A
Thesis
On

"A simple and efficient Symmetrical Hybrid Sine PWM inverter for PV power cells"

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(POWER ELECTRONICS & ASIC DESIGN)
By

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CERTIFICATE

DEPARTMENT OF ELECTRICAL ENGINEERING
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This is to certify that the dissertation entitled ***“A simple and efficient Symmetrical hybrid Sine PWM inverter for PV power cells”*** carried out by **Mr. Ramaprasad Panda** (Regd. No. 2004PE06) for the partial fulfillment of the requirement for the degree of Master of Technology in Power Electronics & ASIC Design is a bonafide record of work done by the candidate under my guidance. To the best of my knowledge and belief, this work has not been submitted earlier for the award of any other degree or diploma.

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Dedicated

To

The omnipresent GOD

&

My loved

Mother

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RAMAPRASAD PANDA

AUTHOR'S DECLARATION

I, Ramaprasad Panda, student of M.Tech, Electrical Engineering Department (Power Electronics & A.S.I.C Design), Regd. No. 2004PE06, hereby declare that the work done in this thesis is my own work and it has not been submitted elsewhere for the award of any degree. And if it is found to be so, then I will be responsible for it.

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ABSTRACT

The world's energy demand is steadily increasing. In future, demand of energy would be difficult to meet with conventional sources of fossil fuel. Therefore alternate source of energy must be found, in order to meet the future requirement of energy. One type of renewable energy source is the photovoltaic (PV) cell, which converts sunlight to electrical energy, without any form for mechanical or thermal interlink. PV cells are usually connected together to form PV modules, consisting of 72 PV cells, which generate a DC voltage between 23 Volt to 45 Volt and a typical maximum power of 160 Watt, depending on temperature and irradiance. The electrical infrastructure around the world is based on AC voltage, with a level of 120 Volt or 230 Volt in the distribution grid. PV modules can therefore not be directly connected to the grid, but must be connected through an inverter. The inverter has two main tasks:

1) Load the PV module optimal, in order to harvest as much energy as possible,

2) Inject a sinusoidal current into the grid.

Presently the cost of energy from PV cells is very high due to low efficiency. To make this source of energy more competitive is by developing inexpensive, development of efficient inexpensive and reliable inverters are required. The aim of this thesis is therefore to develop new concepts for converting electrical energy with high efficiency & reliability, from the PV module to the grid. The inverter is developed with focus on simple topology, efficient and high reliability. The thesis contains a state-of-the-art analysis of different inverter topologies.

The proposed module is a simple, efficient single phase Hybrid sine PWM inverter to be used for generating 230V, 50 HZ, sine wave AC voltage from 48V DC (Generated from a photo Voltaic array). It is multi stage based product in which 48V DC is boosted to 350V DC in the first stage. The second stage is a full bridge inverter which employs Symmetrical hybrid pulse width modulation technique (SHSPWM). The conventional Hybrid Sine PWM technique uses two set of switching signals for the inversion stage. The first set is high frequency sine PWM signals while the second set is low frequency (50 HZ) square wave signals. In one leg of the full bridge inverter there are two switches, which are supplied with high frequency SPWM switching signals while

the other leg uses low frequency square wave signals. The hybrid PWM method which uses both high and low switching signals reduces the overall switching losses. However the switches driven with high frequency switching signals dissipates more heat compared to the switches driven with low frequency switching signals. This results in unequal temperature rise in the switches leading to low reliability. The proposed method uses symmetrical hybrid PWM switching scheme which makes the switching losses of all four switches equal leading to higher efficiency and grater reliability.

In the boosting stage 48 volt DC is inverted to 20 KHz square wave AC which is stepped up by a high frequency transformer to 350 volt square wave AC. Transformer out put is rectified and filtered for the SHSPWM inverter input. High frequency switching harmonics are attenuated by providing a low pass filter at the inverter out put. A close loop control is provided between out-put of the inverter and first stage (DC-DC converter) for an efficient voltage regulation to take care of input voltage and load variations. In the boosting stage high frequency AC minimizes transformer size as well as the filter requirements. Use of SHSPWM techniques in inversion stage reduces switching losses, which results higher efficiency with grater reliability. A simple technique provides the required dead time between two half cycles in the inversion stage to avoid short circuit of DC link and over heating of the switches.

