Independent University, Bangladesh

Design of a Transformer-less Grid-Tie Photovoltaic Inverter Using Dual-stage Buck and Boost Converters

An undergraduate thesis submitted by

Sajib Chakraborty

in consideration of the partial fulfillment of the requirements for the degree of

BACHELOR OF SCIENCE
in
ELECTRICAL AND ELECTRONIC ENGINEERING

Department of Electrical and Electronic Engineering
Summer 2013

DECLARATION

I do hereby solemnly declare that the research work presented in this undergraduate thesis has been carried out by me and has not been previously submitted to any other University / Institute / Organization for an academic qualification / certificate / diploma or degree.

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Date: 19 August, 2013

APPROVAL

The project work report titled “Design of a Transformer less Grid-Tie Photovoltaic Inverter Using dual-stage Buck & Boost Converters” has been submitted by Sajib Chakraborty(ID# 1020397) of Electrical and Electronic Engineering (BSC. in EEE), to the Department of Electrical & Electronic Engineering at Independent University Bangladesh, for the fulfillment of the requirements for the Degree of Bachelor of Science.

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ACKNOWLEDGEMENTS

All praises go to God, the almighty, for the successful completion of this thesis and fulfillment of author's dream into reality. However, thanks and gratitude are also due to the following persons for their continuous support in research and in preparing this report.

First of all, author would like to express his gratitude to his supervisor Dr. M. Abdur Razzak, Associate Professor, Department of Electrical & Electronic Engineering, Independent University, Bangladesh, for his wisdom, patience, and for giving the opportunity to study with him. His guidance and support were the most important assets that led the completion of this thesis.

Special thanks are extended to the author's fellow roommates Wahidul Hasan, Md. Mahamudul Hasan, Afzal Hussain and classmates of the Department of Electrical and Electronic Engineering, Independent University, Bangladesh for their helping hand, continuous support and cooperation during this research.

Finally, the author proud fully acknowledges the great sacrifices, good wishes, moral support, fruitful advice, inspirations and encouragements from his family members, relatives and friends during the research.

The Author
August 2013
Dhaka, Bangladesh

ABSTRACT

Due to swift growth of photovoltaic (PV) power generation, highly efficient and cost effective pure sine wave inverters are greatly demanded in the local market. This thesis paper explores a topology for transformer less pure sine wave grid tie photovoltaic inverter for residential application using dual-stage Boost converter. My proposed gird tie inverter employs dual-stage switch mode boost converter, dual-stage switch mode buck converter, an H bridge inverter, and a T-LCL Immittance conversion circuit. The switching technique of proposed inverter consists with a combination of sinusoidal pulse width modulation (SPWM) and square wave along with grid synchronization condition. As the suggested method is entirely transformer less, it ridiculously reduces total harmonic distortion (THD) which is less than0.1%, minimizes size and swells inverter efficiency up to 97%. T-LCL Immittance conversion circuit provides a nearly constant output current which stabilize system rapidly and reduces harmonics generated by inverter. Overall performance of the proposed inverter is simulated through the PSIM. The simulation results are analysis through PSIM and MATLAB software. The results of simulation show that this new method can be eliminated vast harmonics and is highly efficient. Therefore it may able to meet the challenges of power crises in Bangladesh.

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CHAPTER 1

INTRODUCTION

1.1 Background

With the world energy demand increasing at an exponential rate, the search for energy sources other than fossil fuels is no longer a luxury. Although the fossil fuels offer a temporary solution to this energy crisis, they cause the emission of carbon dioxide and other greenhouse gases, which are harmful to the environment. This has paved the way for research on renewable energy technology and other researches in the fields of power electronics and hence, the cost of utilizing the renewable energy is at an ever decreasing rate [1]. One such source of renewable energy, the Sun, offers unlimited energy for harnessing and for this very reason, Photovoltaic (PV) systems consisting of PV modules, for generating environmental friendly power are gaining more and more recognition with each passing day. The PV modules comprise of several solar cells, which convert the energy of the sunlight directly into electricity, and are connected as required to provide desired levels of DC current and voltage. They produce electricity due to a quantum mechanical process known as the “photovoltaic effect”. The major drawback with these PV systems is that their cost is much high compared to the conventional sources such as fossil fuels and their efficiency are also quite low.

Power semiconductor devices represent the heart of the modern power electronics, and are being extensively used in power electronic converters in the form of a matrix of on or off switches, and help to convert power from one form to another. There are four basic conversion functions that normally can be implemented such as AC to AC, AC to DC, DC to AC and DC to DC. Inverter is one of the converter families which are called DC to AC converter. It converts DC power to AC power to a symmetric AC output voltage at desired magnitude and frequency (Ahmed, 1999). Inverter is widely used in industrial applications such as variable speed AC motor drives, induction heating, standby power supplies and uninterruptible power supplies. The DC power input of inverter is obtained from the existing power supply network. It can be a battery, photovoltaic, wind energy, fuel cell or other DC sources.

SPWM or sinusoidal pulse width modulation is widely used in power electronics to digitize the power so that a sequence of voltage pulses can be generated by the on and off of the power switches (Ismail, 2006a). The pulse width modulation inverter has been the main choice in power electronic for decades, because of its circuit simplicity and rugged control scheme (Bellar et al., 1998). SPWM switching technique is commonly used in industrial applications (Ismail, 2006b) (Rashid, 2004). SPWM techniques are characterized by constant amplitude pulses with different duty cycle for each period. The width of this pulses are modulated in order to obtain inverter output voltage control and to reduce its harmonic content.

In this proposed paper, recommended PV configuration consists of five main components: 1) a PV array for energy conversion solar to electrical, 2) dual-stage DC-DC boost converter with MPPT, 3) an H-bridge DC-AC inverter to acquire AC voltage, 4) a T-LCL immittance converter to deliver a nearly constant output current and 5) dual-stage AC-DC buck converter which is used at gate signal by combining SPWM and square wave for switching of inverter shown in Fig.1.1.

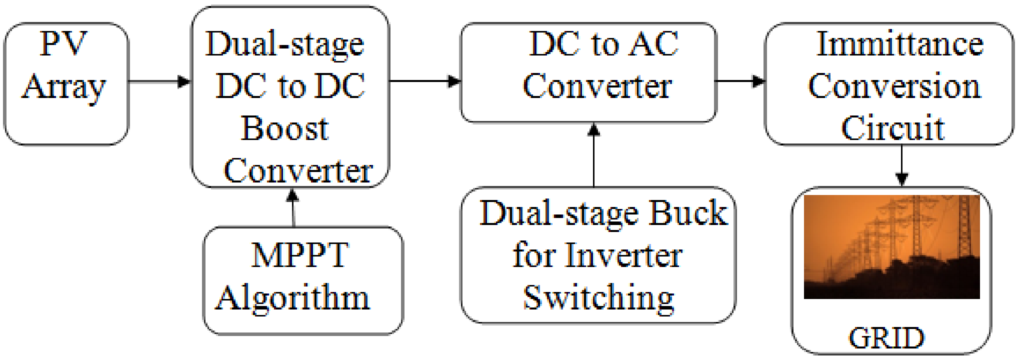

Fig. 1.1: Block diagram of transformer less GTI

1.2 Problem Statement

Inverter is one of power conversion device that widely used in the world to convert DC input voltage to AC output voltage. The output voltage waveforms of ideal inverters should be sinusoidal. However, the waveform of practical inverter is non-sinusoidal and contains harmonics. Then, for this project, it should get closer sinusoidal waveform within +- 1% harmonics contains. Harmonic contents in inverter output depends more to number of pulses per cycle. As an example, square wave switching method will produce more harmonic contents in inverter output compared to pulse width modulation switching technique. This is due to number of pulses per cycle of pulse width modulation can be modified on the frequency of triangular carrier waveform. The frequency of triangular waveform can be modified from lower frequency to higher frequency. If higher frequency is used, the number of pulses per cycle also increased and at the same time it will reduce the harmonic contents of the inverter.

In switching losses problem, the number of pulses per cycle also affected. The use of high switching technique will contribute to the high power losses and it also needs to take care on the inverter switching design. The following factors are to be considered in order to meet the requirement.

i. Cost of equipment
ii. Size of filter
iii. Total harmonic distortion
iv. Power loss in switching elements

In order to fulfill the requirement, the new switching technique had been analyzed and recommended in this thesis, namely SPWM which is generated with combination of high frequency triangular wave and square wave. Then T-LCL filter is used which will be provided a nearly constant output current which stabilize system rapidly and reduces harmonics generated by inverter.

1.3 Objectives

The aim of this research is mainly to design and develop the SPWM switching pulse for single phase Grid-Tie Inverter (GTI) application. The main objectives of this research can be summarized as:

- To design and implement switching strategy for inverter application, which are simple, reliable, low cost and high efficiency.
- To use the power electronics simulation software, PSIM version 9.001 to simulate the designed circuits with variety switching conditions to obtain optimum performance
- To develop gate pulse switching of GTI with combination of SPWM and square wave
- To develop a complete prototype of inverter with 2500W power rating for photovoltaic application
- To compare and analyze the simulated results
- As transformers are bulky, heavy weighted and expensive so the paper target is to implement an inverter circuit without transformer which will help to provide pure sine wave AC output voltage while maximizing efficiency and reducing the total harmonic distortion (THD).

1.4 Research Methodology

The methods that will use to finish this thesis are illustrated through the flow chart shown in Fig.1.2:

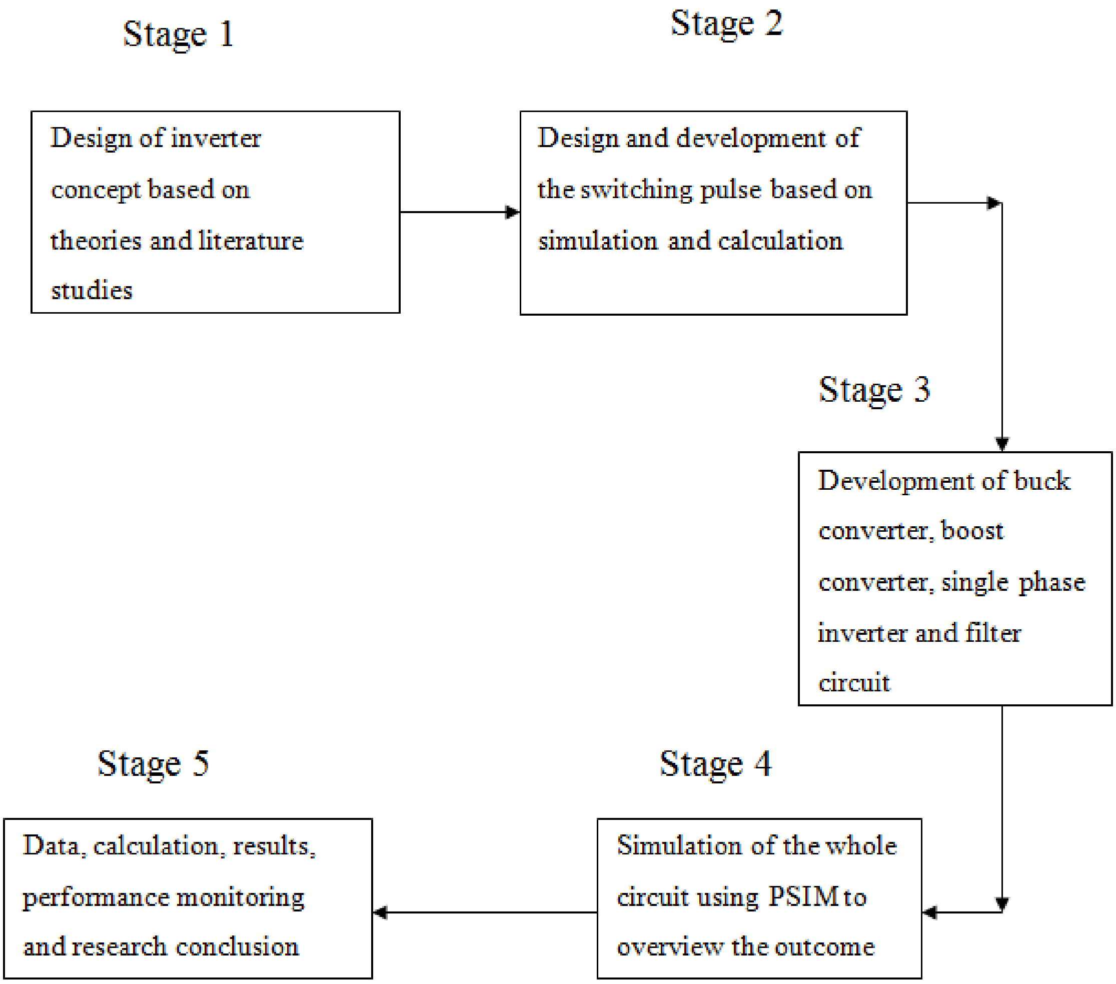

Fig. 1.2: Research Methodology

1.5 Organization of this Report

The thesis consists of five chapters. A short explanation is introduced here:

- **Chapter 1: Introduction**

  This chapter discuss about the issue relating to the background of the thesis objectives, methodology and research structure.

- **Chapter 2: Literature Review**
- This chapter discusses mainly about PV array, buck converter, boost converter, new technique of sinusoidal pulse width modulation, different inverter technique, converter topology, and application. Some of literature regarding this thesis topic is also included in this chapter.
- **Chapter 3: Design and circuit analysis**

  The Chapter 3 describes in detail the ideal Grid-Tie Inverter, design value and the circuit analysis of the DC-DC boost converter, DC-DC buck converter, T-LCL type immittance converter which includes the derivation of the input-output current and voltage equations and the efficiency equations.

- **Chapter 4: Simulation of Inverter**

  The chapter 4 will focus on mainly to the procedure, method, and theory implementation through simulation designing and of proposed PV inverter related to the thesis topic.

- **Chapter 5:Result and Discussion**

  The PV inverter is simulation tested, and verified. The tests include the efficiency of the designing DC-AC PV system and its performance.

- **Chapter 6: Conclusion**

  Finally, a conclusion on the obtained results is presented. This also includes the novelties within the work, and suggestions for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Analysis Design of PV Array

When sun rays diving into PV cell it converts solar energy into electricity. There exists two layer in a PV array, N-type layer and P-type layer, the two layers work together and generate electricity when photon exceeds band gap of solar cell. The equivalent circuit of a solar cell can be described as a current source is parallel with a diode and shown in Fig.2.1.

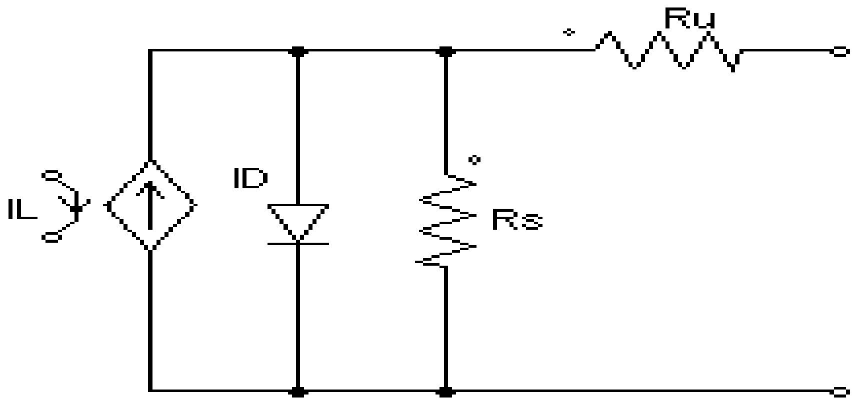

Fig.2.1 Equivalent circuit of solar cell

This research discus the control algorithm of PV system by using simple model which ignoring insignificant voltage losses through series and parallel resistor of PV array, thus the V-I characteristics formula is simplified as following formula [1-2].

$$I = I_{sc} - I_d \left[e^{\frac{q(V + IR_S)}{AKT}} - 1 \right] \tag{2.1}$$

$$V = \frac{AKT}{q} \ln \frac{I_{sc} + I_d - I}{I_d} \tag{2.2}$$

$$P_{\max} = VI = V \left[I_{sc} - I_d \left(e^{\frac{qV}{AKT}} - 1 \right) \right] \tag{2.3}$$

$$\frac{dI}{dV} = \frac{q}{AKT} \left(I + I_d - I \right) \tag{2.4}$$

In above formula all values are taken under Standard Test Condition (STC). Here, T is cells temperature, q is electron charge, A is a non-dimensional fitted curve constant (1≤A≤2), K is a Boltzmann constant (K=1.38×10 - 23J/K). Isc is photo - generated current and Id is reversed saturation leakage current in diodes. The value of Isc and Id also depend on intensity of the sun light and environmental temperature and $P_{\max}$ is maximum power exerted from the PV array.

2.2 Photovoltaic system(PV) in Building Environment

Renewable energy sources (RES) are considered as a technological option for significantly contributing to the sustainable energy supply in Europe. PV energy generates electricity from solar radiation and, at present, represents one of the RES emerging technologies due to the continuous cost reduction and technological progress. The minimum element in the manufacturing of PV systems is the PV module. A typical panel is composed of 30–36 series-connected solar cells, with an open-circuit voltage (*V*oc) near 20 V and a short-circuit current (*I*sc) around 3–4 A. For most applications, e.g., integration in building environment and autonomous applications, the power of one PV module is not enough.

As a result, it becomes necessary to group PV modules until the desired current and voltage levels are achieved. The efficiency of commercial PV modules is about 14%–16%. However, PV systems show additional losses that are important in many cases. If not considered during the PV design phase, unreal estimations will be foreseen, and public image of PV energy could be damaged. Issues carried out by the University of Tokyo over 71 Japanese PV systems have shown losses of up to 25%. Causes are varied, ranging from load mismatching (although most PV systems have maximum power point tracking (MPPT) incorporated), differences in current–voltage ($I–V$) characteristics, shadows, dust, losses in PV inverter, low-radiation losses, and MPPT losses [1].

Various alternatives architectures for grid connected PV system configurations are available, such as centralized module, AC module and modular configuration where the last topology perfectly fits with an intelligent PV module concept [2]. A few possible configurations of grid connected PV systems are shown in Fig.1. A centralized inverter configuration is illustrated in Fig. 2.2(a) that interfaced huge number of PV modules. But, there are some severe limitations in the design of centralized inverters, such as power loss for using a central MPPT, PV modules with mismatch losses due to the high voltage dc cabling connecting the PV modules with the inverter, string diode loss etc. Fig. 2.2(b) shows the AC module configuration, which is a simplified version of the centralized inverter topology.

