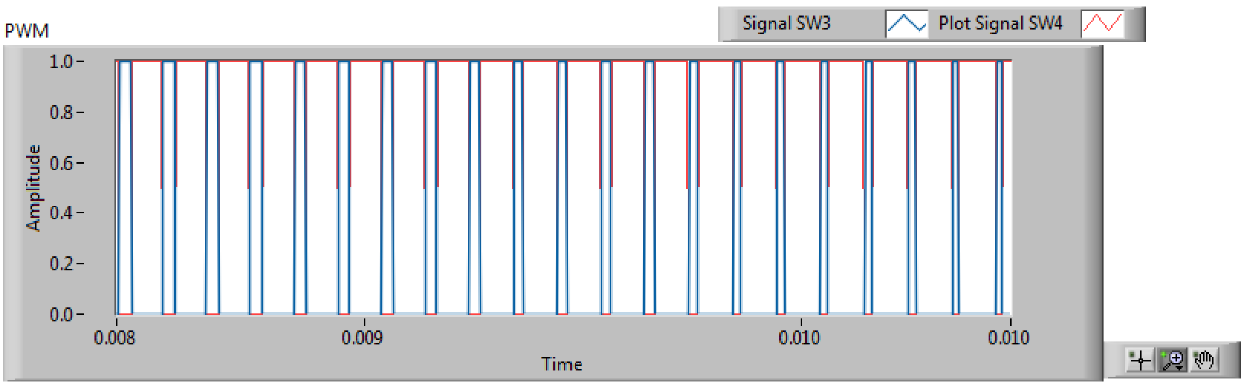


Fig 5.6: PWM switching pulses as simulated in NI LabView

Chapter 6

Inverter Simulation, Discussion, Conclusion and Future Work

6.0 Introduction

This chapter explains the details of the converter power stage designed in this thesis. The circuit is drawn in Multsim Circuit Design Suit 12.0. The converter topology is then implemented using NI LabView for control and user interface. The output of the converter power stage is obtained for both filtered and unfiltered waveforms. Inviter voltage and current is compared to that of the grid. The conclusion will be made and propose the future work for this project.

6.1 Discussion and Simulation

6.1.1 System description

The dual power stage designed in this thesis as presented in Fig 6.1 has the ratings described in Table 6.1. The inverter is designed based on the literatures discussed in previous chapters. The fixed voltage from the PV array is taken as 100V, which is assumed to be the only voltage available all the time at the PV arrays. The full bridge single phase inverter is used to amplify the voltage and to provide galvanic isolation between the PV array and the grid.

The DC-Link voltage is estimated to 400V that is enough to give the desired output AC voltage of 230V. The DC- bus voltage is maintained at the secondary of the transformer with turn ratio of 1: 1.3 and this will be controlled by the MPPT controller, not discussed in this thesis. The L-C-L output filter is designed to minimize the harmonics that present in the inverter output due to switching.