The whole system was simulated using P-SIM software. For the novel SHSPWM technique employed for inversion stage, a prototype inverter module is prepared in the laboratory to verify its feasibility. The experimental results are verified with the simulated results.

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CHAPTER: 1

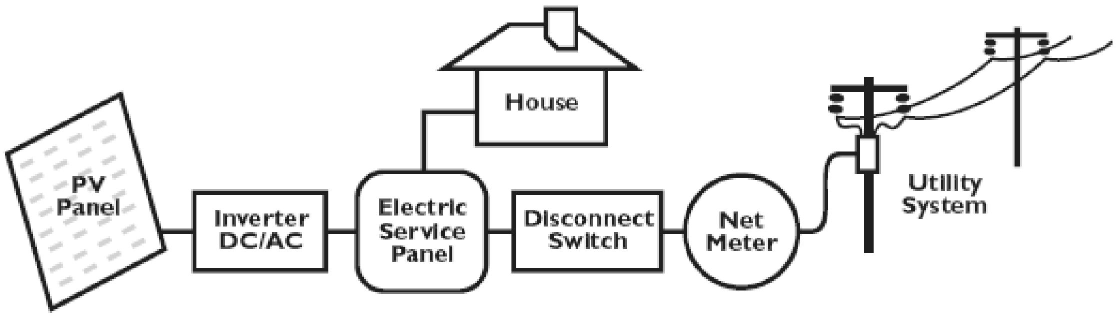
Introduction

According to U.S.A. Energy Information administration [1] World electricity demand is projected to grow at an average rate of 2.6 percent per year, from 14,275 billion kilowatt-hours in 2002 to 21,400 billion kilowatt-hours in 2015 and 26,018 billion kilowatt-hours in 2025. The effect of global warming and abnormal climatic changes needs a large reduction in greenhouse gas (GHG) emissions. This prevents aiding of new power plants, which use conventional energy sources such as burning of primary fossil fuel such as coal, oil, natural gas, etc. [2].

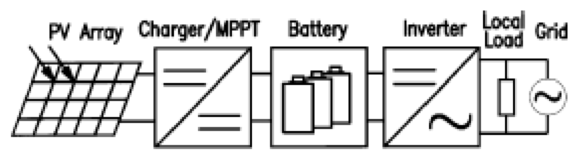
This presents significant opportunities for distributed power generation (DG) [3] system using renewable energy recourses such as solar, wind and fuel cells. Both consumers and power utilities can benefit from the widespread deployment of DG systems which offer secure and diversified energy options, increase generation and transmission efficiency, reduce greenhouse gas emissions, improve power quality and system stability, cut energy costs and capital expenditures, and alleviate the bottleneck caused by distribution lines.

1.1 Distributed Power Generation (DG)

DG systems are usually small modular devices close to electricity users, including wind turbines, solar energy systems, fuel cells, micro gas turbines, and small hydro systems, as well as the relevant controlling/managing and energy storage systems. Such systems commonly need dc–ac converters or inverters as interfaces between their single-phase loads and sources as shown in Fig. 1, which depicts a typical renewable DG system using photovoltaic (PV) as energy source. DG inverters often experience a wide range of input voltage variations due to the fluctuations of energy sources, which impose stringent requirements for inverter topologies and controls.



(a)



(b)

Figure: 1.1(a) lay out of a renewable DG system using photovoltaic (PV) as energy source, 1.1 (b) Block diagram of a photovoltaic system.

1.2 Use of Renewable Energy

According to market analyst frost and Sullivan the renewable energy based market is likely to be the biggest consumers of inverter, with various governments extending full support to projects that utilizes power from non-conventional sources such as solar, wind and fuel cells. These energies can be reliably used if they can be stored. This is done by the help of storage batteries (lead acid cells). This stored energy only can be used when it can make to consume requirements level (1 phase /3 phase, 230V/400V, 50Hz AC). This is achieved by the help of inverters.

1.3 Indian Scenario

India is riddle with poor power quality and outages. Sometimes power cuts are large more than 6hrs. In this scenario, inverters are come in households. The inverters cells are likely to grow 32 to 35% in the year 2005-2006. A new market will emerge in rural areas for solar power based inverters

In India only 30% of the inverter industry is organized. Unorganized players dominate as they are able to manufacture cheaper inverters due to fewer overheads.