A single string of PV module is connected with an inverter. Each string can be applied with a separate MPPT, as there is no loss attributed to string diodes. In comparison to the centralized inverter the overall efficiency is increased. Fig.2.2(c) shows the modular configuration. A common inverter is joined with multiple strings connected to individual DC-DC converter. The benefit of this modular configuration over centralized system is that each string can be controlled individually and ensure less cabling loss thereby enhancing the overall system efficiency[3],[6],[10].

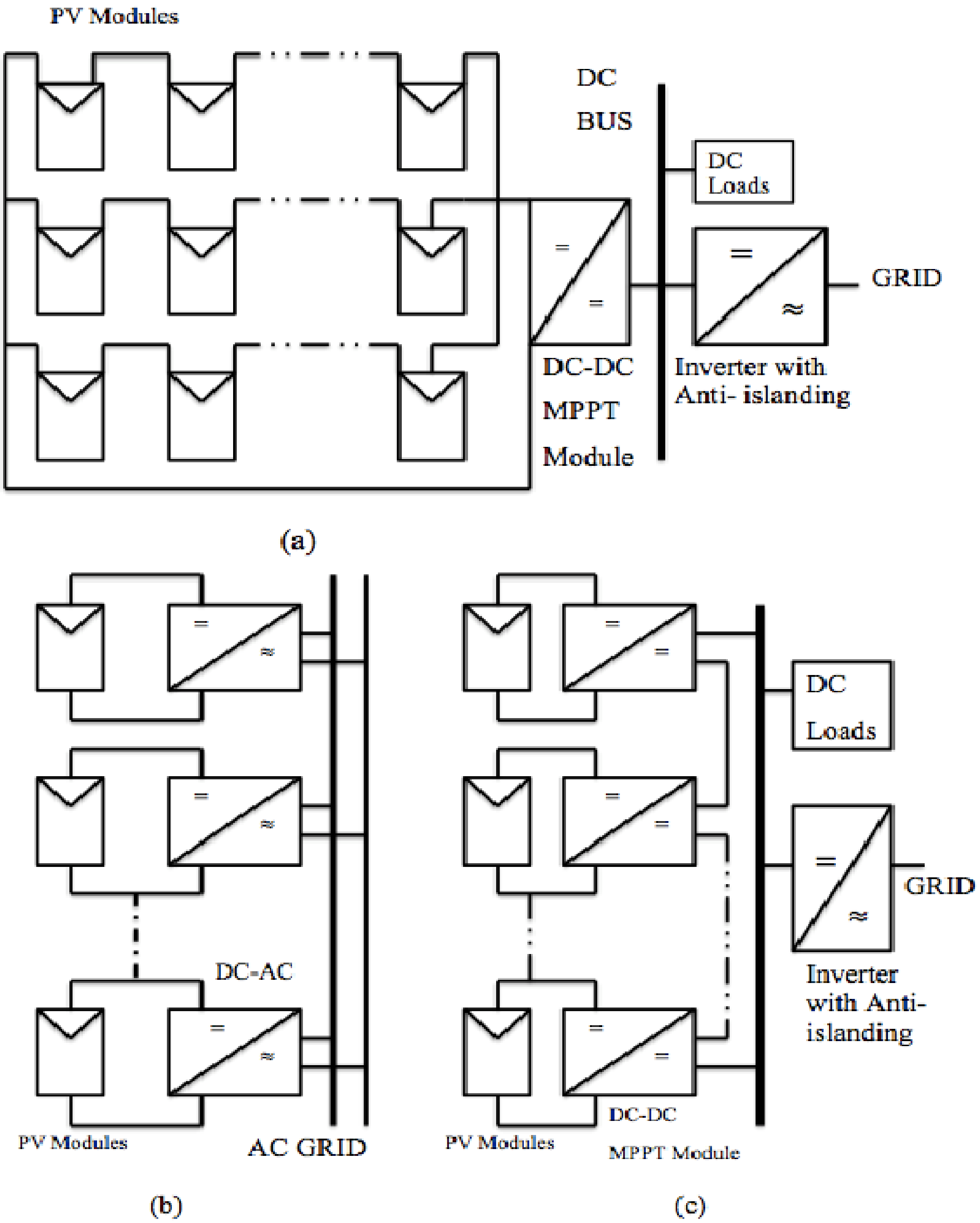

Fig.2.2. Grid connected PV system configurations (a) Centralized module (b) AC- Modules (c) Modular system

2.3 Control Strategy for MPPT Perturbation &Observation (P&O) Algorithm

There subsists different algorithm for MPPT design such as: Perturb-and-observe algorithm, Open and short circuit algorithm, Incremental conduction algorithm, Fuzzy logic algorithm among all algorithms P&O is one of the best because of its simple design and high reliability. It is just following “Trial and Error”. The algorithm is driving periodically by compared output power with the previous cycle. Depending on output power perturbing cycle ether rises or fall.

If output power is increasing the cycle will continue by remaining unchanged and enters into the next cycle, else the perturbation cycle way will be reversed. Therefore array terminal voltage is perturbed for every MPPT cycle. Thus when maximum power is determined P&O will be started to oscillate around it [1-3], [10]. The flow chat of P&O algorithm is given in Fig.2.3.

In P&O method at first P (N) is calculated from present value of voltage V (N) and current I (N). Subsequently P (N) is compared with the next level of power P (N+1). If the power increases then the voltage is changed through the same direction as the previous changes else the change will be reversed.

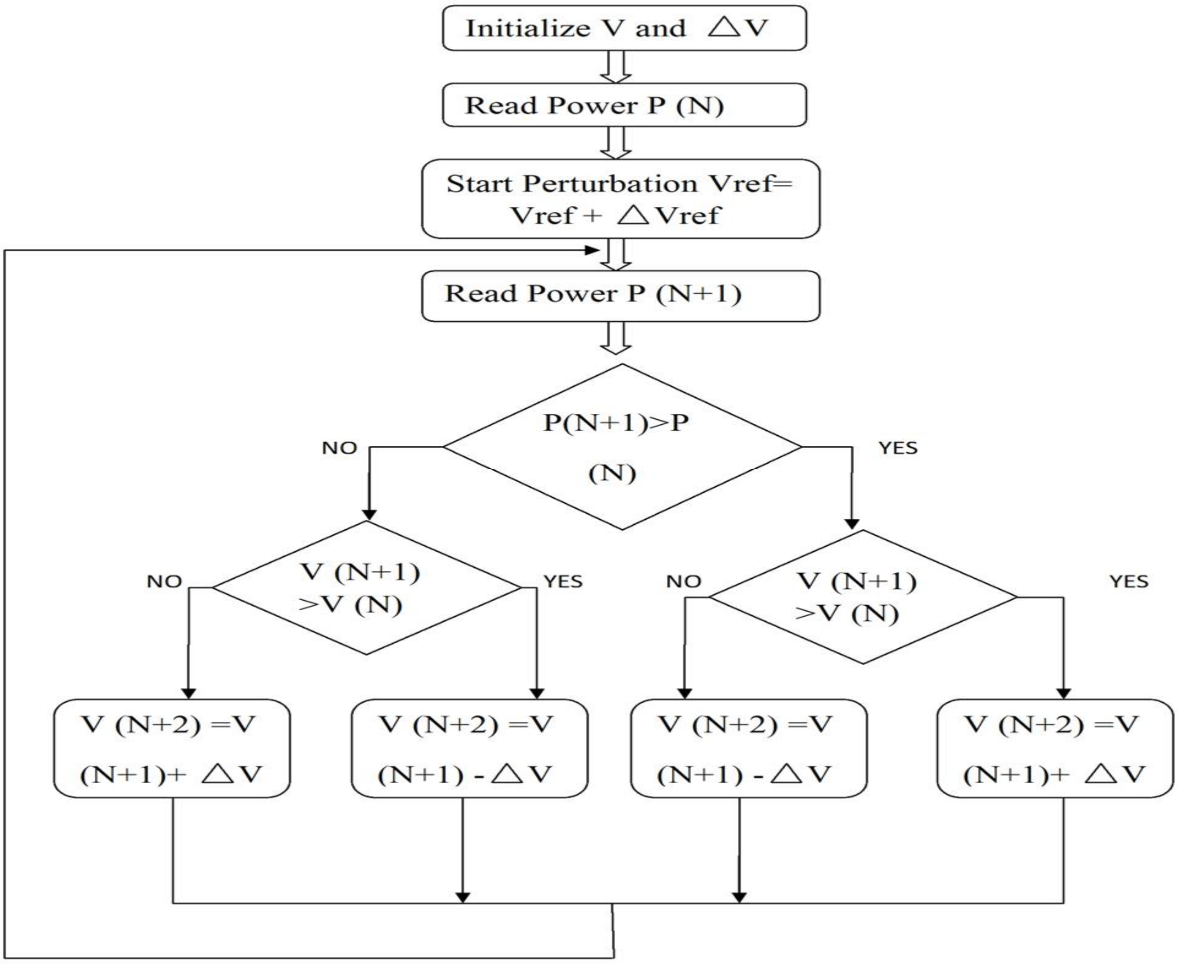

Fig.2.3. MPPT Perturbation &Observation (P&O) Algorithm

2.4 Power Electronics

Power electronics to process and control the flow of electric energy by supplying voltage and current in from that is optimally suited for user load. In power electronics, an electrical device should be able to achieve the highest efficiency compare to the linear electronics. Linear electronics utilize semiconductor devices that operate at their active region and a transformer just for electrical isolation. Fig.2.4 shows the power electronics systems that utilize a close loop operation.

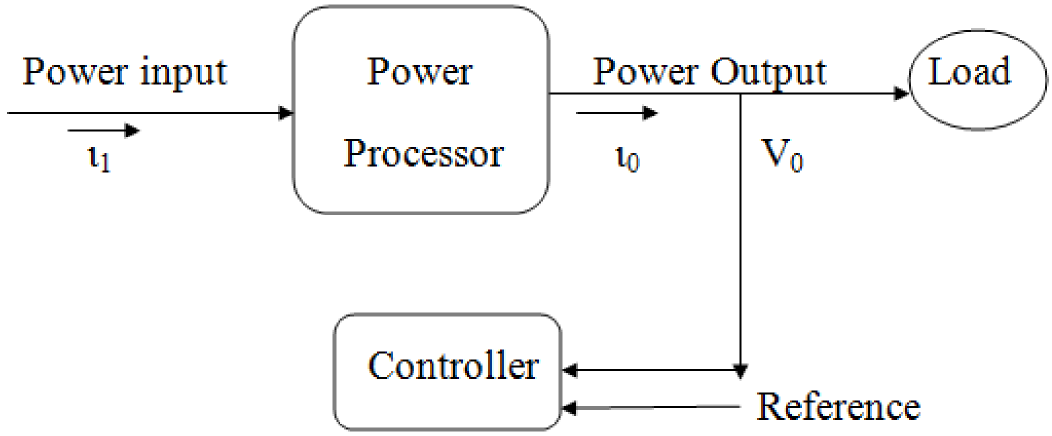

Fig.2.4. Power electronic system

In managing the energy consumed by load, power electronics system utilized switching methods to minimize the appearance of active region in semiconductor device. Although it is impossible to remove all power dissipated by semiconductor, switching mode has greatly reduced the power consumed in semiconductor devices. Therefore, the power consumed in semiconductor is then proportional to the switching frequency. Power electronics is the field of electrical engineering related to the use of semiconductor devices to convert power from the available source to that required by a load. The load may be AC or DC, single-phase or three-phase, and may or may not need isolation from the power source. The power source can be a DC source or an AC source (single-phase or three-phase with line frequency of 50 or 60 Hz), an electric battery, a solar panel, an electric generator or a commercial power supply. A power converter takes the power provided by the source and converts it to the form required by the load. The power converter can be an AC-DC converter, a DC-DC converter, a DC-AC inverter or an AC-AC converter depending on the application [10-12].

2.5 Dual-stage DC-DC Boost converter

A DC to DC converter is a type of power converters which converts a source of direct current (DC) from one voltage level to another, by storing the input energy momentarily and then releasing that energy to the output at a different voltage. The storage should be in electric field storage components or in magnetic field storage components. There are three basic types of converter: buck converter, boost converter, and buck-boost converter. In my proposal, DC-DC boost converter is used for converting unregulated voltage to a fixed level regulated voltage. In my design I preferred boost converter in case of steady environmental condition that successfully amplify PV arrays voltage into required level that is shown in Fig.2.6. This power converter is controlled by Pulse Width Modulation (PWM) and applied through transistor. To achieve desire output from power converter the duty cycle of the PWM should be large and from datasheet it is found conventional transistors will not response at that level of high duty cycle [13]. Therefore to make convenience duty cycle power conversion done through 2stage. Fig. 2.5 is shown boost power converter circuit of dual-stage boost power converter that operates via MPPT algorithm of an intellectual PV system and increases the power of solar system which ensures optimum load impedance by varying duty cycle [8], [13].

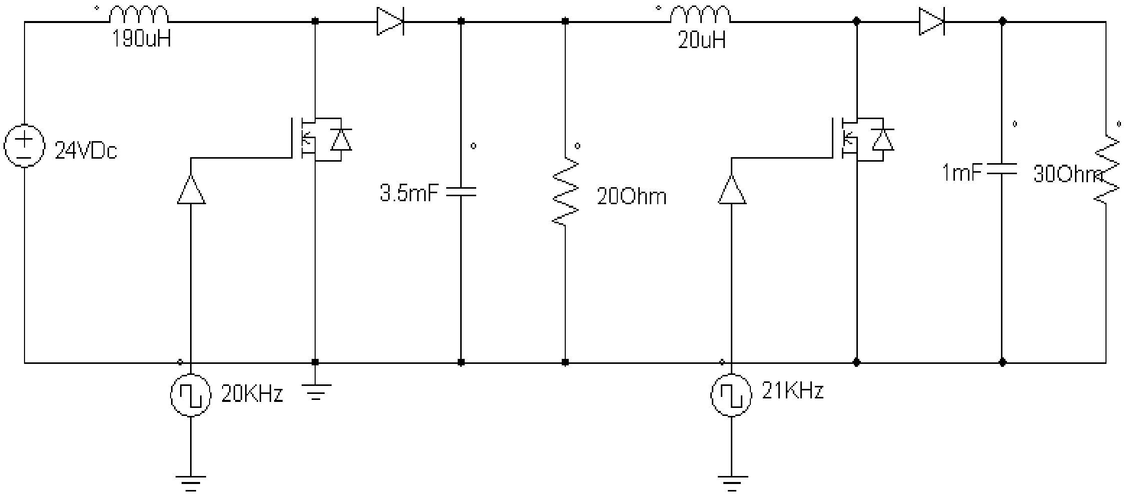

Fig.2.5. Dual-stage Boost Power Converter

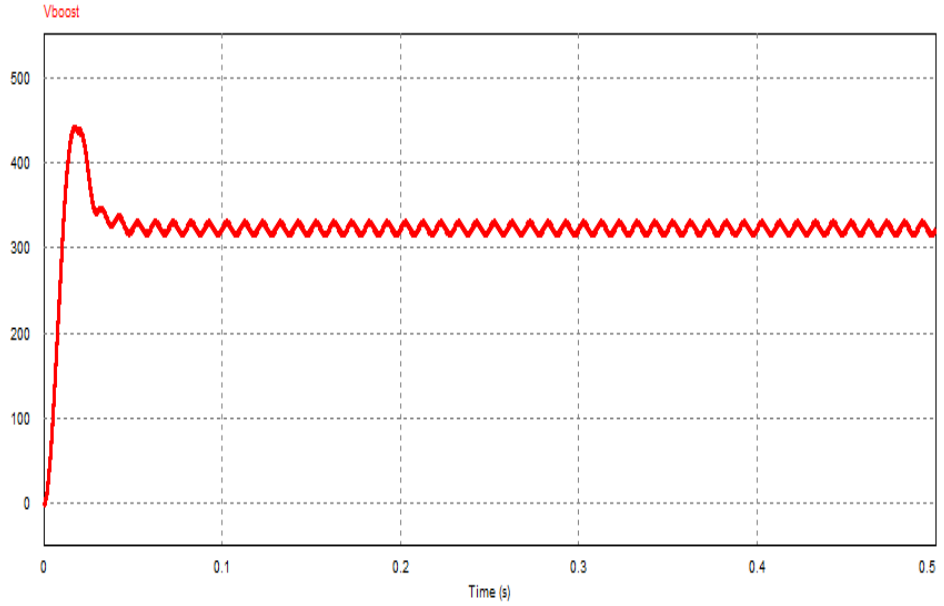

Fig.2.6. Dual-stage Boost converter output

The boost converter is used for 24V-312V conversion and it is used instead of transformer. Therefore in case of inverter use harmonics is the main consideration. If the harmonic of boost converter is more than transformer than it will be well to use transformer moreover transformer is bulky in size whereas boost converter circuit is light in weight.

2.6 Harmonics

In power electronics application, high switching mode can result harmonic components in output waveform. Harmonic of a wave is a component frequency that is an integer multiple of fundamental frequency [12].