Rated Power	1kVA
Frequency	50Hz
Power factor	1
Output phase voltage, RMS	230 V

Table 6.1: Power Stage Inverter ratings

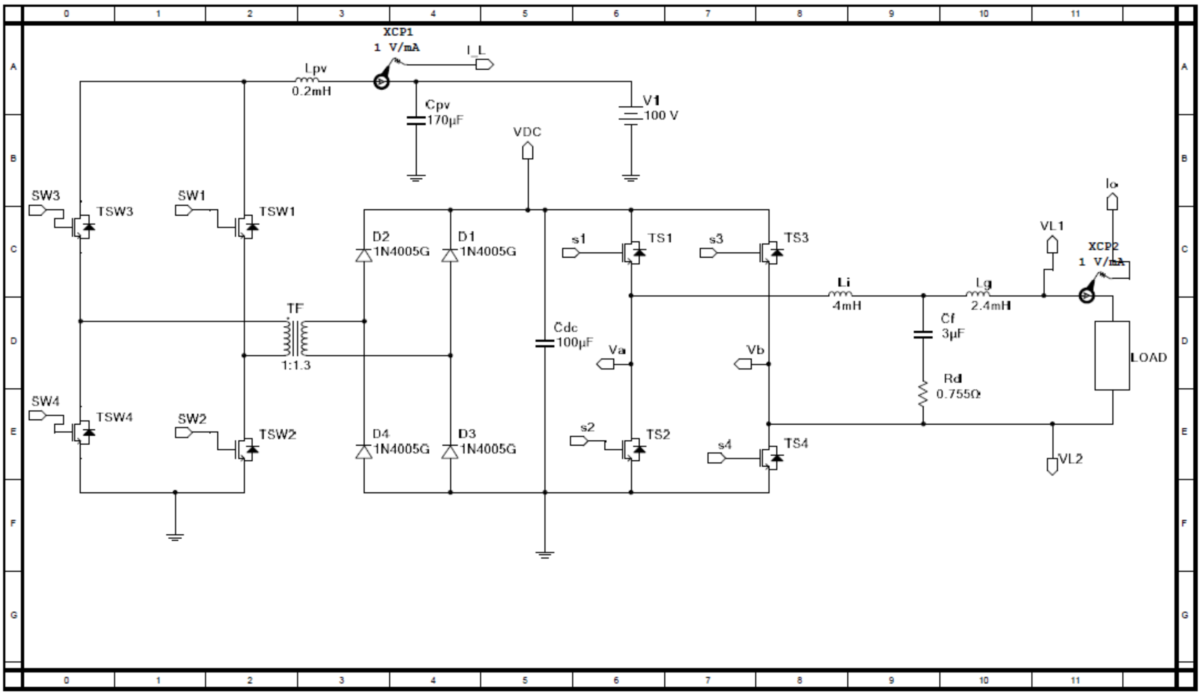


Fig.6.1: Single phase Power Stage Inverter

6.1.2 System control

The circuitry design of the inverter power stage is drawn in Multism detailed in Fig. 6.1 is implemented in LabView. NI LabView controls the Multism circuits and creates a suitable user interface the front panel window detailed in Fig. 6. 3. LabView controls the output voltage of the inverter by SPWM generated from the IP Cores shown in the Appendix and discussed in section 5.2.

The system control illustrated in Fig. 6.2 clearly describes different control function blocks. The general idea is to present the whole PV-Grid system together as real and visible system in a LabView environment. In the control system there are function blocks for converting the inverter output to RMS value. It also gives the frequency at each time the simulation is running up to when 50Hz grid frequency is attained. The three phase grid is shown and one phase is taken to compare with the inverter outputs as well for switching signal generation.