Inverter kits are easily available in "knock down condition". Assembling of such inverters does not require any technical expertise however a quality and reliability of these inverters are debatable.

1.4 Power quality

In India the demand of electrical energy is always more than the supply, the consumers of electrical energy do not bother about the quality of power. However quality of power is of great concern for sensitive loads such as process industries, IC manufacturing industry, and hospital using sophisticated biomedical instruments etc. power quality means the available power must have

1) constant voltage
2) constant frequency
3) pure sinusoidal
4) balanced (In case of a three phase system)
5) uninterrupted power supply

Hence a good inverter must satisfy the above power quality requirement.

Most of the inverters available in the market are of quasi square wave type whose output contains a large chunk of 3^{rd} harmonic. This causes higher EMI, looses, lower efficiency etc. also lack of feedback arrangements results in poor voltage regulation

1.5 Technological Trends

Technologically the inverters are progressed

1. Power handling devices which decides the rating
2. Signal processing which decides power conditioning

In earlier days power transistors were used to the maximum extent. The development of high power rated MOSFET and IGBT'S have replace old transistor in the power handling section. Signal processing has advanced rapidly with the development of cheaper and Feature rich microcontrollers and digital signal processors. Another required trend is the smaller size with larger power handling capacity. All these can be achieved by adopting high frequency PWM technique.

Very little R&D has been done for inverter in India. All that has being done is actually the change in design and development of new topologies.

1.6 Problem Statement of Thesis

Generation of AC supply (220V, 50Hz) from solar energy is of important utility of non-conventional energy. Solar photovoltaic cells produce DC potential difference when exposed to solar radiations. Array of such cells are connected in series parallel combinations to generate DC supply of required capacity. The voltage generated from the photovoltaic array charges a lead acid battery through a charger circuit. The energy stored in the batteries (series parallel combination of lead acid cell to generator 48V at desired current) is used for generating mains supply required by the consumer. Conversion of solar energy stored in the lead acid battery (48V DC) to 220V, 50Hz, single phase, Sinusoidal alternating voltage to supply 1KVA load, is the theme of this thesis. In this thesis a multistage topology is used for high power application. Also a novel switching technique is employed in the inverter stage for better efficiency and grater reliability.

1.7 Organization of Thesis

The whole thesis consists of eight chapters. The first chapter introduces the need of Inverters for DG systems with a brief introduction abut the technological trends. The second chapter describes the fundamentals of PV cells. The third chapter deals with literature survey where evolution of PV Inverters and topological features of single phase Inverters are described. The fourth chapter gives general description of components that an Inverter contains. The fifth chapter gives system overview of the proposed Inverter module. Chapter no six provides the detailed design procedure for the proposed inverter. Seventh chapter gives both simulation and experimental results for the Inverter module. The last chapter concludes with advantages, applications and scope for future work.

CHAPTER: 2

Photovoltaic Fundamentals

2.1 Current PV Technology [25]

Photovoltaic (PV)] or solar cells as they are often referred to are semiconductor devices that convert sunlight into direct current (DC) electricity. Groups of PV cells are electrically configured into modules and arrays, which can be used to charge batteries, operate motors, and to power any number of electrical loads. With the appropriate power conversion equipment, PV systems can produce alternating current (AC) compatible with any conventional appliances, and operate in parallel with and interconnected to the utility grid.

2.2 History of Photovoltaic

The first conventional photovoltaic cells were produced in the late 1950s, and throughout the 1960s were principally used to provide electrical power for earth-orbiting satellites. In the 1970s, improvements in manufacturing, performance and quality of PV modules helped to reduce costs and opened up a number of opportunities for powering remote terrestrial applications, including battery charging for navigational aids, signals, telecommunications equipment and other critical, low power needs.

In the 1980s, photovoltaic became a popular power source for consumer electronic devices, including calculators, watches, radios, lanterns and other small battery charging applications. Following the energy crises of the 1970s, significant efforts also began to develop PV power systems for residential and commercial uses both for stand-alone, remote power as well as for utility-connected applications. During the same period, international applications for PV systems to power rural health clinics, refrigeration, water pumping, telecommunications, and off-grid households increased dramatically, and remain a major portion of the present world market for PV products. Today, the industry's production of PV modules is growing at approximately 25 percent annually, and major programs in the U.S., Japan and Europe are rapidly accelerating the implementation of PV systems on buildings and interconnection to utility networks.