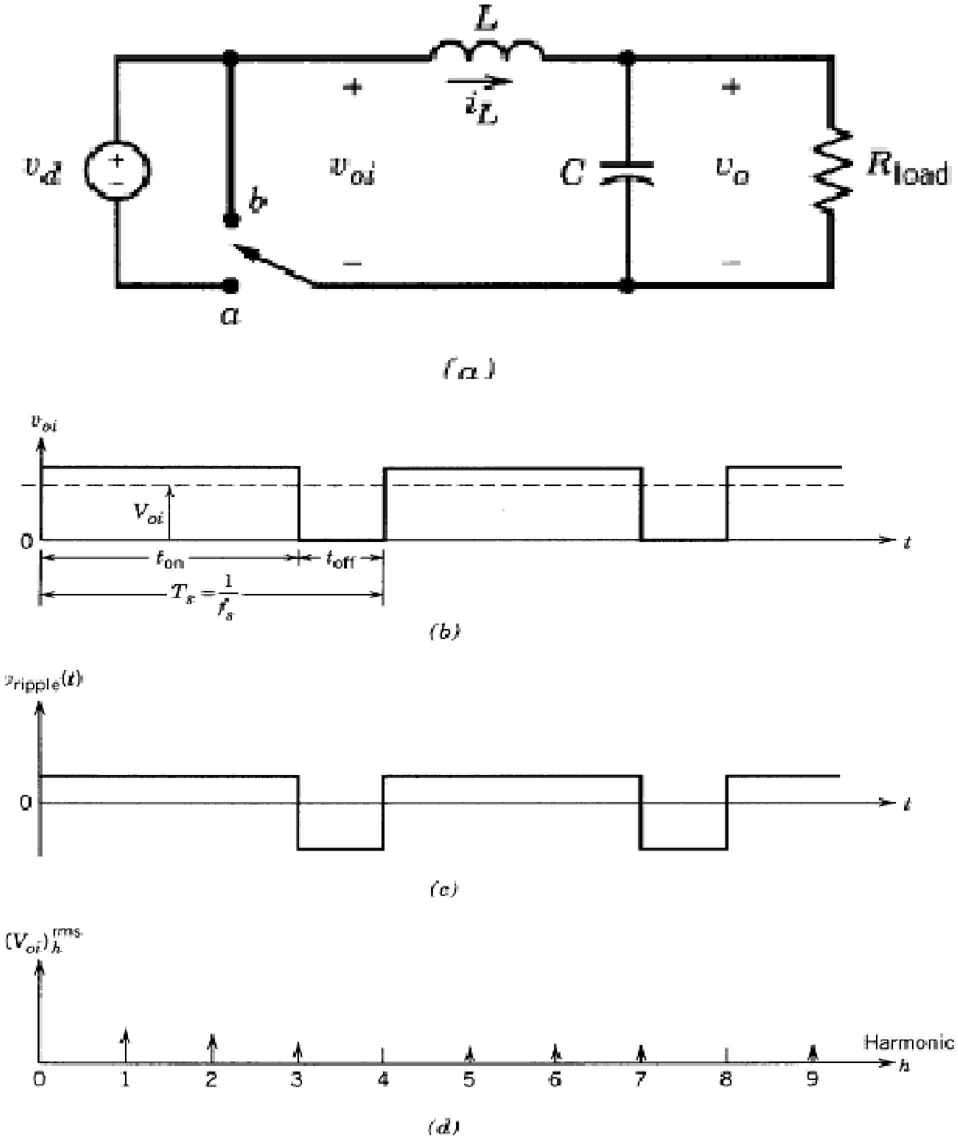

Fig.2.7. Harmonics happen at switching

Fig.2.7 (a) harmonic is created during fast switching mode. A DC voltage V_{oi} is the desired output. While V_d(DC voltage) is the voltage source that is greater than V_{oi}. Switching is used to get an average value of output waveform equal to V_{oi}. The result waveform is depicted Fig.2.7 (b). Dashed V_{oi} in Fig. 2.6 (c) known as fundamental component and Fig.2.7 (d) is known as its harmonics. The sum of fundamental and harmonic will result the actual waveform.

2.7 Dual-stage AC-DC Buck converter

In proposed buck power converter the input is taken from grid. And grid AC voltage is converted into pulse setting DC through full bridge rectifier shown in Fig.2.8. Subsequently pulse setting 220V DC is converted into 5V DC by using buck power converter. To achieve desire output from power converter the duty cycle of the PWM should be very small and from datasheet it is found conventional transistors will not response at that level of low duty cycle [11]. Therefore to make convenience duty cycle power conversion done through dual-stage. The buck converter is used to take sample from grid. The sampled 5V pulse setting DC is used to generate the SPWM signal thus ensuring output voltage from GTI will have same frequency as the grid [8],[14]. Fig.2.9. illustrates output signal of buck converter.

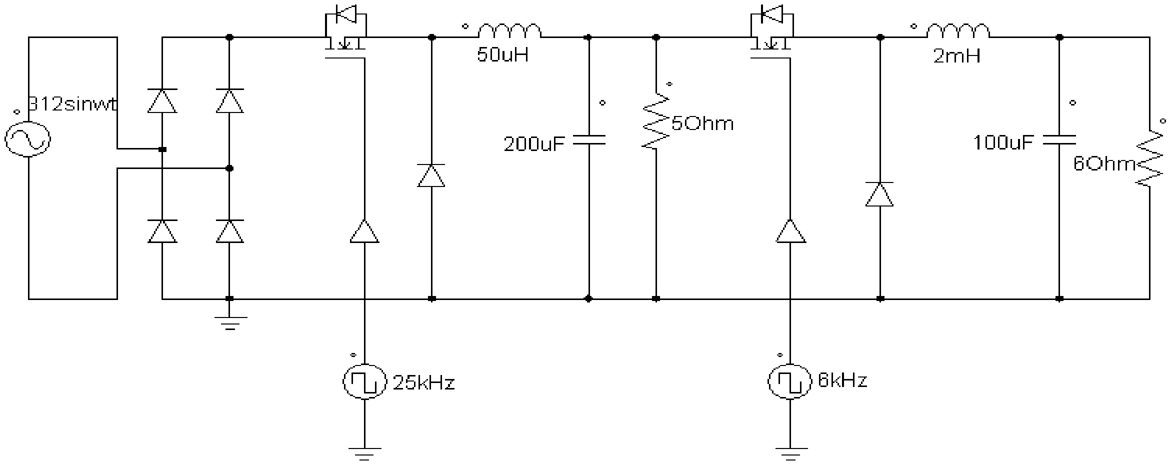

Fig.2.8. Dual-stage Buck power converter

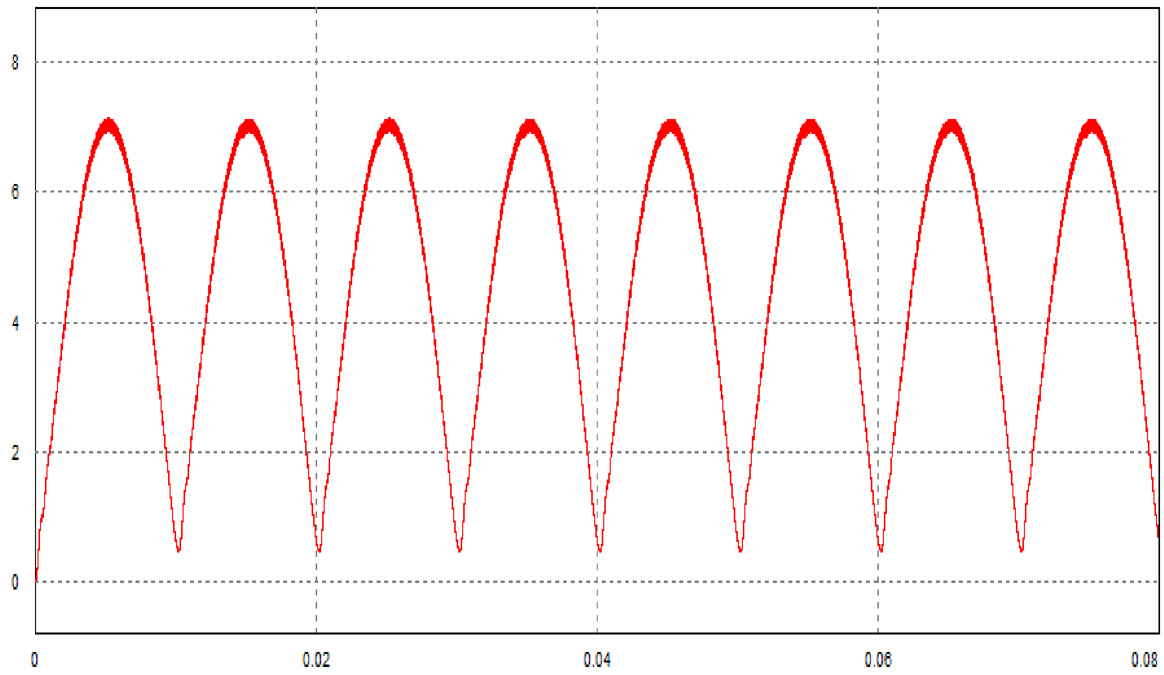

Fig.2.9. Dual- stage buck converter output (RMS 5V)

Buck converter is used for grid synchronization as well buck is used for gate drive circuit to reduce harmonics. As the input voltage of buck is taken from grid hence frequency of inverter output will be as equal as grid frequency. As microcontroller input is 5v therefore buck conversion is used to convert 312V-7.07V means RMS 220V-5V conversion.

2.8 Sinusoidal Pulse Width Modulation

In a conventional inverter design, normally the switching will used one type of the switching technique only. However, in this proposed design instate of using one type of switching signal to switch the inverter, a combination of SPWM and square wave is used [3]. With this kind of combination switching, the switching loss across the switches of the inverter will be greatly reduced due to reduce of switching frequency. The block diagram of the proposed switching circuit is as shown in Fig.2.10. In order to simplify the synchronizing process, instate of generating the sine wave from the analog oscillator or from the microcontroller and digital-to-analog converter (DAC), the sine wave of the proposed design will be sampled from the power grid by using the buck power converter to step down the 220V grid voltage to 5V is shown in Fig.2.7. With the sine wave sampled from the grid and used to generate the SPWM signal, the frequency of the output voltage from the GTI will be having the same frequency as the grid voltage where this is one of the most important requirement for the GTI as stated in the section2.7.

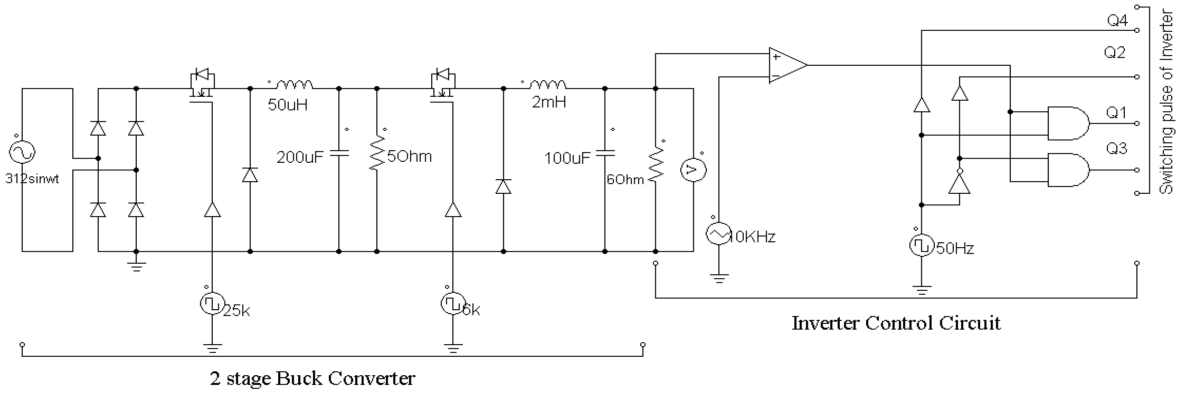

Fig.2.10. Block diagram of the proposed switching circuit

Besides processing the sampled sine wave, to produce a SPWM signal, a high frequency triangle wave also required. In this proposed design the high frequency triangle wave wills also generated by the analog oscillator and the frequency will be 10 kHz. The comparison of sampled grid rectified wave $V_{modulation}$ and high frequency triangular wave V_{tri} is shown in Fig.2.11.

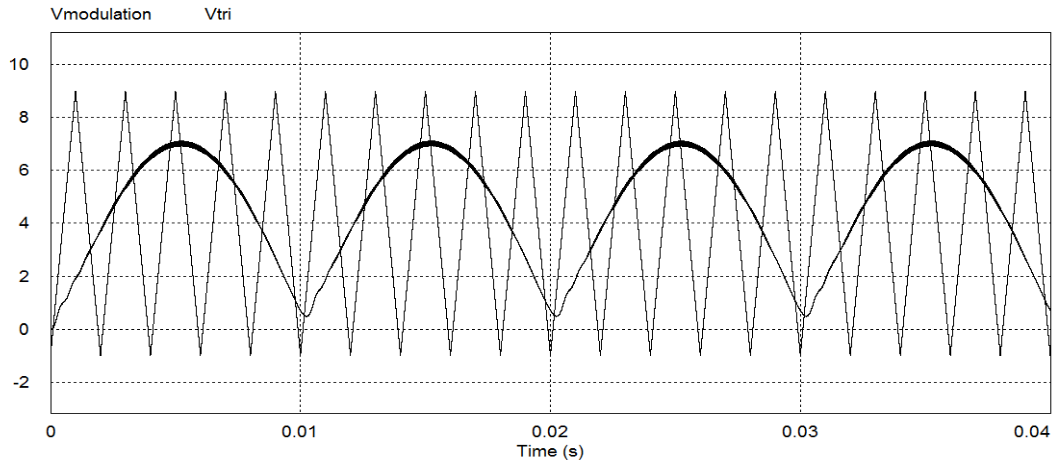

Fig.2.11. Sinusoidal pulse width modulation generation

These two signals will then pass though a comparator to produce SPWM for the switching signal. These two signals will produce a uni-polar SPWM as shown in Fig.2.12. The uni-polar SPWM signal have only positive value and will be change from +5V to 0V and back to +5V again.

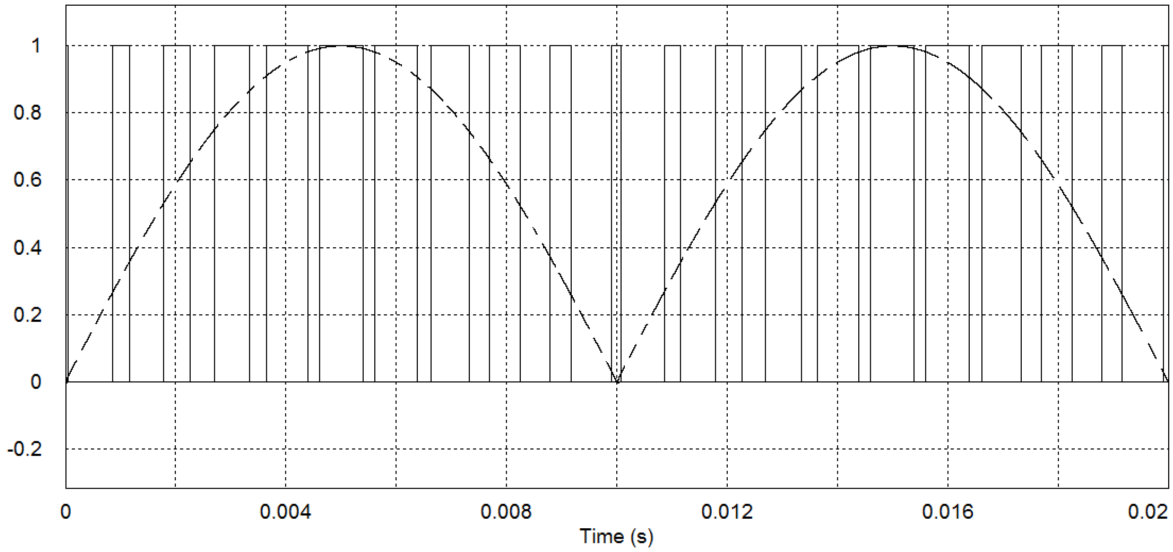

Fig.2.12.Uni-polar sinusoidal PWM switching signal.

After getting the SPWM signal for the switching of the IGBT as many conventional inverter circuits, the proposed GTI will also have square wave signal for the switching. This square wave signal will be in line frequency (50 Hz for Bangladesh) and in phase with the SPWM. This square wave signal will pass though a NOT gate and creating another set of signal which is 180^0 out phase from the original square wave.

Therefore switching of the transistors is done independently which results in four intervals per cycle. For two intervals V_L equals E or –E which forces the load current to increase exponentially in the positive or negative direction respectively. Uni-polar PWM method has the ability to produce less harmonics and at lower amplitudes than the bipolar method because of the uni-polar voltage switching difference of E is half the bipolar method of 2E. The other advantage is derived from the fact that the unipolar method effectively doubles the switching frequency of the bipolar method. To take advantage of this, the frequency modulation ratio M_f should be chosen to be even. This results in the even harmonics having the same phase because the voltage waveforms are displaced by 180° of the fundamental frequency (Mohan et al. 1985). In addition, the sidebands of the switching frequency harmonics will also cancel as will the dominant harmonic at twice the switching frequency. The outcome of this setup is that the uni-polar method will only produce odd numbered harmonics. The inverter switching frequency is determined by the frequency of V_{tri}. The frequency ratio of V_{tri} to $V_{modulation}$ is known as the modulating frequency ratio M_f that is defined by following equation [7].

$$M_f = \frac{f_{tri}}{f_{\text{mod}\,ulation}} \tag{2.5}$$

The amplitude modulation ratio (M_A) is the ratio of the peak amplitudes of $V_{modulation}$ to $Vtri$. The amplitude modulation determined by the following equation [7].

$$M_A = \frac{V_{\text{mod}\,ulation}}{V_{tri}} \tag{2.6}$$

The technique of this new switching method is used because; to match grid frequency grid voltage was sampled through buck power converter, to match grid phase sequence square wave was implied and the photovoltaic system was designed to operate using the uni-polar method over the bipolar method because of the advantage of reducing the inverter output harmonics.

Advantages of SPWM:

- Low power consumption.
- High energy efficient up to 90%.
- High power handling capability.
- No temperature variation-and ageing-caused drifting or degradation in linearity.
- Easy to implement and control.
- Compatible with today’s digital microprocessors

Disadvantages of SPWM:

- Drastically increased switching frequencies that leads to greater stresses on associated Switching devices and therefore de-rating of those devices.

2.9 DC-AC Inverter

Inverter is an electrical device that converts a direct current DC into an alternating current (AC). The basic principle is to convert a DC into an AC is by controlling the electrical switching components. Fig. 2.13 represents the basic inverter circuit with ideal switch.

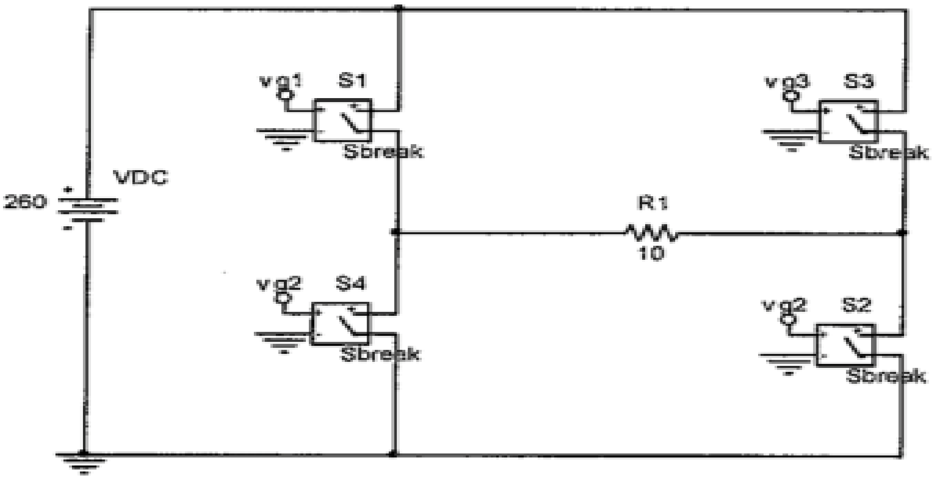

Fig.2.13. Basic inverter circuit with ideal switch

2.10 Inverter Design Requirement

The requirements for inverter go as follows:

- Output Voltage Equal to 220 V_{rms}
- Fixed Output Frequency of 50 Hz
- Capable of Supplying Power up to 2500W
- Maximum Load Current of 12 A
- Input DC Voltage Between 24 V
- Efficiency at Full Load Current Greater than 98%
- Through Hole Soldering of the Integrated Circuits

2.11 Classification of Inverter

Inverters are basically two major types

- Single phase inverter
- Three phase Inverter

Again single phase inverter are further classified few more types that is discussed below

2.11.1 Square Wave Inverter

Square Wave units could be harmful to some electronic equipment, especially equipment with transformers or motors. The square wave output has a high harmonic content, which can lead such equipment components to overheat Square Wave units were the pioneers of inverter development and, like the horse and buggy, are no longer relevant for modern inverter [11].