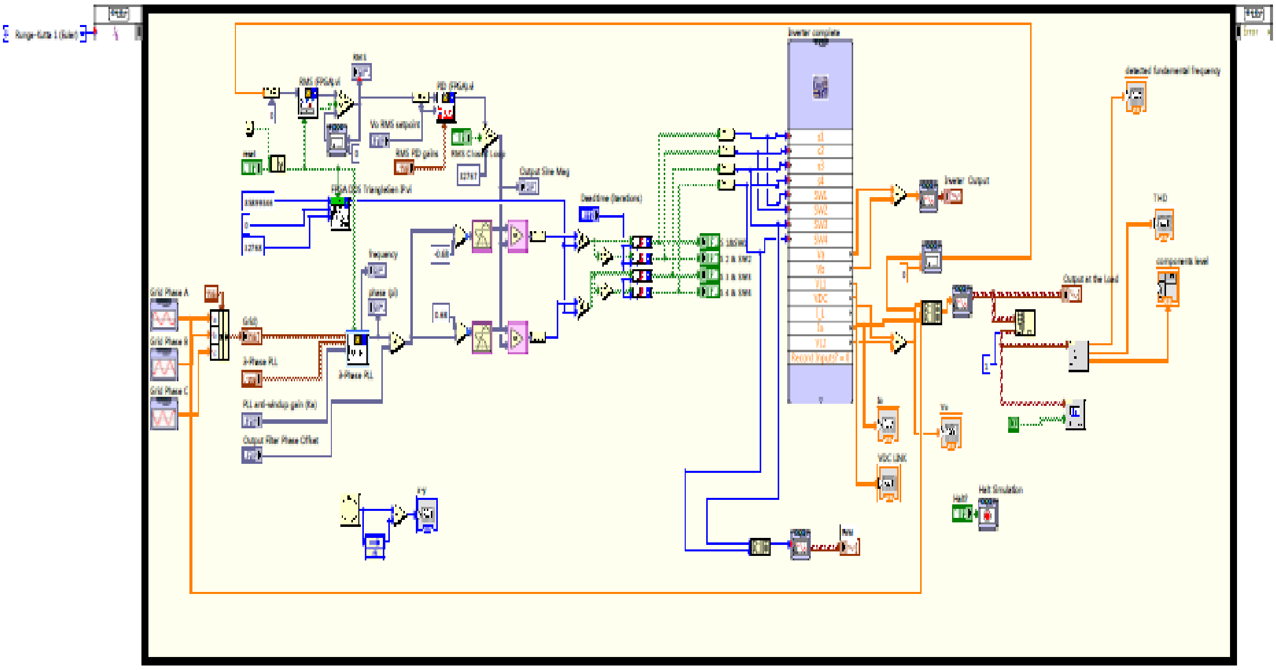


Fig. 6.2: Inverter Power Stage Control in LabView

The IP Cores used in the design are the courtesy of NI LabView. The main control blocks include, RMS IP Core for calculating the RMS value of the output voltage of the designed inverter power stage. PID IP Core for amplitude regulation of the output voltage from the inverter and the grid inputs. The phase locked loop block, locks the phase of the generated PWM signal and the phase of the line voltages signal to be connected to the grid

It has seen very easy and possible to organize the real project idea as whole in NI LabView. This is seen from the DC-DC stage to the DC-AC stage converter topology that has been coordinated from the Multism design to LabView. The inverter power stage from Multsim is seen as one block with inputs and output controls and constants.

Then the clear front panel that provides the detail of every block and easy understood by the user is obtained from the controls blocks. The control gives options to different outputs, regarding to what the user wants to instigate and analyze. There are options for output current and voltage, the harmonic analysis, the PWM signals, DC-Link voltage, inductor and capacitor currents.

The front panel provides a clear interface of what is executed behind the control block diagram. It is very easy to understand and analyze. The front panel of the control of power stage inverter is presented in Fig. 6.3 shows the inverter output before filtering, output current and voltage at the load as compared to the grid voltage. It also shows the pulses for switching one leg of the inverter power stage. Harmonics are analyzed by three indicators set in the front panel as per component level of harmonics, Total Harmonic distortion (THD) and the detected fundamental frequency.