2.3 How PV Cells Work?

A typical silicon PV cell is composed of a thin wafer consisting of an ultra-thin layer of phosphorus-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon. An electrical field is created near the top surface of the cell where these two materials are in contact, called the P-N junction. When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light-stimulated electrons, resulting in a flow of current when the solar cell is connected to an electrical load.

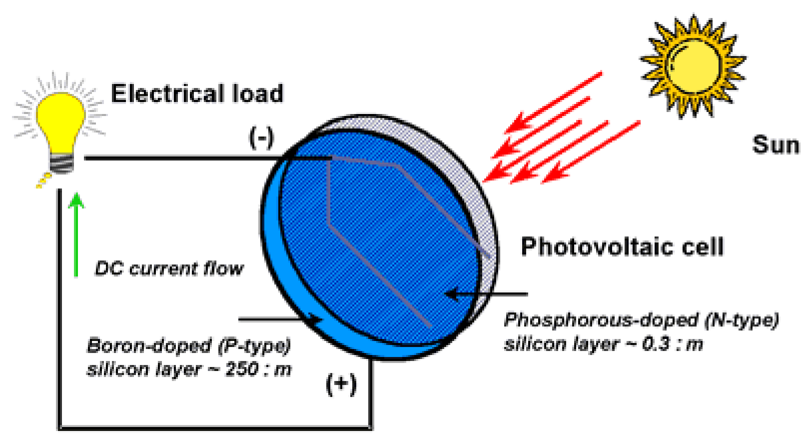


Figure: 2.1 Operation of photovoltaic cell.

Regardless of size, a typical silicon PV cell produces about 0.5 – 0.6 volt DC under open-circuit, no-load conditions. The current (and power) output of a PV cell depends on its efficiency and size (surface area), and is proportional the intensity of sunlight striking the surface of the cell. For example, under peak sunlight conditions a typical commercial PV cell with a surface area of 160 cm^2 (~25 in^2) will produce about 2 watts peak power. If the sunlight intensity were 40 percent of peak, this cell would produce about 0.8 watts.

2.4 The Need for Solar Cells

The development of solar cell use has been stimulated by:

- The need for low maintenance, long lasting sources of electricity suitable for places remote from both the main electricity grid and from people; eg satellites, remote site water pumping, outback telecommunications stations and lighthouses;
- The need for cost effective power supplies for people remote from the main electricity grid; e.g Aboriginal settlements, outback sheep and cattle stations, and some home sites in grid connected areas.
- The need for non polluting and silent sources of electricity; e.g. tourist sites, caravans and campers
- The need for a convenient and flexible source of small amounts of power; e.g. calculators, watches, light meters and cameras;
- The need for renewable and sustainable power, as a means of reducing global warming.

Together, these needs have produced a growing market for photovoltaic, which has stimulated innovation. As the market has grown, the cost of cells and systems has declined, and new applications have been discovered.

2.5 PV Module

The modules are manufactured by 'stringing' cells of appropriate size (i.e. each cell is cut to generate the required current) into a series. Each typical cell generates 0.5V (approximately). So to charge a 12V battery it is customary to use a module of generation capacity of 19V+ (to charge the lead acid battery to 14.4V+ series diode-schotty barrier type +drops). To get proper wattage output two or more modules of same capacity are parallel. A series –parallel combination of solar modules are used to generate the required voltage/power output.

As single PV cells have a working voltage of about 0.5 V, they are usually connected together in series (positive to negative) to provide larger voltages. Panels are made in a wide range of sizes for different purposes. They generally fall into one of three basic categories:

Low voltage/low power panels are made by connecting between 3 and 12 small segments of amorphous silicon PV with a total area of a few square centimeters for voltages between 1.5 and 6 V and outputs of a few milli-watts. Although each of these panels is very small, the total production is large. They are used mainly in watches, clocks and calculators, cameras and devices for sensing light and dark, such as night-lights.