2.11.2 Modified Sine Wave Inverter

The most common, general-use inverters available are "Modified Sine Wave". Usually available at more moderate pricing compared to pure sine wave models. Modified Square Wave (or “Modified Sine Wave” and “Quasi Sine Wave”) output inverters are designed to have somewhat better characteristics than Square Wave units, while still being relatively inexpensive. Although designed emulate a Pure Sine Wave output, Modified Square Wave inverters do not offer the same perfect electrical output. As such, a negative by-product of Modified output units is electrical noise, which can prevent these inverters from properly powering certain loads. For example, many TVs and stereos use power supplies incapable of eliminating common mode noise. As a result, powering such equipment with a Modified Square Wave may cause a "grain" or small amount of "snow" on your video picture, or "hum" on your sound system. Likewise, most appliances with timing devices, light dimmers, battery chargers, and variable speed devices may not work well [12].

2.11.3 Pure Sine Wave Inverter

Pure or True Sine Wave inverters provide electrical power similar to the utility power you receive from the outlets in your home or office, which is highly reliable and does not produce electrical noise interference associated with the other types of inverters. With its "perfect" sine wave output, the power produced by the inverter fully assures that your sensitive loads will be correctly powered, with no interference. Some appliances that are likely to require Pure Sine Wave include computers, digital clocks, battery chargers, light dimmers, variable speed motors, and audio/visual equipment. If your application is an important video presentation at work, opera on your expensive sound system, surveillance video, a telecommunications application, any calibrated measuring equipment, or any other sensitive load, you must use a Pure Sine Wave inverter [10-12].

2.11.4 H-Bridge Inverter

A typical DC-AC converter is commonly named as inverter. This takes a DC input voltage and converts into sinusoidal ac output voltage and frequency as grid standard. Fig. 2.14 shows a typical H-bridge inverter circuit diagram. The H-bridge inverter has high conversion efficiency, low stress and also easily interfaced with renewable energy source such as PV panel [12].

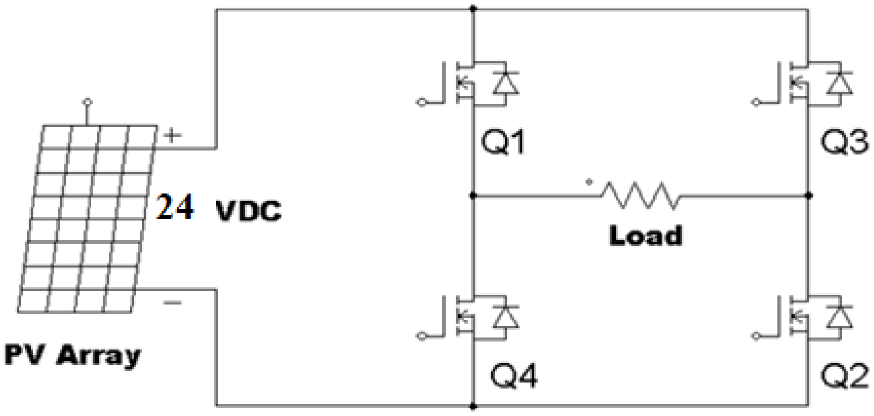

Fig.2.14. H-Bridge inverter circuit

In switching process, four switches are grouped into two groups, Q1 and Q2 are in one group and Q3 and Q4 are in another group. When Q1 and Q2 are switched, Q3 and Q4 are forced turned off. Similarly, when Q3 and Q4 are switched, Q1 and Q2 are forced off.

2.12 Inverter Applications

Everyday appliances such as microwaves, power tools, TVs and VCRs, lights, audio/visual equipment, battery chargers and computers are common loads.

Pure Sine Wave inverters are ideal for running sensitive test equipment such as communications equipment, oscilloscopes, scales, high end stereos & video equipment, communications equipment, etc.

The most useful use in renewable energy conversion such as to convert solar energy to electrical energy.

2.13 T-LCL filter

A lumped-constant reactor L and capacitor C can be used for the implementation of an immittance converter in a compact design. Some lumped-constant configurations of the immittance converter have been studied previously [1-13]. There are four typical configurations of the immittance converter that consist of three lumped reactive elements namely T-LCL type, π-CLC type, T-CLC type and π-LCL type. Converters with more than four reactive elements are bigger, heavier and costlier and their analysis and design is more complicated [14]. Hence converters having more than four reactive elements have not been studied. The T-LCL topology and its applications have been studied the most [15-18].The immittance conversion circuit or immittance converter is actually an impedance-admittance converter. It is thus named as in this particular topology; the impedance is converted into admittance. The input impedance is proportional to the output load and the output current is proportional to the source voltage. In the immittance circuit, the input current is also proportional to the output voltage. By means of an immittance converter, a constant voltage source is converted into a constant current source. The immittance conversion circuit used in the proposed SWI is a T-LCL configuration [4-5]. The T-LCL immittance conversion circuit is not only efficient in the reduction of harmonic distortion to produce a pure sinusoidal output but it also helps to maintain the desired constant current output is shown in Fig.2.15.

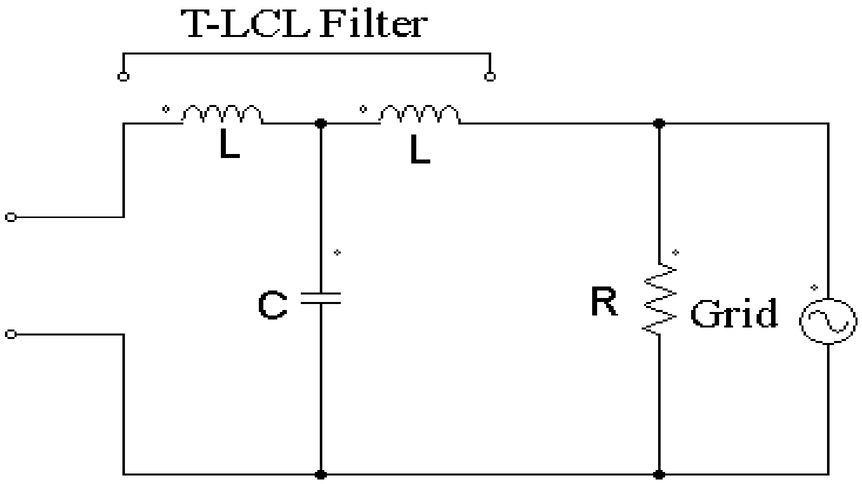

Fig.2.15.T-LCL filter

2.14 Power Inverter Protection Systems

According to their production technologies, solar power inverters can include many different protection systems. The most well known protection systems are:

Over temperature shutdown

They are also known as thermal protection systems. When a power inverter converts power over the capacity it has or at values very close to this capacity it may overheat and break down. Electronic parts generally start to break down over 90 ^{0}C. In order to prevent this from happening, heat sensitive sensors are placed inside the power inverters, and this enables shutdowns at high temperatures or decrease of the power transmitted. These parts called PTC or NTC send the necessary temperature information to the central processing unit when high temperatures are reached and this activates the protection.

Automatic Overload Protection

Overload protection which is another protection system, works in order to prevent breakdowns caused by burns of the parts which are caused by power load which exceeds the capacity of the device. For example, if an inverter which has 4000W capacity is loaded with

4300W power, the protection system is activated and gives the necessary warning to the user such as closing the device and decreasing the transferred power.

Ground Fault Protection:

In high capacity solar cell power inverters, grounding systems are essential. In order to protect the devices that are connected to the system and in order for the inverter to work more efficiently, the grounding should be done properly. If a high capacity power inverter has not been grounded properly, by means of the protection system that it has inside, it will warn the user and carry out the necessary processes. If grounding is not done properly, ground, not short circuit connection is carried out automatically and thus the system is protected.

Short Circuit Protection

By means of this protection system, the short circuit problem which is caused by the output cables touching one another due to user misuse is prevented. During short circuit, the device is immediately put on passive condition and is shut down. Other names for this protection system are known as AC Over current protection and DC Over current protection.

2.15 Powersim (PSIM) Software

PSIM provides an ultimate simulation environment for power conversion and control. It is mainly designed for power electronics, motor drives, analog and digital control, magnetic and dynamic system studies. It enables fast simulation and it is quite user-friendly. The PSIM simulation environment includes the PSIM Circuit Schematic, the Simulation engine and the SIMVIEW for viewing and analyzing the waveforms. The PSIM schematic program is highly interactive and user-friendly in building the circuit as well as editing it. The PSIM software has been used for carrying out all the simulations and analysis of the waveforms so obtained in the thesis.

CHAPTER 3

DESIGN & CIRCUIT ANALYSIS

3.1 Derivation of DC-DC Boost converter

In boost regulator the output voltage is greater than the input voltage-hence the name of the converter is “BOOST”. The operation of the circuit is explained now. The essential control mechanism of the circuit in Fig. 2.4 is turning the power semiconductor switch on and off. When the switch is ON, the current through the inductor increases and the energy stored in the inductor builds up. When the switch is off, current through the inductor continues to flow via the diode D, the RC network and back to the source. The inductor is discharging its energy and the polarity of inductor voltage is such that its terminal connected to the diode is positive with respect to its other terminal connected to the source. It can be seen then the capacitor voltage has to be higher than the source voltage and hence this converter is known as the boost converter. It can be seen that the inductor acts like a pump, receiving energy when the switch is closed and transferring it to the RC network when the switch is open.

When the switch is closed, the diode does not conduct and the capacitor sustains the output voltage. The circuit can be split into two parts, as shown in Fig. 3.1. As long as the RC time constant is very much larger than the on-period of the switch, the output voltage would remain more or less constant [11-12].

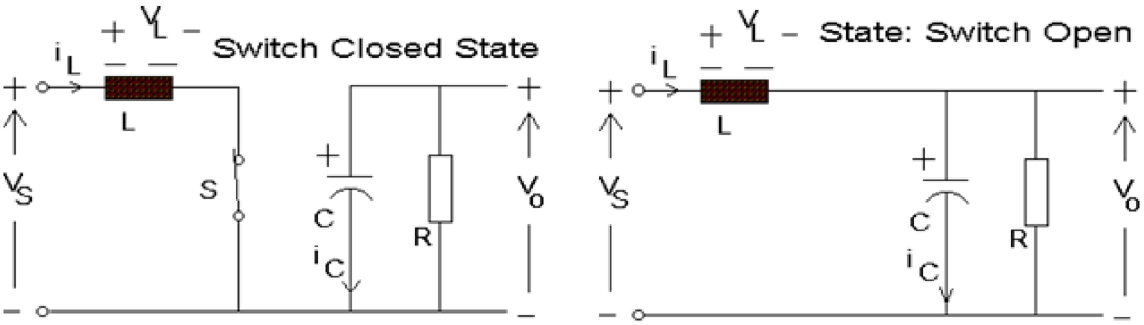

Fig.3.1. Equivalent circuits of boost converter

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1 and duty cycle, D=t_1/T;

$$V_i = \frac{I_2 - I_1}{t_1} \times L \tag{3.1}$$

$$t_1 = \frac{\Delta IL}{V_i} \tag{3.2}$$

And the inductor current falls linearly from I_2 to I_1 in time t_2.

$$V_i - V_o = -\frac{\Delta IL}{t_2} \tag{3.3}$$

Where $\Delta I = I_2 - I_1$ is the peak –to –peak ripple current of inductor L. From Eqs. (3.1) and (3.3)

$$\Delta I = \frac{V_i t_1}{L} = \frac{(V_o - V_i)t_2}{L} \tag{3.4}$$

Substituting t_1=DT and t_2 = (1-D) T in Eq. (3.4) yields;

$$D = 1 - \frac{V_i}{V_o} \tag{3.5}$$

Assuming a lossless circuit, V_sI_s=-V_aI_a and the average input current $I_s$is related to average output current I_a by

$$I_s = \frac{I_a}{1-D} \tag{3.6}$$

$$T = \frac{1}{f} = t_1 + t_2 = \Delta IL \frac{V_o}{V_i(V_0 - V_i)} \tag{3.7}$$

$$L = \frac{V_{in}(V_{out} - V_{in})}{\Delta I_L \times f_s \times V_{out}} \tag{3.8}$$

When the transistor is on, the capacitor supplies the load current for $t=t_1$. The average capacitor current during time t_1 is $I_c=I_a$ and the peak to peak ripple voltage of the capacitor is;

$$\Delta V_c = \frac{1}{C}\int_0^{t_1} I_c \, dt \tag{3.9}$$

$$= \frac{I_a t_1}{C} \tag{3.10}$$

Substituting $t_1 = \frac{(V_o - V_i)}{fV_0}$ at Eq. (3.10)

$$C = \frac{I_{out} \times D}{f_s \times \Delta V_{out}} \tag{3.11}$$

3.2 Design parameter of Boost Power Converter

Boost is designed in two stages (N=2), compared to straight boost converting this technique provides a more symmetrical duty cycle and reduced voltage stress on the MOSFET. Moreover in straight boost converter required duty cycle is tough to handle by switching. Therefore the conversion of boost converter is done based on conversion ratio($x^2 = \frac{312}{24}$) which converted 24V DC to 86V DC then 86V DC to 312V DC [8-9], [13]. The design parameters of boost converters are listed in Table-3.1 and Table-3.2:

Table 3.1 Design parameters of first stage Boost converter

Symbol	Actual Meaning	Value
V_{in}	Given input Voltage	24V
V_{out}	Desired average output Voltage	86V
f_s	Minimum switching frequency of the converter	20KHz
I_{LMax}	Maximum Inductor current	261A
ΔI_L	Estimated inductor ripple (1.75% of Inductor current)	4.55A
ΔV_{out}	Desired output voltage ripple (0.4% of output voltage)	0.44V
I_{out}	Maximum Output current(V_{out}/R)	4.3A

Duty Cycle: Maximum duty cycle, $D = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{24}{86} \approx 0.72$

Table 3.2 Design parameters of second stage Boost converter

Symbol	Actual Meaning	Value
V_{in}	Given input Voltage	86V
V_{out}	Desired average output Voltage	312V
f_s	Minimum switching frequency of the converter	21KHz
I_{LMax}	Maximum Inductor current	260A
ΔI_L	Estimated inductor ripple (3.85% of Inductor current)	10A
ΔV_{out}	Desired output voltage ripple (0.1% of output voltage)	0.35V
I_{out}	Maximum Output current(V_{out}/R)	10.4A

Duty Cycle: Maximum duty cycle, $D = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{86}{312} \approx 0.72$

Inductor Selection:

The smoothing Inductor is used to limit current ripple. As in conventional process inductor value have to chosen from recommended data sheets [13]. But in this report I have to convert a large scale of voltage from 24V DC to 86V DC for this part no inductor range is given, the following equation is a good estimation for choosing right inductor value [11-13]:

$$L = \frac{V_{in}(V_{out} - V_{in})}{\Delta I_L \times f_s \times V_{out}} = \frac{24 \times (86 - 24)}{4.55 \times 20000 \times 86} \approx 190\mu\text{H}$$

Same estimation is used for choosing inductor (86V DC to 312V DC) in second stage boost converter.

$$L = \frac{V_{in}(V_{out} - V_{in})}{\Delta I_L \times f_s \times V_{out}} = \frac{86 \times (312 - 86)}{10 \times 21000 \times 312} \approx 20\mu\text{H}$$

Capacitor selection:

In this report the following equations can be used to adjust the output capacitor
values for a desired output voltage ripple [11-13].

$$C = \frac{I_{out} \times D}{f_s \times \Delta V_{out}} = \frac{4.3 \times 0.72}{20000 \times .044} \approx 3.5mF$$

As the conversion is not conventional therefore estimated capacitor value is used in (86V DC to 312V DC) second stage boost conversion.

$$C = \frac{I_{out} \times D}{f_s \times \Delta V_{out}} = \frac{10.4 \times 0.72}{21000 \times .35} \approx 1mF$$

3.3 Derivation of Buck Converter

A buck converter or step-down switch mode power supply can also be called a switch mode regulator. Popularity of a switch mode regulator is due to its fairly high efficiency and compact size and a switch mode regulator is used in place of a linear voltage regulator at relatively high output. In applications where size and efficiency are critical, linear voltage regulators cannot be used. The operation of the buck converter is explained first. This circuit can operate in any of the three states as explained below. The first state corresponds to the case when the switch is ON. In this state, the current through the inductor rises, as the source voltage would be greater than the output voltage, whereas the capacitor current may be in either direction, depending on the inductor current and the load current. When the inductor current rises, the energy stored in it increases. During this state, the inductor acquires energy.

When the switch is closed, the elements carrying current are shown in red color in Fig. 3.2, whereas the diode is in gray, indicting that it is in the off state. In Fig. 3.2, the capacitor is getting charged in first state, whereas it is discharging in second stage [11-12].