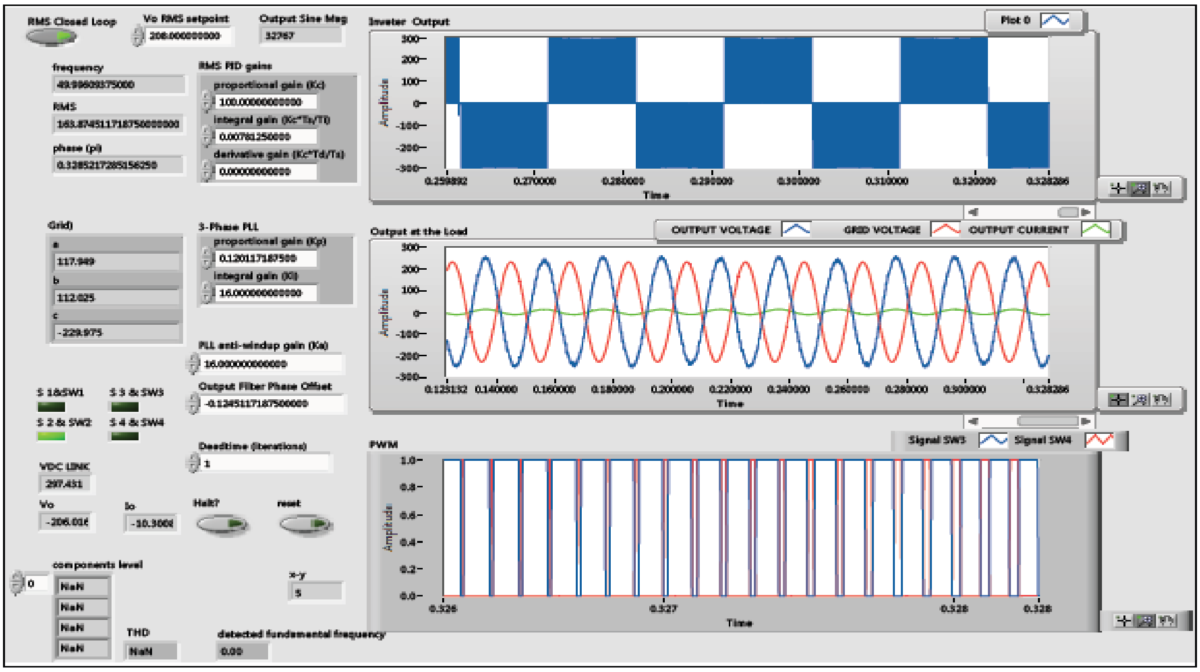
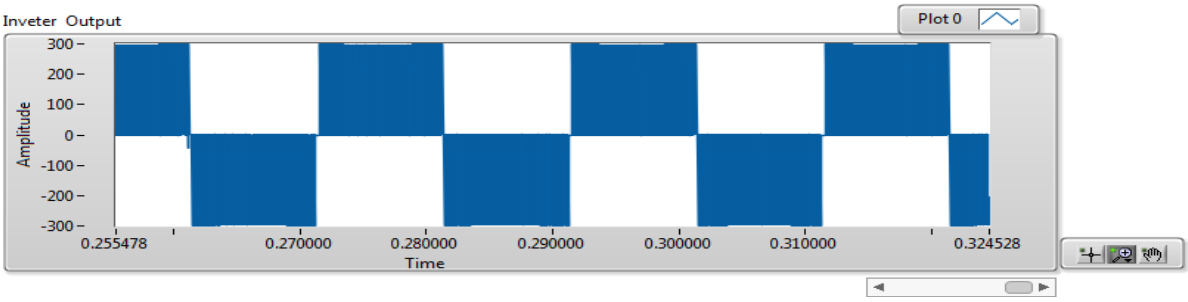


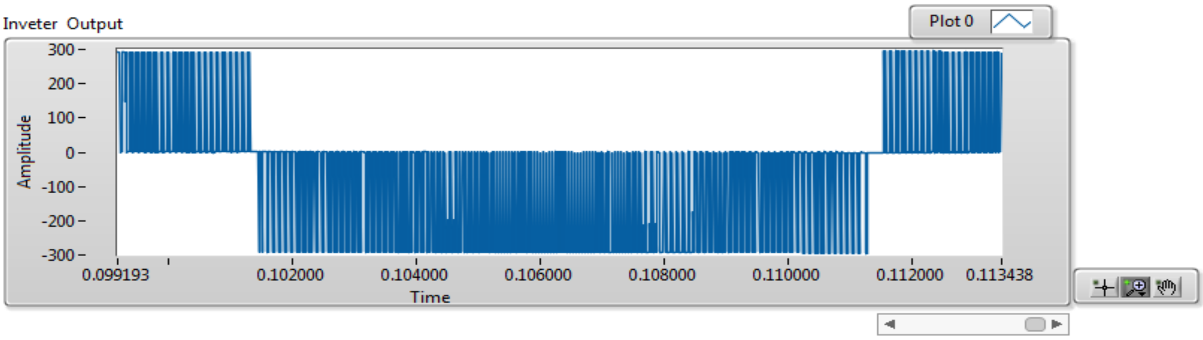
Fig.6.3: Front Panel of the control of Inverter Power stage