- Small panels of 1 - 10 watts and 3 - 12 V, with areas from 100cm2 to 1000cm2 are made by either cutting 100cm2 single or polycrystalline cells into pieces and joining them in series, or by using amorphous silicon panels. The main uses are for radios, toys, small pumps, electric fences and trickle charging of batteries.
- Large panels, ranging from 10 to 60 watts, and generally either 6 or 12 volts, with areas of 1000cm2 to 5000cm2 are usually made by connecting from 10 to 36 full-sized cells in series. They are used either separately for small pumps and caravan power (lights and refrigeration) or in arrays to provide power for houses, communications pumping and remote area power supplies (RAPS).

If an application requires more power than can be provided by a single panel, larger systems can be made by linking a number of panels together. However, an added complexity arises in that the power is often required to be in greater quantities and voltage, and at a time and level of uniformity than can be provided directly from the panels.

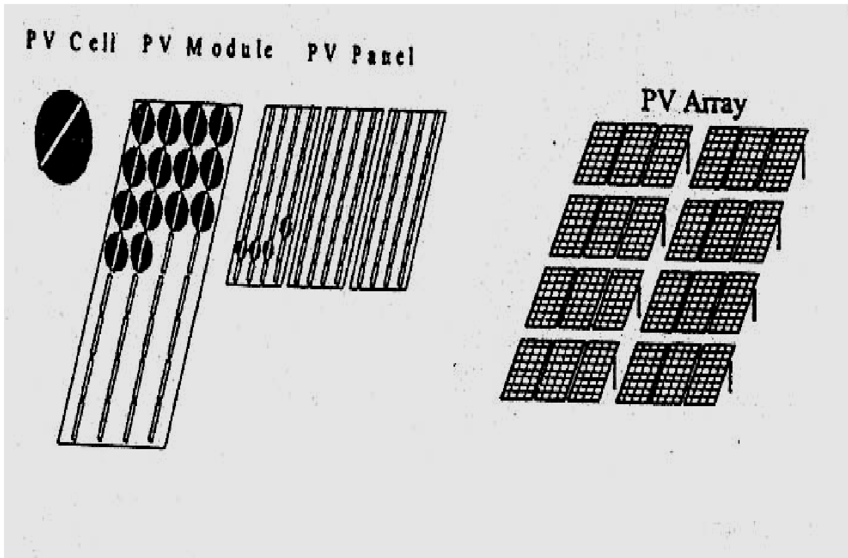


Figure (2.2): PV cell, PV module, PV panel, PV Array

Design of PV module: [26] If an application requires more power than it can be provided by a single panel. Larger systems can be made by linking a number of panels together. However, an added complexity arises in that the power is often required to be in greater quantities and voltage and at a time and level of uniformity than can be provided directly from the panels.

The graph shows the power output from a module in a day when arranged in fixed and sun tracking mechanism respectively. The vary shape of the graph itself suggests that the energy harnessed from a module is always less than the peak power multiply by total number of hours exposed to sun usually in practice just 3-4 Hrs out of the total days exposure is taken for calculation purpose.

The daily energy output from PV panels will vary depending on the orientation, location, daily weather and season. On average, in summer, a panel will produce about five times its rated power output in watt hours per day, and in winter about two times that amount. For example, in summer a 50 watt panel will produce an average of 250 watt-hours of energy, and in winter about 100 watt-hours.

Trackers are used to keep PV panels directly facing the sun, thereby increasing the output from the panels. Trackers can nearly double the output of an array.