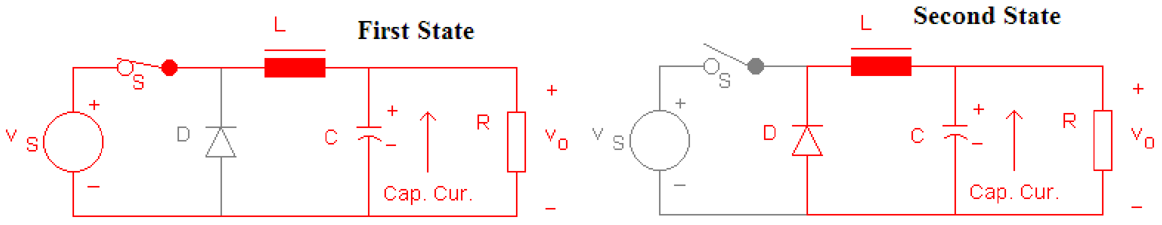

Fig.3.2. Equivalent circuits of buck converter

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1 and duty cycle, D=t_1/T;

$$V_i - V_o = \frac{I_2 - I_1}{t_1} \times L \tag{3.12}$$

$$t_1 = \frac{\Delta IL}{V_i - V_o} \tag{3.13}$$

And the inductor current falls linearly from I_2 to I_1 in time t_2.

$$-V_o = -\frac{\Delta IL}{t_2} \tag{3.14}$$

Where $\Delta I = I_2 - I_1$ is the peak –to –peak ripple current of inductor L. From Eqs. (3.12) and (3.13)

$$\Delta I = \frac{V_o t_2}{L} = \frac{(V_o - V_i)t_1}{L} \tag{3.15}$$

Substituting t_1=DT and t_2 = (1-D) T in Eq. (3.15) yields;

$$D = \frac{V_o}{V_i} \tag{3.16}$$

Assuming a lossless circuit, V_sI_s=-V_aI_a and the average input current $I_s$is related to average output current I_a by;

$$I_s = DI_a \tag{3.17}$$

$$T = \frac{1}{f} = t_1 + t_2 = \Delta IL \frac{V_i}{V_o(V_i - V_o)} \tag{3.18}$$

$$L = \frac{V_{out}(V_{in} - V_{out})}{\Delta I_L \times f_S \times V_{in}} \tag{3.19}$$

When the transistor is on, the capacitor supplies the load current for t=t_1. The average capacitor current during time t_1 is I_c=I_a and the peak to peak ripple voltage of the capacitor is;

$$\Delta V_c = \frac{1}{C}\int_0^{t_1} I_c \, dt + V_c \tag{3.20}$$

$$= \frac{\Delta IT}{8C} \tag{3.21}$$

$$C = \frac{\Delta I_L}{8 \times f_S \times \Delta V_{out}} \tag{3.22}$$

3.4 Design parameter of Buck power converter

Buck converter is designed in two stages (N=2), because in straight buck conversion desire duty cycle is very low and is impracticable to apply. Therefore the conversion of buck converter is done based on conversion ratio($x^2 = \frac{220}{5}$) which converts RMS 220V AC to 33V DC then 33V DC to 5V DC [8-9]. The design parameters of buck converters are listed in Table-3.3 and Table-3.4:

Table 3.3 Operating parameter for first stage buck converter

Symbol	Actual Meaning	Value
V_{in}	Given RMS input voltage	220V
V_{out}	Desired output voltage	33V
f_{s}	Minimum switching frequency of the converter	25KHz
I_{Lmax}	Maximum inductor current	50A
ΔI_{L}	Estimated inductor ripple (4.4% of maximum inductor current)	2.2A
ΔV_{out}	Desired output voltage ripple (1.6% of output voltage)	0.05V

$$\text{Duty Cycle: Maximum duty cycle, } D = \frac{V_{in}}{V_{out}} = \frac{33}{220} \approx 0.15$$

Table 3.4 Operating parameters of second stage buck converter

Symbol	Actual Meaning	Value
V_{in}	Given RMS input voltage	33V
V_{out}	Desired RMS output voltage	5V
f_{s}	Minimum switching frequency of the converter	6KHz
I_{Lmax}	Maximum inductor current	14A
ΔI_{L}	Estimated inductor ripple (3% of maximum inductor current)	0.35A
ΔV_{out}	Desired output voltage ripple (1.6% of output voltage)	0.05V

$$\text{Duty Cycle: Maximum duty cycle, } D = \frac{V_{in}}{V_{out}} = \frac{5}{33} \approx 0.15$$

Inductor selection for buck converter:

The smoothing Inductor is used to limit current ripple. As in conventional process inductor value has to be chosen from recommended data sheets. But no inductor range is given for a large scale conversion like from 202V to 33V. Therefore, in the present design, the following equation is a good estimation for choosing right inductor value [11-12], [14]:

$$L = \frac{V_{out}\left(V_{in} - V_{out}\right)}{\Delta I_L \times f_S \times V_{in}} = \frac{33\left(220 - 33\right)}{2.2 \times 25000 \times 220} \approx 50 \mu\text{H}$$

And this estimation is also used to choose inductor for 33V to 5V conversion

$$L = \frac{V_{out}\left(V_{in} - V_{out}\right)}{\Delta I_L \times f_s \times V_{in}} = \frac{5\left(33 - 5\right)}{0.35 \times 6000 \times 33} \approx 20 m\text{H}$$

Capacitor selection for buck converter:

The basic selection of the output capacitor is based on the ripple current and ripple voltage, as well as on loop stability considerations. In the present design, the following equations can be used to adjust the output capacitor values for a desired output voltage ripple in 220V to 33V conversion [8], [9], [11]:

$$C = \frac{\Delta I_L}{8 \times f_S \times \Delta V_{out}} = \frac{22}{8 \times 25000 \times 0.55} \approx 200 \quad \mu\text{F}$$

Same estimation is used in selection of capacitor for second stage (33 V to 5 V) buck conversion:

$$C = \frac{\Delta I_L}{8 \times f_s \times \Delta V_{out}} = \frac{0.35}{8 \times 6000 \times 0.07} \approx 100 \quad \mu\text{F}$$

3.5 T-LCL Type Immittance Converter

The circuit diagram of the T-LCL immittance converter is shown in Fig. 3.3. It consists of two inductors L_1 and L_2, and a capacitor C, in a T shape. The inductors are assumed to have series internal resistances r_1 and r_2 and the capacitor is assumed to be ideal. A load Z_2 is connected across the output terminals [4-5]. The input and output voltages and currents are as shown in the diagram.

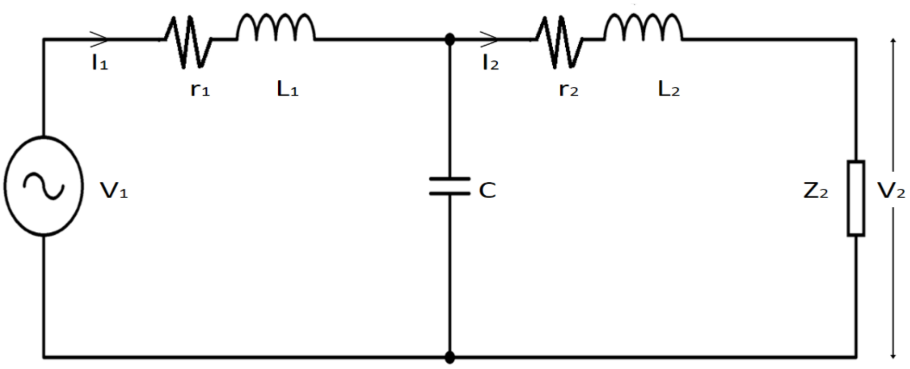

Fig.3.3. T-LCL type immittance converter

Four Terminal Matrixes:

Applying Kirchhoff's Voltage Law (KVL) in the two loops, following equation are gotten,

$$\dot{V}_1(s) = \dot{Z}_{L_1}(s)\dot{I}_1(s) + \dot{V}_C(s) \qquad (3.23)$$

$$\dot{V}_C(s) = \dot{Z}_{L_2}(s)\dot{I}_2 + \dot{V}_2(s) \qquad (3.24)$$

Where, $\dot{Z}_{L_1}$ and $\dot{Z}_{L_2}$ is the total impedance of L_1 and L_2 taking into account the internal resistance:

$$\dot{Z}_{L_1} = r_1 + L_1 S,\ \ \dot{Z}_{L_2} = r_2 + L_2 S \qquad (3.25)$$

Now,

$\dot{V}_C(s) = \dot{I}_C(s)\frac{1}{CS}$, where $\frac{1}{CS}$ is the reactance of the capacitor.

Applying Kirchhoff's Current Law (KCL),

$$\dot{I}_C(s) = \dot{I}_1(s) - \dot{I}_2(s)$$

Therefore,

$\dot{V}_C(s) = \dot{I}_C(s)\frac{1}{CS}$,

$$\dot{V}_C = \frac{1}{CS}(\dot{I}_1 - \dot{I}_2) \tag{3.26}$$

From equations (3.23) ~ (3.26), the values are described as follows:

$$\dot{V}_1(s) = (SL_1 + r_1)\dot{I}_1(s) + \left(\frac{1}{CS}\right)(\dot{I}_1(s) - \dot{I}_2(s))$$

$$\dot{V}_1(s) = \left[(L_1S + r_1) + \left(\frac{1}{CS}\right)\right]\dot{I}_1(s) - \left(\frac{1}{CS}\right)\dot{I}_2(s) \tag{3.27}$$

And,

$$\left(\frac{1}{CS}\right)\left(\dot{I}_1(s) - \dot{I}_2(s)\right) = (L_2S + r_2)\dot{I}_2(s) + \dot{V}_2(s)$$

$$\dot{V}_2 = \left(\frac{1}{CS}\right)\dot{I}_1(s) - \left[(L_2S + r_2) + \left(\frac{1}{CS}\right)\right]\dot{I}_2(s) \tag{3.28}$$

$$\dot{I}_1(s) = (CS)\left[\dot{V}_2(s) + \left\{(L_2S + r_2) + \left(\frac{1}{CS}\right)\right\}\dot{I}_2(S)\right] \tag{3.29}$$

Putting this expression to equation (3.5.5), I get

$$\dot{V}_1(s) = \left[(L_1S + r_1) + \left(\frac{1}{CS}\right)\right](CS)\dot{V}_2(s)$$
$$+ (CS)\left[(L_1S + r_1) + \left(\frac{1}{CS}\right)\right]\left[(L_2S + r_2) + \left(\frac{1}{CS}\right)\right]\dot{I}_2(s) - (\frac{1}{CS})\dot{I}_2(s)$$

$$\begin{aligned}\dot{V}_1(s) = {} & [(L_1S + r_1)(CS) + 1]\dot{V}_2(s) \\ & + [(L_1S + r_1)(L_2S + r_2)(CS) + (L_1S + r_1) \\ & + (L_2S + r_2)]\dot{I}_2\end{aligned} \tag{3.30}$$

Therefore, from above equation;

$$\left.\begin{aligned}
\dot{A} &= (L_1S + r_1)(CS) + 1 \\
\dot{B} &= (L_1S + r_1)(L_2S + r_2)(CS) + (L_1S + r_1) + (L_2S + r_2) \\
\dot{C} &= CS \\
\dot{D} &= \left[(L_2S + r_2) + \left(\frac{1}{CS}\right)\right]CS
\end{aligned}\right\} \tag{3.31}$$

From theory of AC circuits, or the frequency domain it is recalled that the operator “S” may also be replaced with “jω”

At resonant frequency, (taking resonant frequency, $\omega_r = \omega$)

$$\omega L = \frac{1}{\omega C};\ \omega^2 = \frac{1}{LC}\ ;\ Z_0 = \sqrt{\frac{L}{C}}\ ;\ Q_1 = \frac{\omega L}{r_1}\ ;\ Q_2 = \frac{\omega L}{r_2}$$

Here Q_1 & Q_2 are known as the quality factor of the circuit that comes from the inductors.

Considering $L_1 = L_2 = L$, the $\dot{A}, \dot{B}, \dot{C}, \dot{D}$ parameters can be represented as:

$$\dot{A} = (L_1S + r_1)(CS) + 1$$

$$\dot{A} = (j\omega L + r_1)(j\omega C) + 1$$

$$= (j\omega)^2 LC\left(1 + \frac{r_1}{j\omega L}\right) + 1 = -\omega^2 LC\left(1 - \frac{r_1}{j\omega L}\right) + 1 \qquad \text{At resonance } \omega^2 LC = 1$$

$$= -\left(1 - \frac{r_1}{j\omega L}\right) + 1 = -1 + j\frac{1}{Q_1} + 1 = j\frac{1}{Q_1}$$

$$\dot{B} = (L_1S + r_1)(L_2S + r_2)(CS) + (L_1S + r_1) + (L_2S + r_2)$$

$$\dot{B} = (j\omega L + r_1)(j\omega L + r_2)(j\omega C) + (j\omega L + r_1) + (j\omega L + r_2)$$

$$= (j\omega)^3 L^2 C\left(1 + \frac{r_1}{j\omega L}\right)\left(1 + \frac{r_2}{j\omega L}\right) + (j\omega L)\left(1 + \frac{r_1}{j\omega L}\right) + (j\omega L)\left(1 + \frac{r_2}{j\omega L}\right)$$

$$= -j\omega^3 L^2 C\left(1 - j\frac{1}{Q_1}\right)\left(1 - j\frac{1}{Q_2}\right) + (j\omega L)\left(1 - j\frac{1}{Q_1}\right) + (j\omega L)\left(1 - j\frac{1}{Q_2}\right)$$

$$= (j\omega L)\left[-\omega^2 LC\left(1 - j\frac{1}{Q_1}\right)\left(1 - j\frac{1}{Q_2}\right) + \left(1 - j\frac{1}{Q_1}\right) + \left(1 - j\frac{1}{Q_2}\right)\right]$$

$$= (j\omega L)\left[-(1 - j\frac{1}{Q_1} - j\frac{1}{Q_2} - j\frac{1}{Q_1 Q_2}) + \left(1 - j\frac{1}{Q_1}\right) + \left(1 - j\frac{1}{Q_2}\right)\right]$$

$$= (j\omega L)\left[1 + j\frac{1}{Q_1 Q_2}\right] \quad = (j\frac{L}{\sqrt{LC}})\left[1 + j\frac{1}{Q_1 Q_2}\right] \ = (j\sqrt{\frac{L}{C}})\left[1 + j\frac{1}{Q_1 Q_2}\right] \ = jZ_0\left[1 + j\frac{1}{Q_1 Q_2}\right]$$

$$\dot{C} = CS = j\omega C \ = j\frac{C}{\sqrt{LC}} \ = j\sqrt{\frac{C}{L}} \ = j\frac{1}{Z_0}$$

$$\dot{D} = \left[(L_2 S + r_2) + \left(\frac{1}{CS}\right)\right] CS$$

$$\dot{D} = (j\omega L_2 + r_2)(j\omega C) + 1$$

$$= \left[(j\omega)^2 LC\left(1 + \frac{r_2}{j\omega L}\right) + 1\right] = \left[\omega^2 LC\left(1 - \frac{r_2}{j\omega L}\right) + 1\right]$$

$$= \left[-\left(1 - \frac{r_2}{j\omega L}\right) + 1\right] = -1 + j\frac{1}{Q_2} + 1 \ = j\frac{1}{Q_2}$$

Therefore, all parameters become:

$$\left.\begin{aligned} \dot{A} &= j\frac{1}{Q_1} \\ \dot{B} &= jZ_0\left[1 + j\frac{1}{Q_1 Q_2}\right] \\ \dot{C} &= j\frac{1}{Z_0} \\ \dot{D} &= j\frac{1}{Q_1} \end{aligned}\right\} \qquad (3.32)$$

Since Q_1, $Q_2 >> 1$, the real part of these parameters becomes close to zero. Therefore, the following approximation is possible for the four-terminal matrix of the T-LCL type converter:

$$\begin{bmatrix}\dot{V}_1\\ \dot{I}_1\end{bmatrix} = \begin{bmatrix} j\frac{1}{Q_1} & jZ_0 \\ j\frac{1}{Z_0} & j\frac{1}{Q_2}\end{bmatrix}\begin{bmatrix}\dot{V}_2\\ \dot{I}_2\end{bmatrix} \tag{3.33}$$

If Q_1 & Q_2 are very high then $\dot{A} = \dot{D} = 0$ and BC=1; which is properties of an ideal immittance converter.

Output current equation:

From equation (3.33),

$$V_1 = Z_0\left[1 + \frac{1}{Q_1}\frac{Z_2}{Z_0}\right] I_2$$

$$\frac{V_1}{Z_0} = \left[1 + \frac{1}{Q_1}\frac{Z_2}{Z_0}\right] I_2$$

From this equation the output current can be written as:

$$I_2 = \frac{V_1}{Z_0}\left[1 + \frac{1}{Q_1}\frac{Z_2}{Z_0}\right]^{-1}$$

Now using the binomial theorem the above equation becomes

$$I_2 \cong \frac{V_1}{Z_0}\left[1 - \frac{1}{Q_1}\frac{Z_2}{Z_0}\right] \tag{3.34}$$

In equation (3.34) the first term is the ideal term and the second term is the loss term resulting from the internal resistance of the inductance. When the internal resistance is negligible or zero, the quality factor becomes infinity. Under this condition, the second term becomes zero, giving the ideal condition:

$$I_2 \cong \frac{V_1}{Z_0} \tag{3.35}$$

3.6 Design of T-LCL filter

From above derivation it is proved that the low pass filter is applied to suppress harmonic influence and to acquire pure sine wave at output of the inverter. In this article T-LCL immittance conversion circuit is applied as a filter circuit because it is not only capable in the reduction of harmonic distortion to produce a pure sinusoidal output but it also helps to sustain the desired constant current output [4-5].

Equation (3.35) shows that the output current does not depend on the load impedance and depends only on input voltage and characteristic impedance $Z_0 = \sqrt{(L/C)}$. Therefore, in ideal condition, the immittance circuit will provide constant current or constant power.

And the output voltage does not depend on the load impedance but depends only on input current and characteristic impedance Z_0. Therefore, the ideal immittance circuit will provide constant voltage.

At resonant frequency, (taking resonant frequency,$\omega_r = \omega$)

$$\omega L = \frac{1}{\omega C};\ \omega^2 = \frac{1}{LC};\ Z_0 = \sqrt{\frac{L}{C}}$$

These values are for the case; where w_0 = 1 radian per second and should be frequency scaled by dividing through by $w_0 = 2\pi f_c$. Here cutoff frequency, f_c=50Hz and characteristic impedance 20Ω [4-5].

$$C = \frac{1}{2\times\pi\times f_c \times R} = \frac{1}{2\times\pi\times 50\times 20} \approx 0.159mF$$

$$L = \frac{R}{2\times\pi\times f_c} = \frac{20}{2\times\pi\times 50} \approx 63.60mH$$

$$z = \sqrt{\frac{L}{C}} = \sqrt{\frac{63.6mH}{0.159mF}} \approx 20\Omega$$

$$f = \frac{1}{2\pi\sqrt{LC}} = 50Hz$$

CHAPTER4

SIMULATION of INVERTER

4.1 Introduction

Here proposed inverter design consists of firstly calculation and then simulation on PSIM software.