6.1.3 Inverter output voltage

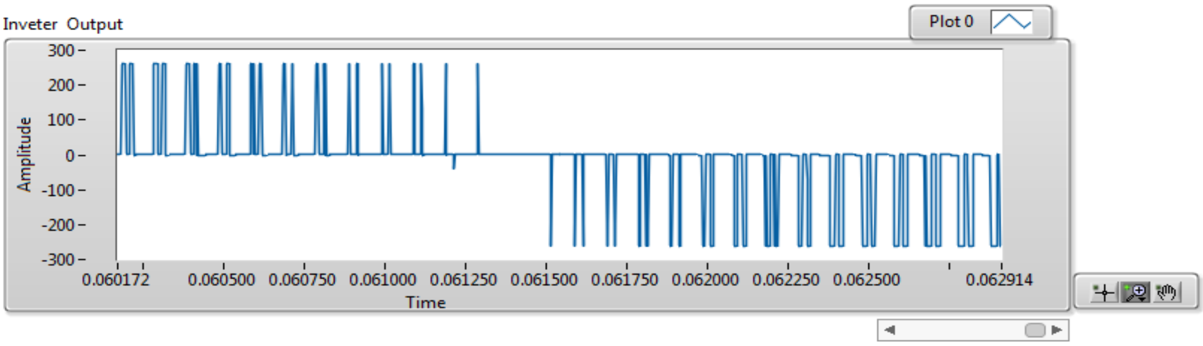
The output voltage of the power stage inverter is shown in Fig 6.4 as unfiltered output with switching effects. Its amplitude of peak voltage switched to approximately between -300V and +300V through zero. When all the parameters in the inverter reach steady state, the output of the inverter will switch between positive to negative peak of the DC-link voltage. This voltage is then filtered by the L-C-L filter designed in this thesis to minimize these distortions. The clear output voltage is depicted in Fig. 6.5.



a) Typical Inverter output voltage



b) Moderate detailed



c) More detailed

Fig. 6.4: Unfiltered Inverter output voltage with different zooming levels on LabView

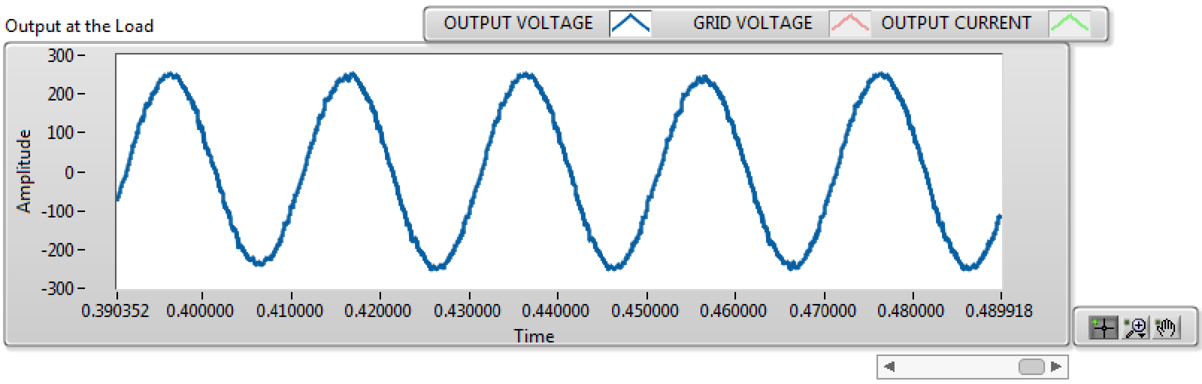
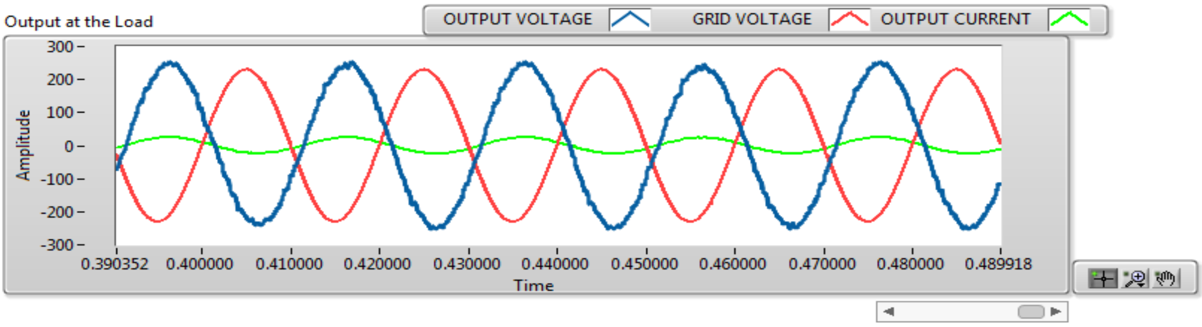