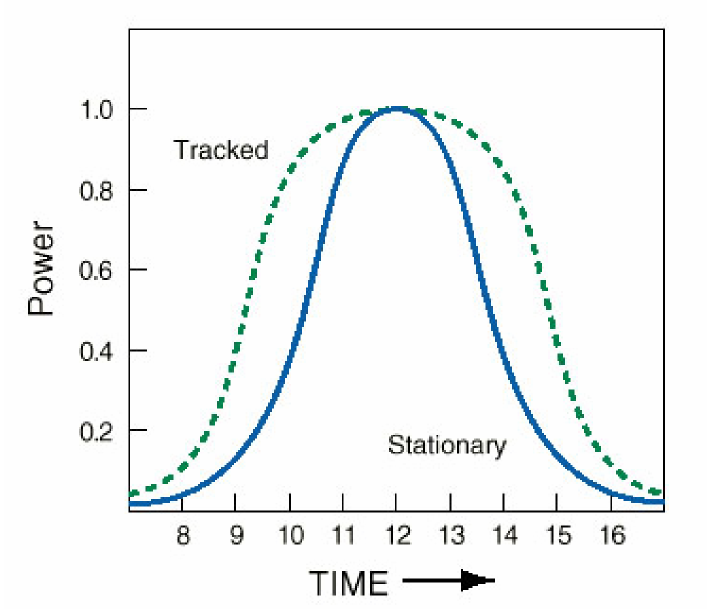


Figure (2.3): The Graph showing power output for tracked and non-tracked array

i.e. energy $\approx W_{peak} \times 3Hrs \approx W_{peak} \times 4Hrs$

The power required calculation involving a 1KW solar power inverter with an efficiency of approximately 80% using 12V/40Wp (4 Nos.)

Energy generated from solar = $40 \times 3 \times 4 \approx 40 \times 4 \times 4$

$= 480$watt-hrs ≈ 640watt-hrs

Say for calculation purpose 500watt-hrs

Input power required @ full load $= \dfrac{1000}{0.8} = 1250$ watts

(Taking 80% efficiency)

$\therefore$ The system can supply a load of 1KW for duration $= \dfrac{500 watt-hour}{1250 watt} = 0.4$ Hrs

CHAPTER 3

Literature Survey

3.1 Evolution of Photovoltaic Inverters

This chapter starts with a historical overview. From the past, when large areas of several PV-modules were interfaced to a centralized inverter, into the present time, where decentralized inverters are interfacing a single or few modules and further into the future where inverter only interfaces a single PV-cell to the grid. Next, an overview of existing power converter topologies for the AC-Module is given. The approaches are further discussed in order to compare the topologies for future applications.

(a) ***A. The Past: Centralized Inverters:*** The past technology was based on centralized inverters, which was interfaced to a number of modules. The modules were normally connected in both series, called a string, and parallel in order to reach a high voltage and power level. This results in some limitation; such as the necessity of high voltage DC cables between the modules and the inverter, power losses due to a centralized MPP Tracking (MPPT) [4], mismatch between the modules and at last the string diodes.

If one of the modules in a string becomes shadowed, then it will operate as a load with lower power generation as a consequence. On the other hand, if the modules are connected in parallel, the shadowed module is still generating power, but the input voltage to the inverter is inevitable lower due to the parallel connection. A third scheme is given in [5], where each module is interfaced by a Generation Control Circuit (GCC). Hence, an individual MPPT is assured for every single module, which also lowers the possibilities of hot spots.

Full shadowing of one PV-cell (in a string of 160 cells) causes a temperature raise, inside the cell, of more than 70 ºC above the ambient temperature, whereas the non-shadowed cells only reach 22 ºC above the ambient temperature (for an ambient temperature equal to 12 ºC). This is of great importance, because an overheated cell rapidly decreases the modules lifetime.

(b) ***The Present: String Inverters and AC-Modules:*** The present technology, which is a hot research topic, is the 'string-inverter'. String-inverters use a single string of modules, to obtain a high input voltage to the inverter. However, the high DC voltage requires an examined electrician to perform the interconnections between the modules and the inverter. On the other hand, there are no losses generated by the string diodes and an individual MPPT can be applied for each string. Yet, the risk of a hot-spot inside the string still remains.

The AC-Module, where the inverter is an integrated part of the PV-module, is also an interesting solution [6], [7]. It removes the losses due to mismatch between modules and inverter, as well as it supports optimal adjustment between the module and the inverter. Moreover, the hot-spot risk is removed. All this together; a better efficiency may be achieved. It also includes the possibility of an easy enlarging of the system, due to the modular structure. The opportunity to become a 'plug and play' device, which can be used by persons without any education in electrical installations, is also an inherent feature.

(c) The Future: AC-Modules and AC-Cells: A solution for the future could be the AC-Cell, which is the integration of one great PV-cell and the inverter [8]. The aim of these cells is to be an integrated part of the climatic-barrier in buildings. The main challenge for the inverter is to amplify the cell's inherent very low voltage up to an appropriate level for the grid-connected inverter and at the same time to reach a high efficiency. For the same reason, entirely new converter technologies are requested.