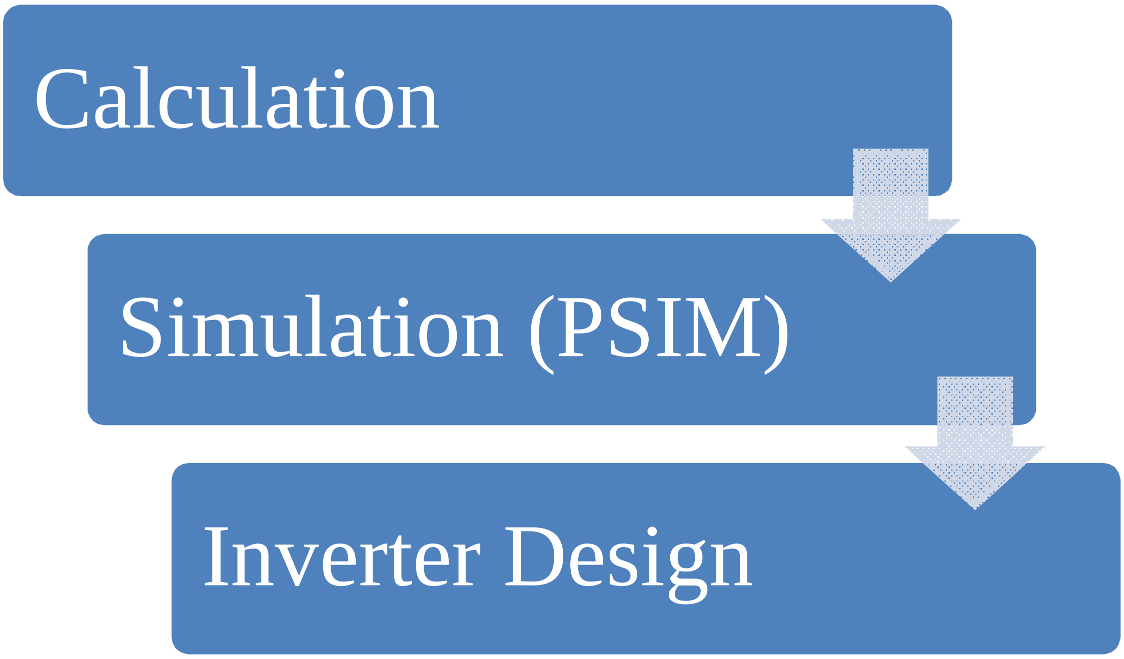

Fig.4.1: Methodology for Inverter Design

4.2 SWITCH SELECTION

MOSFET vs IGBT:

Two main types of switches are used in power electronics. One is the MOSFET, which is designed to handle relatively large voltages and currents. The other is the insulated gate bipolar transistor, or IGBT. Each has its advantages, and there is a high degree of overlap in the specifications of the two.

IGBTs tend to be used in very high voltage applications, nearly always above 200V, and generally above 600V. They do not have the high frequency switching capability of MOSFETs, and tend to be used at frequencies lower than 29kHz. They can handle high currents, are able to output greater than 5kW, and have very good thermal operating ability, being able to operate properly above 100 Celsius. One of the major disadvantages of IGBTs is their unavoidable current tail when they turn off. Essentially, when the IGBT turns off, the current of the gate transistor cannot dissipate immediately, which causes a loss of power each time this occurs. This tail is due to the very design of the IGBT and cannot be remedied. IGBTs also have no body diode, which can be good or bad depending on the application. IGBTs tend to be used in high power applications, such as uninterruptible power supplies of power higher than 5kW, welding, or low power lighting [1-2].

MOSFETS have a much higher switching frequency capability than do IGBTs, and can be switched at frequencies higher than 200 kHz. They do not have as much capability for high voltage and high current applications, and tend to be used at voltages lower than 250V and less than 500W. MOSFETs do not have current tail power losses, which makes them more efficient than IGBTs. Both MOSFETs and IGBTs have power losses due to the ramp up and ramp down of the voltage when turning on and off (dV/dt losses). Unlike IGBTs, MOSFETs have body diode.

Generally, IGBTs are the sure bet for high voltage, low frequency (>1000V, <20kHz) uses and MOSFETs are ideal for low voltage, high frequency applications (<250V, >200kHz). In between these two extremes is a large grey area. In this area, other considerations such as power, percent duty cycle, availability and cost tend to be the deciding factors. Therefore in this simulation MOSFET is used as high frequency and 212V are required.

4.3 Switching Circuit design

In conventional inverter design, Sinusoidal Pulse Width Modulation (SPWM) is generally used to get AC output. But in this article SPWM and square wave combination is used for inverter switching because this new technique reducing losses by reducing switching frequency. To accurately obey grid synchronization process the sine wave of the proposed design will be sampled from power grid by using buck power converter to step down the 220V grid voltage to 5V DC voltage [1], [4-6]. As a result the frequency of GTI output will be as same as grid frequency. After that a high frequency triangular wave (10Hz) is compared with sampled sine wave by using comparator to build SPWM as shown in Fig. 4.3. The square wave is used as per grid frequency (50 Hz in Bangladesh) and is in same phase with SPWM. The square wave is also passed through a NOT gate which produces a signal 180^0 out of phase with the original signal. Both square wave signal shown in Fig.10. The inverter is required four sets of signal as it used four MOSFET in inverter circuit. Under this situation two sets of SPWM signal and two sets of AND gate operation is performed. Eventually four sets of signal can be labeled into two groups. The first group consists of MOSFETs Q1 and Q4 while second group consists of MOSFETs Q2 and Q3. When Q4 is switched on SPWM is appeared at Q1 at that time Q2 and Q3 switches are off. Again when Q2 is turned on SPWM is appeared at Q3 and that time Q1 and Q4 switches are remaining off. For Q1 and Q4 pair positive voltage is emerged across the load. Moreover for Q2 and Q3 pair negative voltage is emerged across the load [4], [7-9]. The switches in each branch is operated alternatively so that they are not in same mode (ON /OFF) simultaneously .In practice they are both OFF for short period of time called blanking time, to avoid short circuiting. These bridges legs are switched such that the output voltage is shifted from one to another and hence the change in polarity occurs in voltage waveform. If the shift angle is zero, the output voltage is also zero and maximal when shift angle is π. The gate switching sequence is shown in Table-4.1.

The gate pulses for switching of inverter are illustrated in Fig.4.5 and Fig.4.6.

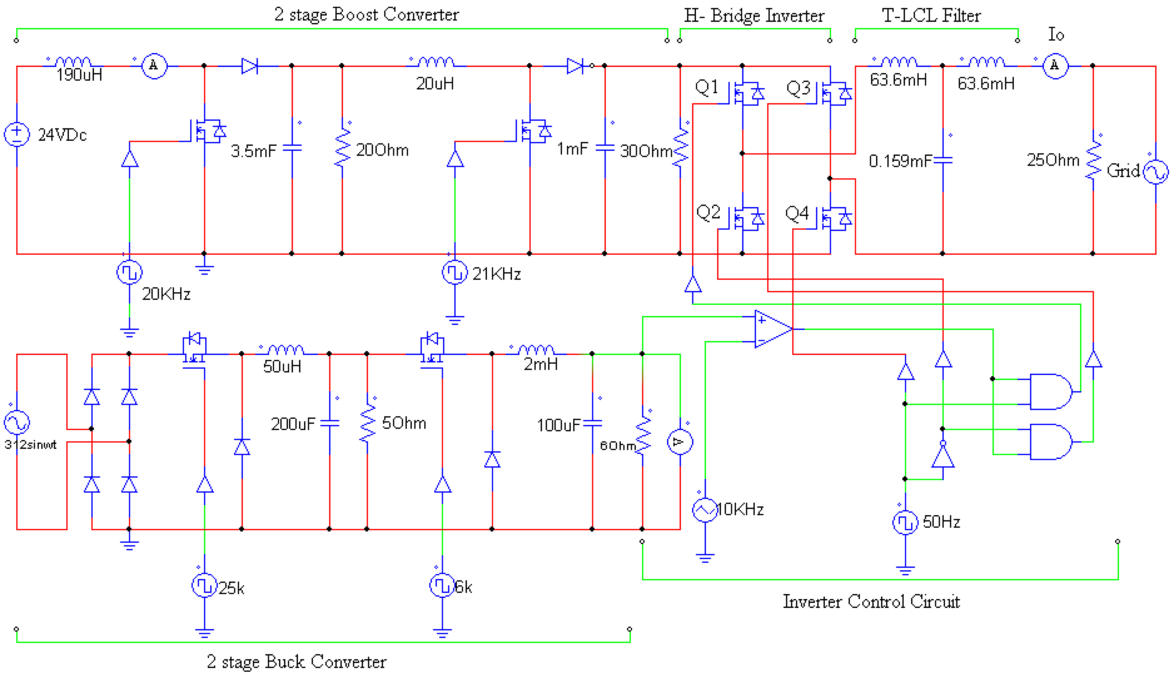

Fig.4.2. Schematic diagram of transformer less GTI for simulation in PSIM

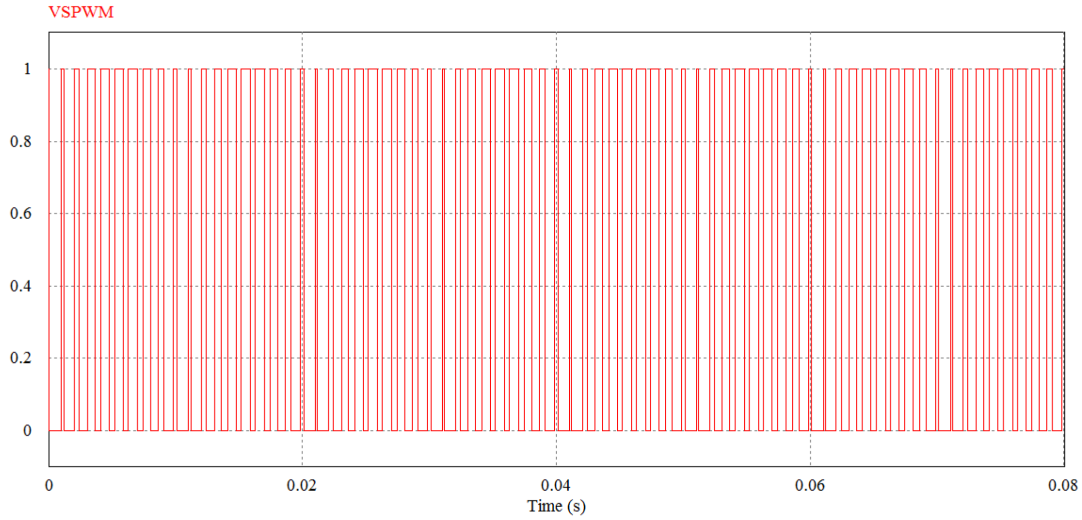

Fig.4.3. SPWM signal for switching

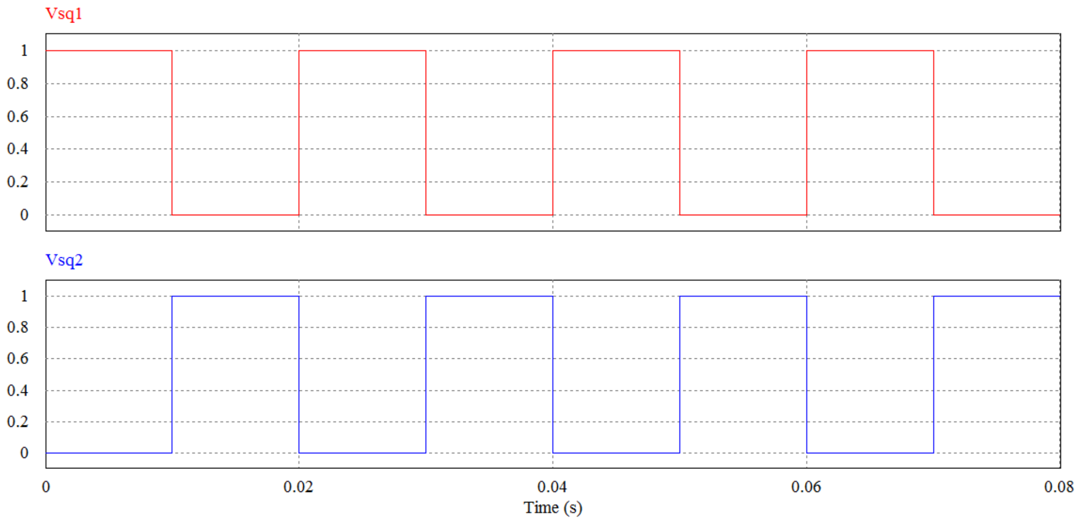

Fig.4.4. Square wave gate pulse 180^0 phase difference

Table-4.1 the gate switch Sequence

Q1	Q2	Q3	Q4	V_{out}
ON	OFF	OFF	ON	+Vs
OFF	ON	ON	OFF	-Vs
ON	OFF	ON	OFF	0
OFF	ON	OFF	ON	0

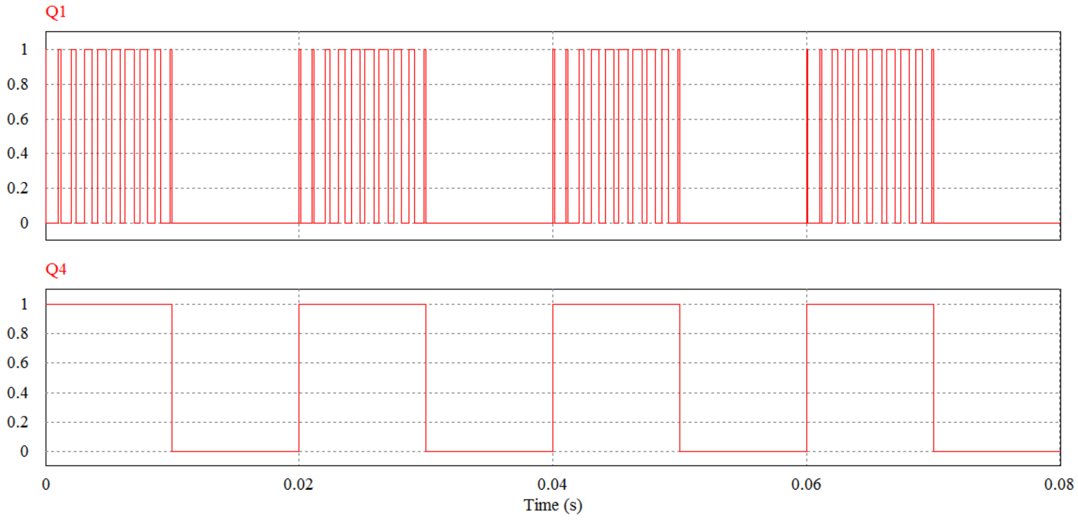

Fig.4.5. Switching signal from control circuit to MOSFETs Q1 and Q4

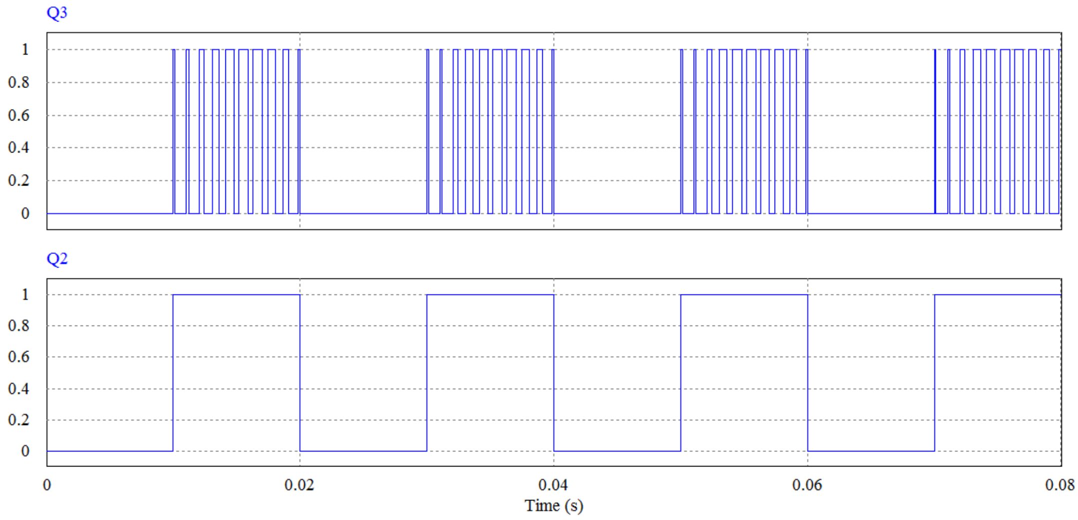

Fig.4.6 switching signal from control circuit to MOSFETs Q1 and Q4

4.4 Grid synchronization technique

The output voltage of a GTI inverter should maintain some fixed requirement so that it may provide power to grid [3]. The requirements are given below:

- The output voltage magnitude should be equal as grid.
- The frequency of inverter should be equal as grid frequency (50Hz in Bangladesh).
- The output phase should as same as grid.

In this proposal to follow the requirement, grid voltage is sampled and is used to set up for switching signal. GTI is directly tied with grid utility and where load is quite large than GTI. Therefore it is transmitted force to GTI for generating power from PV into grid. The real and reactive powers are given below [1], [4], and [7]:

$$P = \frac{|V_{inv}||V_{grid}|}{Z_t}\sin\theta \tag{4.1}$$

$$Q = \frac{V_{inv}^2}{Z_t} \frac{|V_{inv}||V_{grid}|}{Z_t}\cos\theta \tag{4.2}$$

Where, z_t = Linking line impedance

V_{inv} = Output voltage of inverter

V_{grid} = grid power voltage

Θ = angle different between V_{inv} and V_{grid}

Thus from formula (4.1) it can be conclude that for sending maximum power at grid phase angle Θ ought to be equal as 90^0. In practical to stabilize the system the angle is maintained slightly less than 90^0. As resultant value of formula (4.1) is positive both for positive and negative value of $\sin\Theta$ hence to continue real power flow from GTI to grid the angle should be positive and for negative value of Θ power will start to flow in reverse direction. In the first GTI voltage leads grid voltage and second case is vice-versa.

4.5 Power transmitting

According to formula (4.2) the voltage angle of GTI should be grater than grid voltage to transmitting power from PV array to grid utility. Though the sine wave is sampled from grid it is passed through a phase shifter to obey the leading condition. From formula (4.1) it can be stated that for sending maximum power at grid phase angle Θ need to keep 90^0. But in practical to stay the system in stabilize mood the angle is low than 90^0. The load impedance is also very important in case of power transmitting. To reduce noise and maintain current in the output of GTI the article is proposed to employ T-LCL filter [5].

4.6 Design functions of GTI

In a GTI concern function are divided into two major parts: grid synchronization, power transmitting. For synchronizing frequency of GTI with the grid a sampled of sine wave is taken from grid. After ward the sampled sine wave is rectified and passed through a dual-stage buck power converter and the output of buck converter is compared with high frequency triangular wave to build SPWM which ensures same frequency. To match same phase SPWM sets with phase-shift to zero. Then two sets of AND gate operation is performed with combination of SPWM and square wave to construct four individual signal for switching of inverter. The zero crossing detects when inverter output and grid voltage both in phase [6-7].

Once zero crossing is detected inverter and grid connection is tied via connector is shown in Fig.4.7.