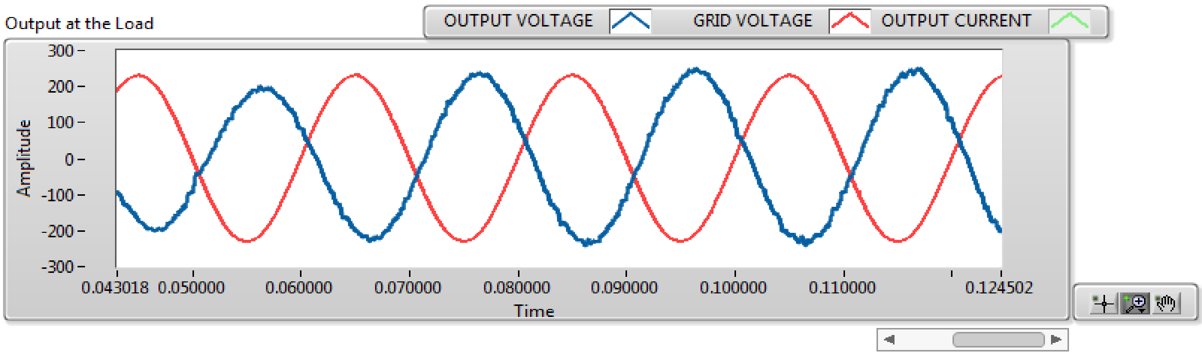
Fig. 6.5: Inverter filtered output voltage

6.1.4 Inverter output and Grid Voltage

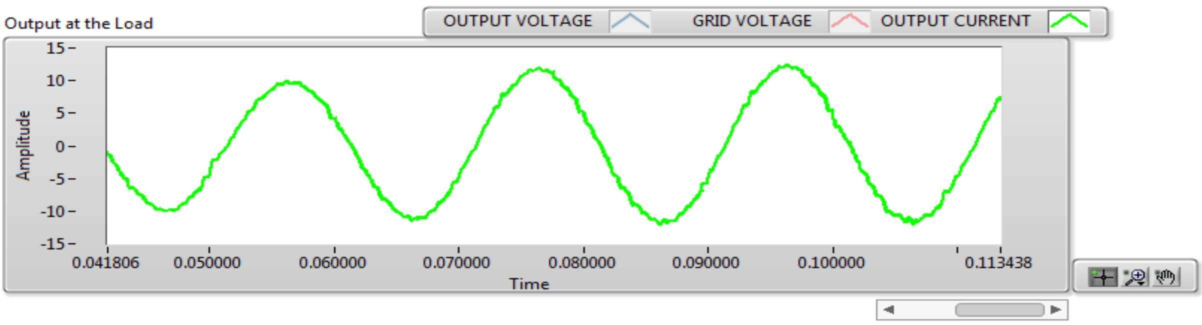
Output waveforms of the inverter in Fig.6.6 shows at the LabView stable response of the grid voltage and output current. It can be seen that the phase of the output current with clean sinusoidal waveform is 180° out of phase with the grid voltage, which means in this case, the electricity generation is realized by the string inverter system. The slightly phase shift between the output is due to the filter output phase.



a) Inverter output Voltage & Current and Grid Voltage



b) Grid Voltage and Inverter Output Voltage



c) Inverter Output Current

Fig 6.6: Inverter Output Voltage and Current with Grid Voltage

6.2 Conclusion

PV system of the NTNU renewable energy laboratory has been proposed in this thesis. The system is very useful for academic purposes and researches. The string of the proposed PV system can easily be integrated with other renewable energy sources available. Each inverter of the system is independent and therefore the supply of electricity will be available all the time regardless of whether one inverter fails. Thus this system is available and reliable.