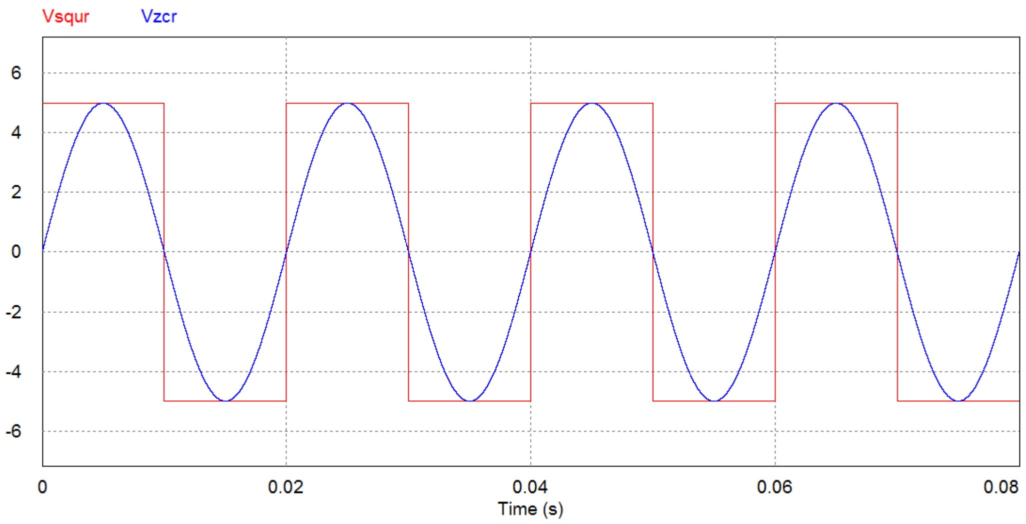

Fig.4.7. Zero crossing detection of Voltage (grid matching)

After inverter and grid connect mutually power starts to transmit from PV array to grid. Now for protection purpose to avoid transmission of power when grid is down due to unavoidable circumstances a relay circuit is employed to trip inverter circuit from grid at this particular situation. A current transformer takes measurement if any fault is occurred at grid relay circuit will be trip and circuit breaker will isolated inverter from grid. Thus measurement and protection purpose of inverter will be served.

The grid synchronization is matched through by following stages:

- As buck input is sampled from grid and buck output is building SPWM for gate signal of H-bridge inverter. Therefore inverter output signal frequency is as same as grid frequency.
- For zero crossing phase detection square wave combination is used with gate signal. Hence phase detection of inverter output is ensured through zero crossing detection.
- To make transformer less inverter boost converter is used which output is 312V and the voltage is used as input of Inverter. Therefore inverter output will be 312V which means RMS 220V.
- Thus phase, frequency and amplitude of inverter will be matched with grid utility. And power transmission will be started from inverter to grid utility.

CHAPTER 5

RESULT & DISCUSSION

5.1 Simulation Result

Fig. 5.1 shows the simulated output voltage waveform that is non-sinusoidal which is distorted, contains excessive harmonics. Thus, a low pass T-LCL filter is employed at the output terminal of the inverter to reduce the harmonics.

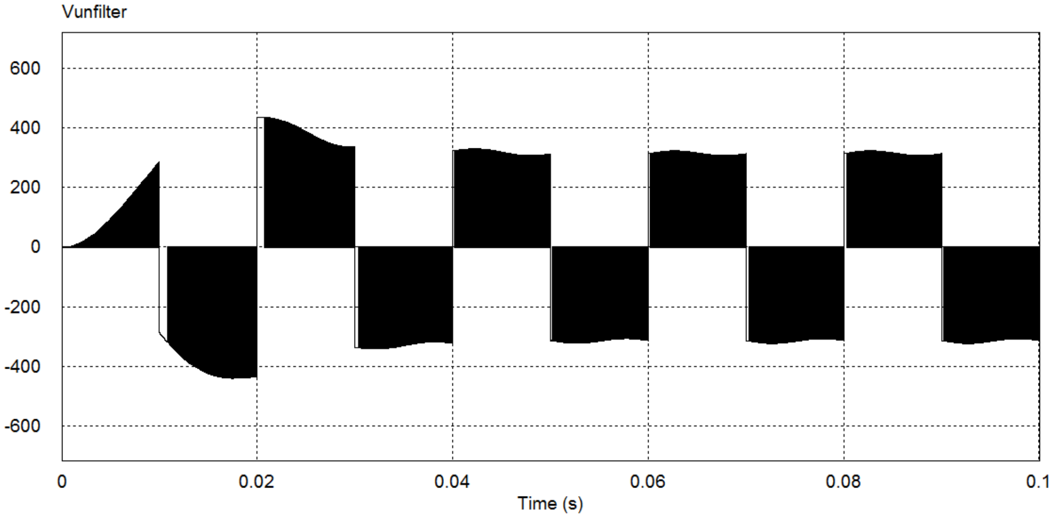

Fig.5.1. Output voltage waveform without filtering in PSIM

After filtering, we obtained 220V (RMS), 50Hz pure sine wave output voltage and current waveform that is shown in Fig. 5.2 and Fig. 5.3. The proposed design helps the output voltage and current to become stable after single cycle.

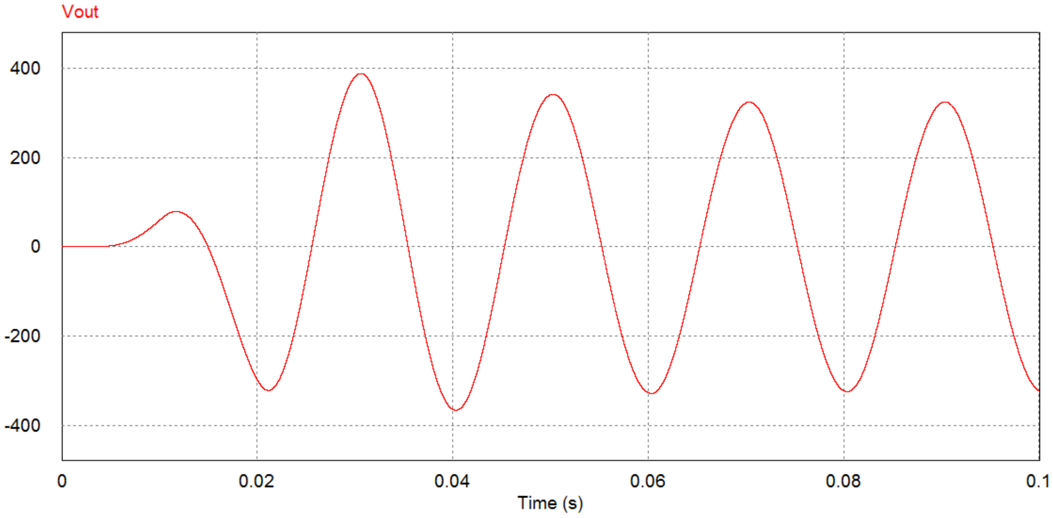

Fig. 5.2 Output voltages after filtering in PSIM

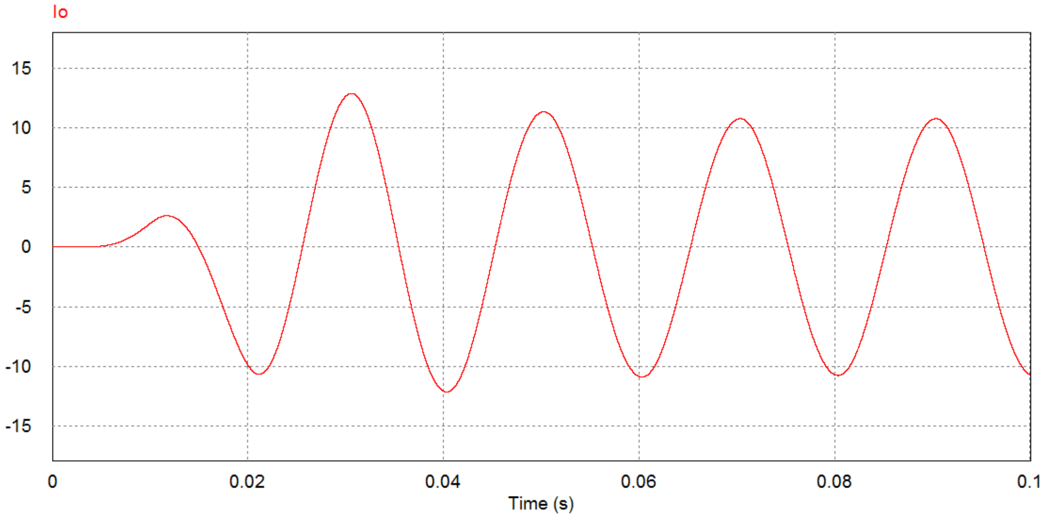

Fig.5.3. Output current waveform in PSIM

Fig. 5.4 presents the FFT analysis of output voltage unfiltered and filtered condition. The fast Fourier transform ensures that unfiltered inverter output has harmonics with mentioned value but filtered output has only fundamental harmonics which lies with in 50Hz and rest of harmonics are negligible. After filtering the output has low level of THD less than 0.1% because the proposed circuit is totally transformer less.

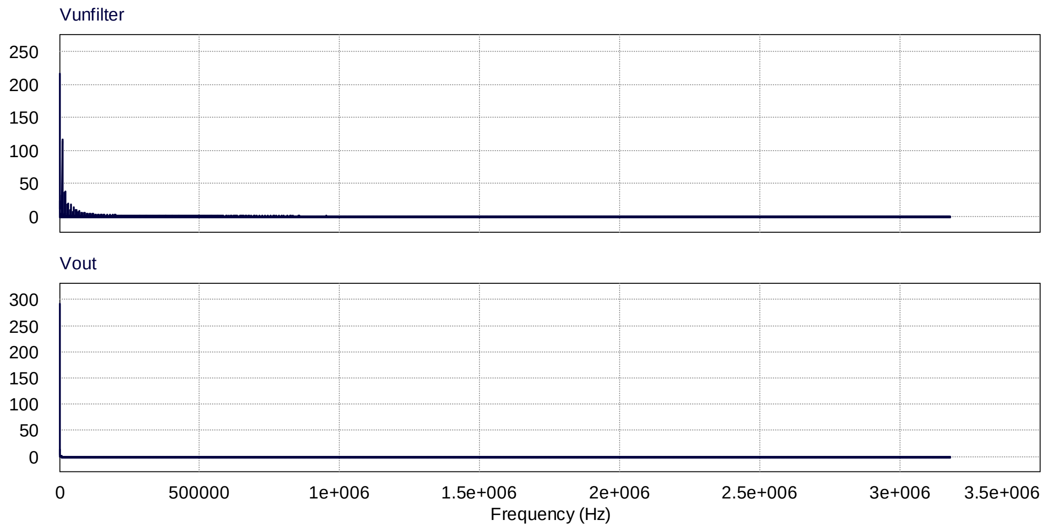

Fig.5.4. Output Voltage's FFT unfiltered and filtered condition in PISM

Fig. 5.5 represents output currents with its FFT. Where again FFT demonstrates that fundamental harmonic component lies at 50 Hz and rest of them are eliminates.

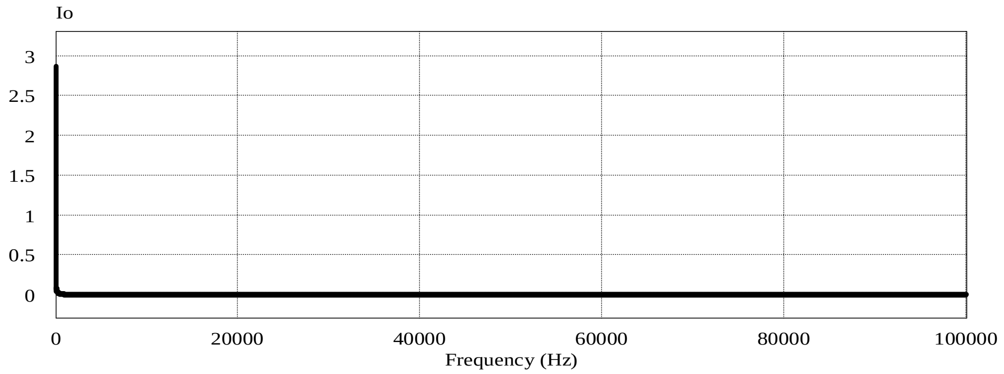

Fig.5.5. Output current's FFT in PSIM

5.2 Inverter Output current

The peak value of the inverter output current is an important factor in designing the inverter stack size. The inverter current rating is normally determined by the filter impedance and the rated load impedance in a steady state. The output current should maintained constant irrespective of load on the inverter and the output voltage is force to change [12].Therefore to maintain constant output current T-LCL filter is employed. It is found from filter equation output current of the inverter does not depend upon load.

$$I_2 \cong \frac{V_1}{Z_0}\left[1-\frac{1}{Q_1}\frac{Z_2}{Z_0}\right] \tag{5.1}$$

In above equation at the time internal resistance is negligible or zero, the quality factor becomes infinity. Under this condition, the second term becomes zero, giving the ideal condition. Fig.5.6 shows load current versus load impedance of GTI for filter circuit.

$$I_2 \cong \frac{V_1}{Z_0} \tag{5.2}$$

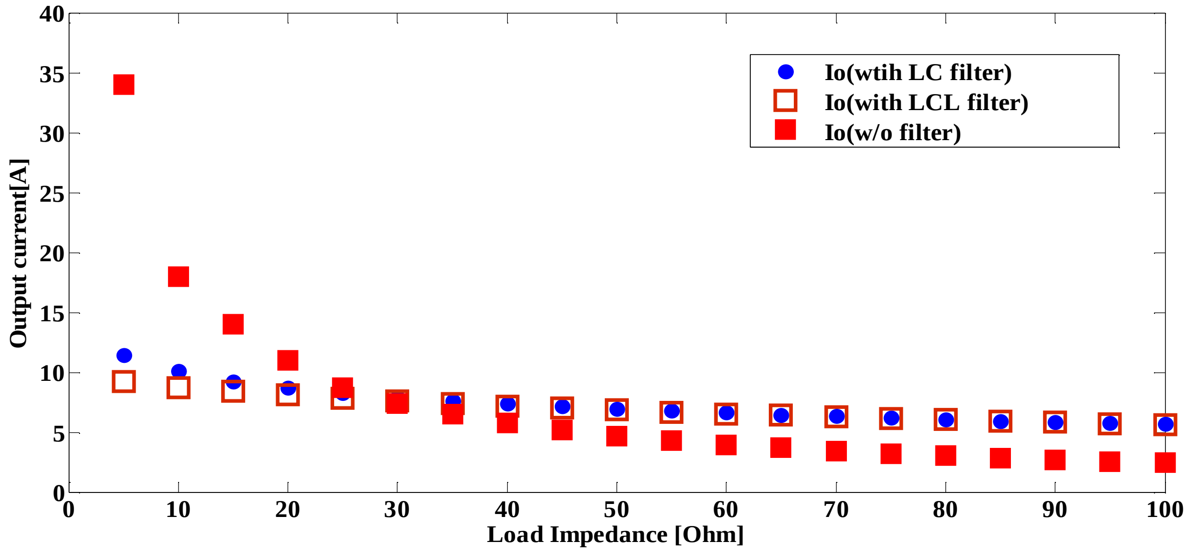

Fig.5.6. Output current vs. load impedance

Here the load impedance was varied from 5Ω to 100 Ω by considering characteristics impedance Z_0=20 Ω and current was measured from load without applying any filter circuit. Same procedure was applied for LC filter and T-LCL filter. It was observed that current across load without filter varying in a quite large range whereas in LC filter for varying load current changed in low scale and in T-LCL filter current is quite constant, which ensures longevity of appliances applied across the load of T-LCL filter and the graph is used data of Table5.1.

Table-5. 1 Inverter data for graphical representation

Load value	Pout [LCL filter]	Pin [LCL filter]	Io	Pin [LC filter]	Pout [LC filter]	Ƞ% [LC]	Io	Io /wo filter	Ƞ% [LCL]
5	651	706	11.42	427	456	93.64	9.24	34	92.2
10	1021	1070	10.1	766	799	95.86	8.75	18	95.42
15	1286	1331	9.26	1061	1101	96.36	8.41	14	96.61
20	1513	1563	8.7	1318	1366	96.5	8.11	11	96.85
25	1708	1771	8.26	1543	1602	96.31	7.85	8.7	96.7
30	1883	1956	7.92	1742	1812	96.13	7.62	7.42	96.27
35	2041	2125	7.63	1919	2002	95.68	7.4	6.48	96
40	2185	2281	7.39	2077	2174	95.53	7.2	5.75	95.79
45	2313	2424	7.17	2220	2331	95.23	7.03	5.17	95.42
50	2432	2558	6.97	2348	2475	94.86	6.86	4.69	95.07
55	2540	2682	6.79	2464	2607	94.51	6.69	4.3	94.7
60	2639	2798	6.63	2570	2730	94.13	6.54	3.97	94.31
65	2729	2905	6.47	2666	2844	93.74	6.41	3.68	93.94
70	2813	3008	6.39	2754	2950	93.35	6.27	3.43	93.51
75	2888	3102	6.2	2834	3049	92.94	6.14	3.22	93.1
80	2957	3191	6.08	2907	3142	92.52	6.03	3.02	92.66
85	3023	3277	5.94	2975	3230	92.1	5.91	2.86	92.24
90	3096	3373	5.86	3042	3319	91.65	5.81	2.71	91.78
95	3166	3466	5.77	3112	3412	91.2	5.71	2.57	91.34
100	3236	3561	5.68	3184	3509	90.73	5.64	2.45	90.87

5.3 Inverter Efficiency

Efficiency means ratio of output and input. The inverter efficiency is calculated through following formula:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{5.3}$$

And by varying load it was monitored that the efficiency of T-LCL filter was higher than the efficiency of LC filter. The efficiency versus load impedance for LC and T-LCL filter is shown in Fig.5.7 and the graph is used data of Table5.1.