One task in the NTNU renewable energy laboratory project is completed by designing the power stage of the inverter of which the work has been done in this thesis. The power stage is designed in such away it takes the minimum available voltage in the PV string of about 100V. Most important parameters of the inverter stage have been estimated and designed in Multism. The circuitry topology of the dual stage DC-AC conveter is clearly detailed in Multism and it easy to understand each block stage of the converter.

The control of the power stage circuit designed in Multism is very easy implemented in NI LabView. The DC-Link voltage, the output current and voltage and the switching mechanisms of the inverter have influenced by LabView. The user interface from the front panel made easy to understand the outputs from the inverter.

The match of the inverter output voltage in Fig. 6.5 with the grid voltage shows clearly that the target of attaining 230V in the design was successfully. The output current in Fig 6.6 is 10A but was varying depending on the load variation during simulation. Although the voltage is not very clearly fine like the grid voltage, it contains fewer distortions. This is due to the performance of the L-C-L filter parameters. Thus the filter designed in this thesis needs little tuning.

The DC-Link voltage was set to be 400V in calculations, but in short time during simulation it reaches 300V.However it takes couple of seconds to attain the steady state of the parameters when simulated with LabView. The switching unipolar SPWM switching works perfectly as expected. The complete designed inverter in Multism and the control block diagram in NI LabView and all necessary files regarding the design are found in a DVD /CD attached to this thesis.

6.3 Future work

To complete this project, Grid Connected PV system with Smart Grid functionality, there is a great need of designing the control system that would control the designed inverter power of this thesis. The control shall be able to integrate the inverter with other renewable energy sources available. The control strategy plays an important role of making the system smart by coordinate with the IT systems such as internet synchronization EtherCAT networks.

The second important work is the inverter prototype. After the simulation of the inverter power stage obtained the next step is the implementation of the prototype. However with the help of LabView it can be implemented in the real time environment and analyze the performances.

Selection of the components and rating is another work to be done. In this design the value obtained are calculated value for simulation. In engineering work, the standard values are needed in order to suit certain working environments. The selection or even design of high frequency transformer, IGBT/MOSFET switches with driver circuits is indispensable.