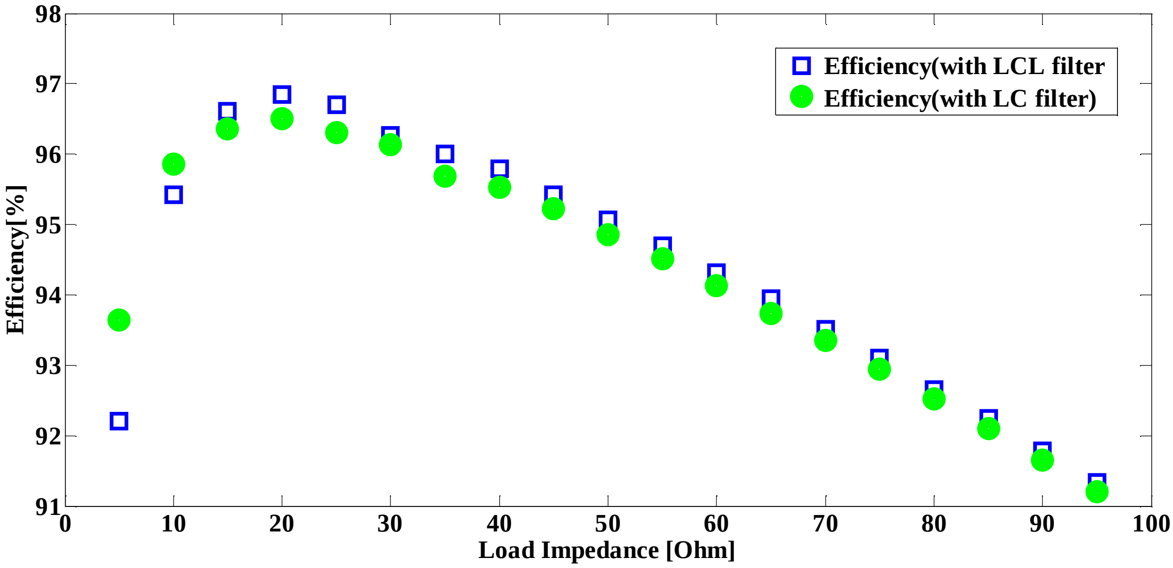

Fig.5.7. Efficiency vs. Load impedance

It is found that the proposed transformer-less GTI is highly efficient while it is transmitting power up to around 1000W to 2400W. At that time inverter efficiency is about 95% and in characteristic impedance the efficiency is 96.7% and when output RMS voltage is 220V and load impedance is 30Ω inverter efficiency is 96.3%.

By analysis PV array system, the paper proposed a dual-stage intelligent PV system, which is similar to modular configuration topology. In an intelligent PV module instead of interconnection between modules they are interconnected with associated DC-DC converter for MPPT tracking which ensures optimal operations of PV module. Various MPPT algorithms exist in different literatures. This research is proposed perturb and observe (P&O) method to extract maximum possible power from solar panel. A dual stage Boost power converter is proposed instead of transformer which will be helped the whole system to make highly efficient, cost effective and light weighted and the whole system efficiency will be rise up to 96.7% with less than 0.01% THD. To make the inverter grid-tie a dual-stage Buck power converter is proposed in this research proposal.

CHAPTER 6

CONCLUSION & FUTURE WORK

6.1 Conclusion

In looking at the components selected and the simulations created before the actual construction of the inverter, everything was built in mind for the purpose of efficiency and keeping power losses to a minimum. In this paper design of a transformer-less grid-tie inverter using new sinusoidal pulse width modulation along with immittance conversion topology and dual stage boost converter and dual stage buck converter have been presented. The simulation results obtained were quite satisfactory and the frequency obtained was in line with the grid. A pure sinusoidal output waveform was obtained and the output current did not change much with the change in the load impedance. The proposed inverter is suitable for constant current load or a dynamic load. It can be conclude that the proposed inverter circuit proved that it is a highly efficient and cost effective product for renewable energy solution.

This project is a stepping stone to a cheaper and efficient pure sine wave inverter, by using the data collected in this report as well as the schematics and recommendations the product produced here can be improved upon.

A dc–ac voltage source converter has been proposed and studied both theoretically and experimentally. According to our opinion, the boost inverter is suitable for applications where the output ac voltage needs to be larger than the dc input and can offer economic and technical advantages over the conventional VSI.

6.2 Future work

The proposed design can be turned into a fully functional grid-tie inverter for establishing connection between the source and the grid for sending power to an electrical grid. The hardware of the proposed grid-tie inverter would also be constructed with the help of a microcontroller and the experimental results would be compared with the ones obtained from the simulation. The simulation results would also be extended in order to expand the horizon of the research.

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Appendix A

Datasheet for inductor and capacitor selection

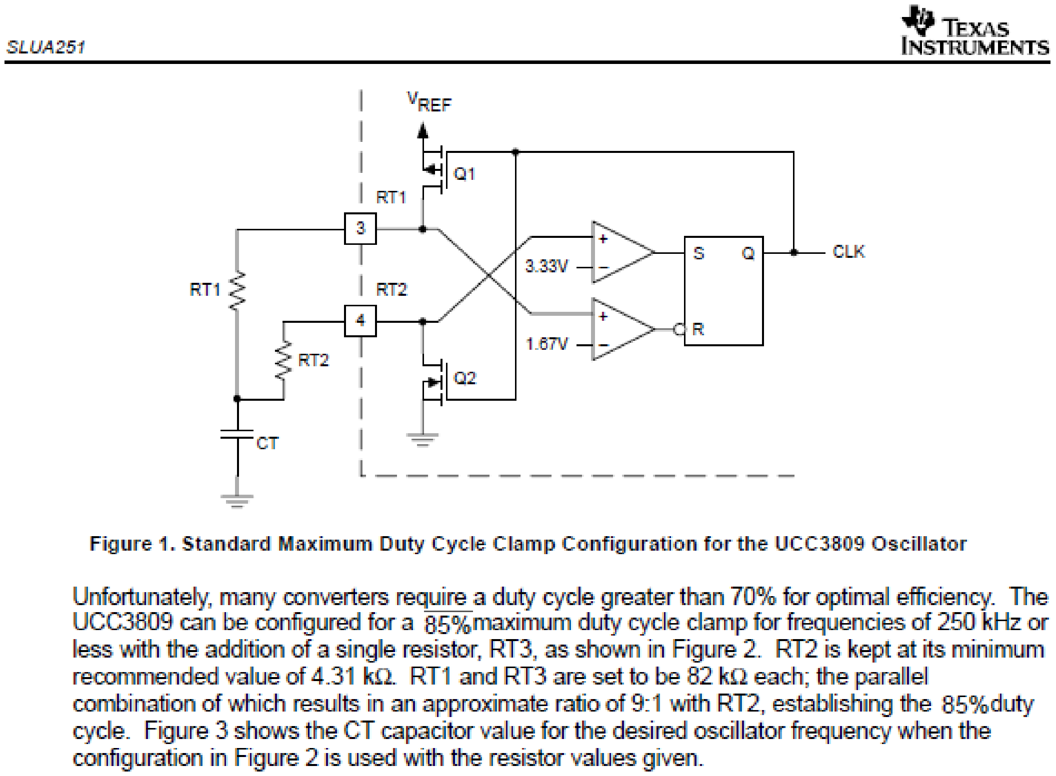
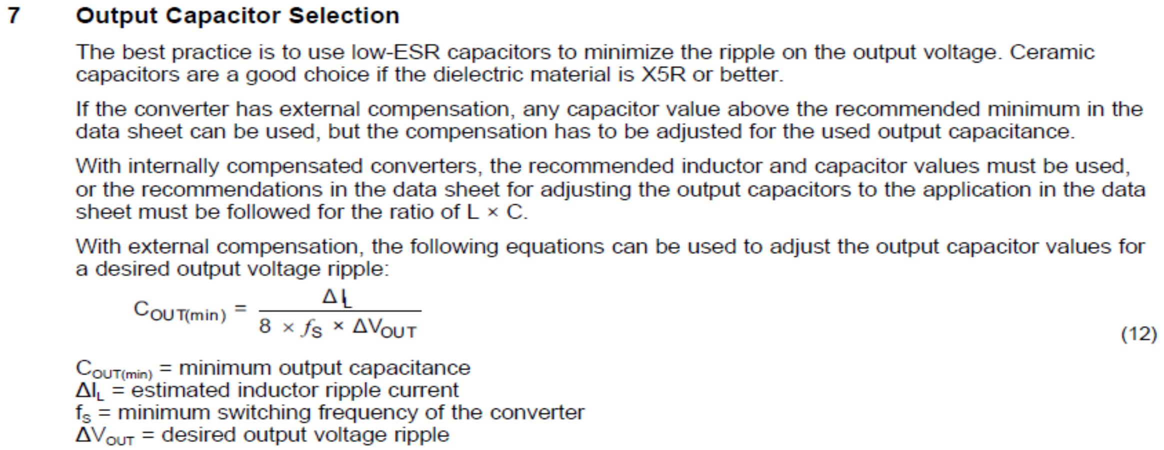


Figure 1. Standard Maximum Duty Cycle Clamp Configuration for the UCC3809 Oscillator

Unfortunately, many converters require a duty cycle greater than 70% for optimal efficiency. The UCC3809 can be configured for a 85%maximum duty cycle clamp for frequencies of 250 kHz or less with the addition of a single resistor, RT3, as shown in Figure 2. RT2 is kept at its minimum recommended value of 4.31 kΩ. RT1 and RT3 are set to be 82 kΩ each; the parallel combination of which results in an approximate ratio of 9:1 with RT2, establishing the 85%duty cycle. Figure 3 shows the CT capacitor value for the desired oscillator frequency when the configuration in Figure 2 is used with the resistor values given.



7 Output Capacitor Selection

The best practice is to use low-ESR capacitors to minimize the ripple on the output voltage. Ceramic capacitors are a good choice if the dielectric material is X5R or better.

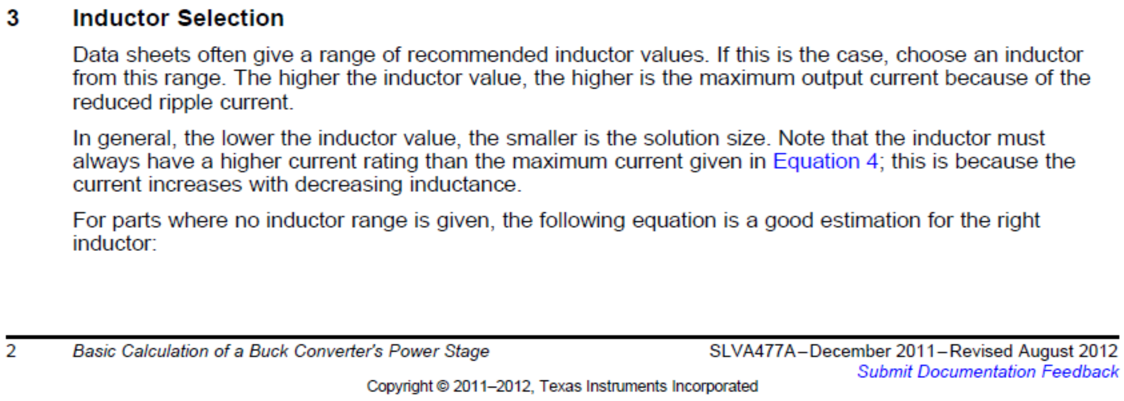
If the converter has external compensation, any capacitor value above the recommended minimum in the data sheet can be used, but the compensation has to be adjusted for the used output capacitance.

With internally compensated converters, the recommended inductor and capacitor values must be used, or the recommendations in the data sheet for adjusting the output capacitors to the application in the data sheet must be followed for the ratio of L × C.

With external compensation, the following equations can be used to adjust the output capacitor values for a desired output voltage ripple:

$$C_{OUT(min)} = \frac{\Delta I_L}{8 \times f_S \times \Delta V_{OUT}} \quad (12)$$

$C_{OUT(min)}$ = minimum output capacitance
ΔI_L = estimated inductor ripple current
f_S = minimum switching frequency of the converter
ΔV_{OUT} = desired output voltage ripple



3 Inductor Selection

Data sheets often give a range of recommended inductor values. If this is the case, choose an inductor from this range. The higher the inductor value, the higher is the maximum output current because of the reduced ripple current.

In general, the lower the inductor value, the smaller is the solution size. Note that the inductor must always have a higher current rating than the maximum current given in Equation 4; this is because the current increases with decreasing inductance.

For parts where no inductor range is given, the following equation is a good estimation for the right inductor:

2 *Basic Calculation of a Buck Converter's Power Stage* SLVA477A–December 2011–Revised August 2012
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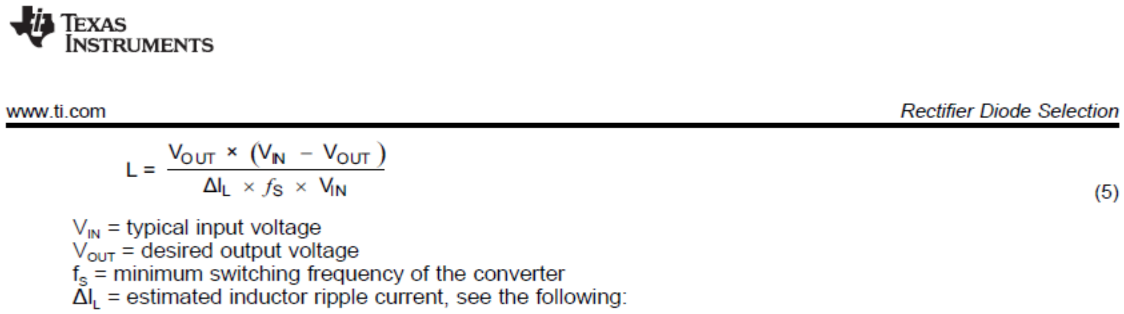


TEXAS INSTRUMENTS

www.ti.com *Rectifier Diode Selection*

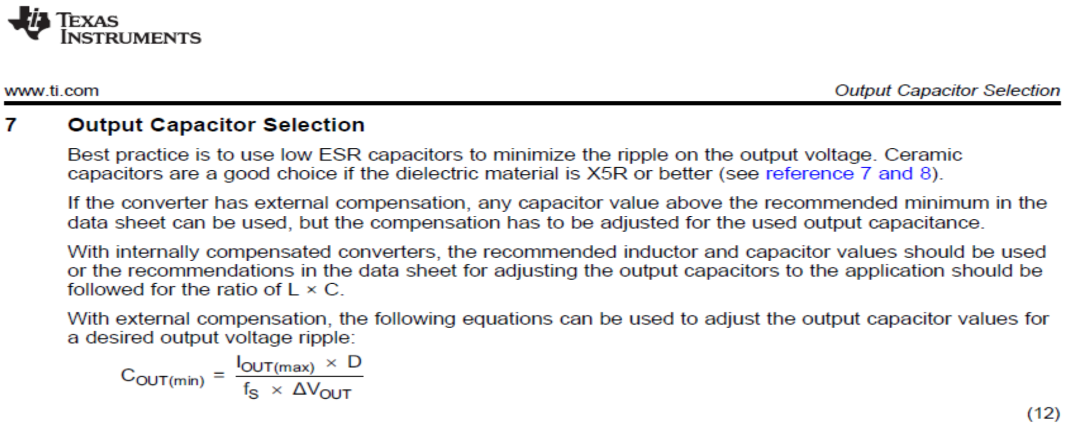
$$L = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{\Delta I_L \times f_S \times V_{IN}} \quad (5)$$

V_{IN} = typical input voltage
V_{OUT} = desired output voltage
f_S = minimum switching frequency of the converter
ΔI_L = estimated inductor ripple current, see the following:

Table 1 shows the specifications of the converter. The inductor current ripple value is desired to be less than 5% of the maximum input current in the case of interfacing a Fuel Cell. A ripple factor less than 4% for the Fuel Cell's output current will have negligible impact on the conditions within the Fuel Cell diffusion layer and thus will not severely impact the Fuel Cell lifetime (Yu et al., 2007).

ΔV_{out_max}	Output voltage ripple (1% of V_{out} = 4 V)
V_{out}	Output voltage (400 V)
F	Switching frequency (20 KHz)
IL_{max}	Inductor current (250 A)
ΔILmax	Inductor current ripple (5% of ILmax = 12.5 A)

Table 1. Standard boost DC-DC converter parameters



TEXAS INSTRUMENTS

www.ti.com *Output Capacitor Selection*

7 Output Capacitor Selection

Best practice is to use low ESR capacitors to minimize the ripple on the output voltage. Ceramic capacitors are a good choice if the dielectric material is X5R or better (see reference 7 and 8).

If the converter has external compensation, any capacitor value above the recommended minimum in the data sheet can be used, but the compensation has to be adjusted for the used output capacitance.

With internally compensated converters, the recommended inductor and capacitor values should be used or the recommendations in the data sheet for adjusting the output capacitors to the application should be followed for the ratio of L × C.

With external compensation, the following equations can be used to adjust the output capacitor values for a desired output voltage ripple:

$$C_{OUT(min)} = \frac{I_{OUT(max)} \times D}{f_S \times \Delta V_{OUT}} \quad (12)$$

3 Inductor Selection

Often data sheets give a range of recommended inductor values. If this is the case, it is recommended to choose an inductor from this range. The higher the inductor value, the higher is the maximum output current because of the reduced ripple current.

The lower the inductor value, the smaller is the solution size. Note that the inductor must always have a higher current rating than the maximum current given in Equation 4 because the current increases with decreasing inductance.

For parts where no inductor range is given, the following equation is a good estimation for the right inductor:

$$L = \frac{V_{IN} \times (V_{OUT} - V_{IN})}{\Delta I_L \times f_S \times V_{OUT}} \tag{5}$$

V_{IN} = typical input voltage
V_{OUT} = desired output voltage
f_S = minimum switching frequency of the converter
ΔI_L = estimated inductor ripple current, see below

ABSOLUTE MAXIMUM RATINGS

over operating free-air temperature range unless otherwise noted[1]

			TPS40060 TPS40061
V_{IN}	Input voltage range	VIN	60 V
		VFB, SS/SD, SYNC	–0.3 V to 6 V
		SW	–0.3 V to 60 V or VIN+5 V (whichever is less)
		SW. transient < 50 ns	–2.5 V
V_{OUT}	Output voltage range	COMP, RT, KFF, SS	–0.3 V to 6 V
I_{IN}	Input current	KFF	5 mA
I_{OUT}	Output current	RT	200 µA
T_J	Operating junction temperature range		–40°C to 125°C
T_{stg}	Storage temperature		–55°C to 150°C
	Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds		260°C

(1) Stresses beyond those listed under *absolute maximum ratings* may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under *recommended operating conditions* is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

Appendix B

MATLAB code for graphical representation

```
data=xlsread('final.xlsx');
x=data(:,1);
y1=data(:,7);
y3=data(:,10);
plot(x,y1,'bo',x,y2,'g* ')
xlabel('Load Impedance [Ohm]');          %  add axis labels and plot title
ylabel('Efficiency[%]');
data=xlsread('final.xlsx');
x=data(:,1);
y1=data(:,4);
y2=data(:,8);
y3=data(:,9);
plot(x,y1,'bo',x,y2,'g* ',x,y3,'ro ')
xlabel('Load Impedance [Ohm]');          %  add axis labels and plot title
ylabel('Output current[%]');
```