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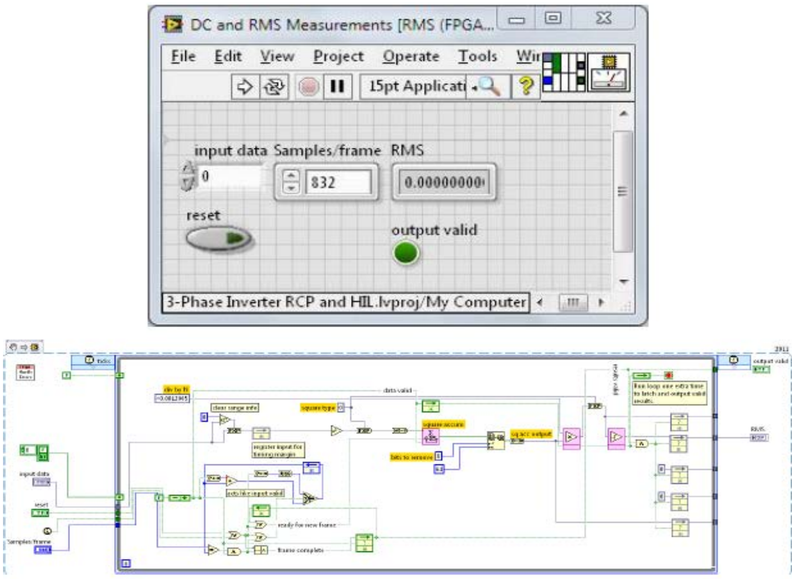
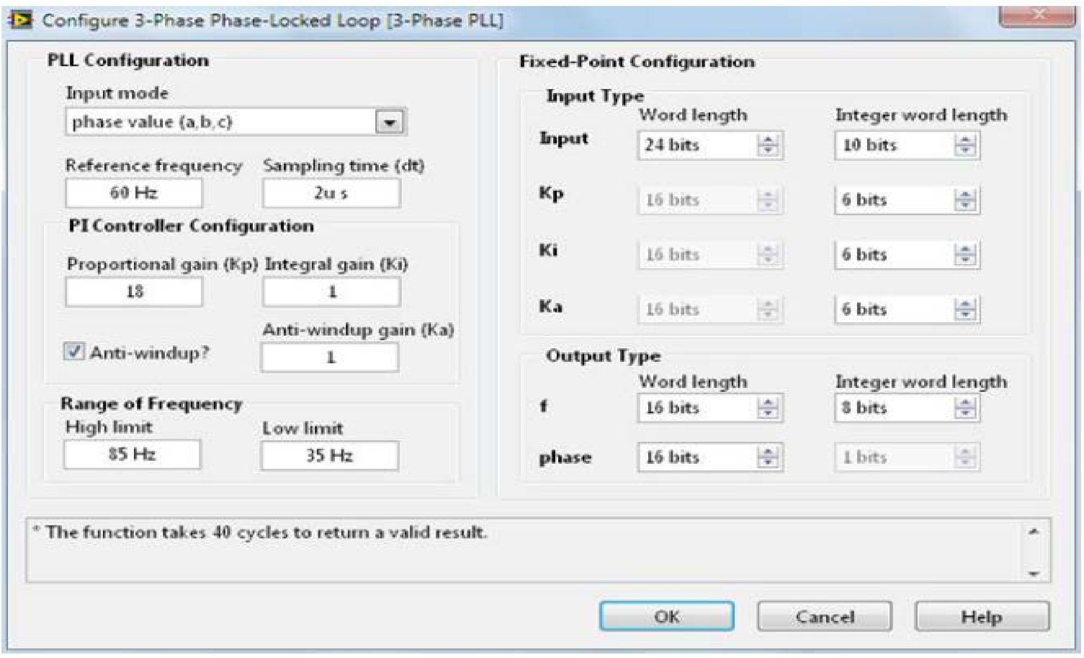
Appendix

NI LabVIEW IP Cores: source www.ni.com [33]

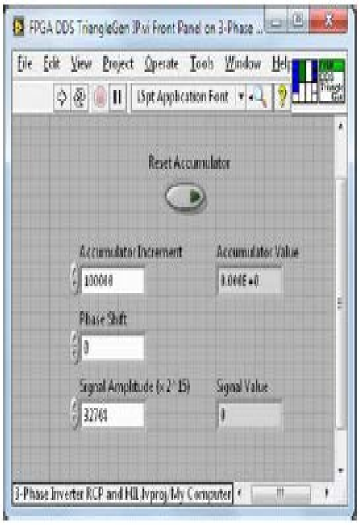
1. RMS VI and Block Diagram

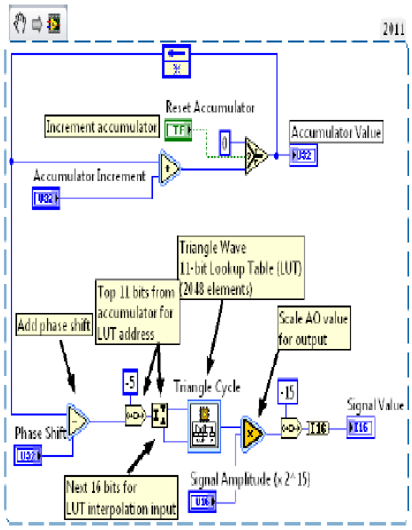


2. PLL Express VI



3. Triangular Wave Generator VI and Block Diagram





4. PID Controller VI and Block Diagram