3.3 Inverter Classification

General classification of inverter types is as follows:

- Central inverters
- Module integrated inverters (AC modules)
- String inverters
- Multi-string inverters

(a) Central inverters: Based on drive system technology the first PV inverters at the end of the 1980's were line commutated inverters (see Fig. 3.1) with power ratings of several kilo watts. Although these topologies are robust, highly efficient and cheap, their major drawbacks are a power factor between 0.6 and 0.7, which has to be compensated with special filters as well as high harmonic content in-the output current. Due to the rapid developments in the semiconductor device industry, thyristors have been increasingly replaced by BJT's, MOSFET's or IGBT's. Today central inverters are mostly self commutated inverters in the power range above 2 kW. Their topologies without and with transformer are shown in Fig. (3.2) and (3.3). They are composed of a PWM full bridge, switching at high frequencies (> 16 kHz) which shapes and inverts the input current into an AC current. Most of the bridges use IGBT's or a combination of IGBT's and MOSFET's. This concept is a well known, robust, efficient and cheap technology which provides high reliability and low price per watt. Their efficiencies are lower than in line commutated concepts due to the high switching frequencies of 16-20KHZ

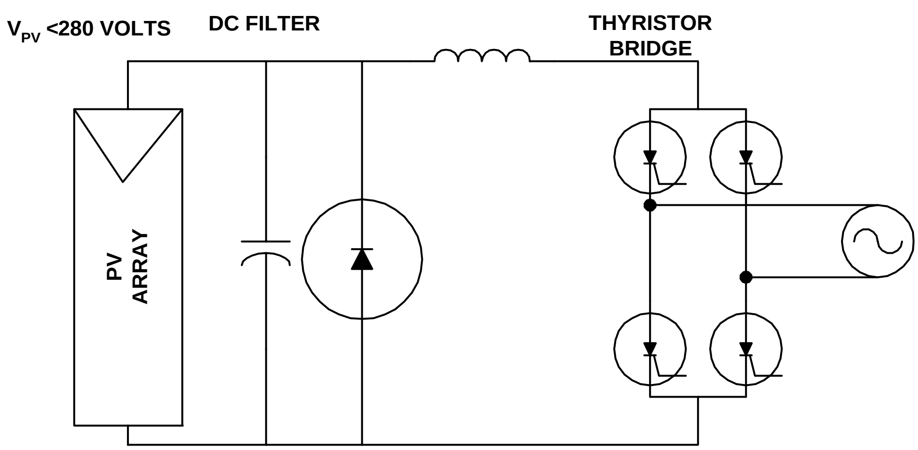


Figure (3.1): Line commutated Transformer less PV inverters

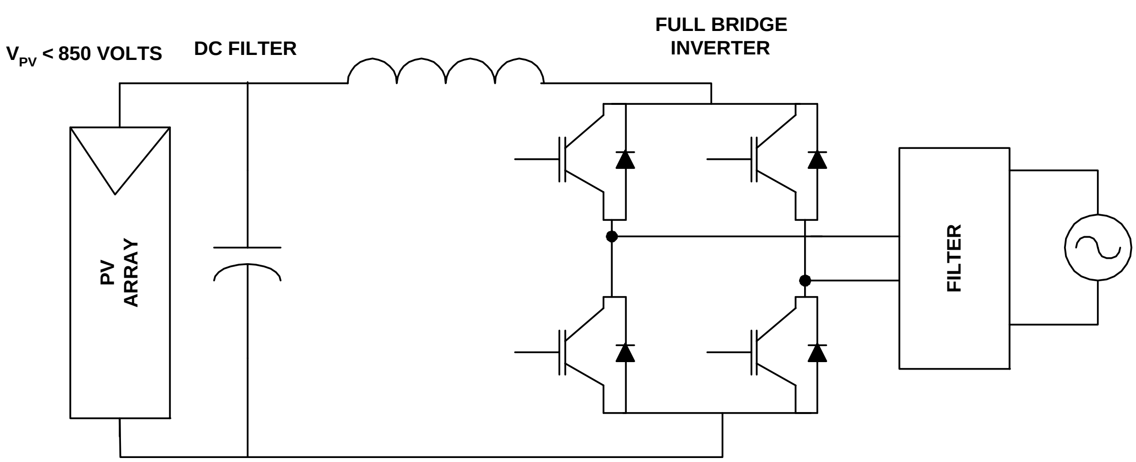


Figure (3.2): Self commutated inverters with out transformer

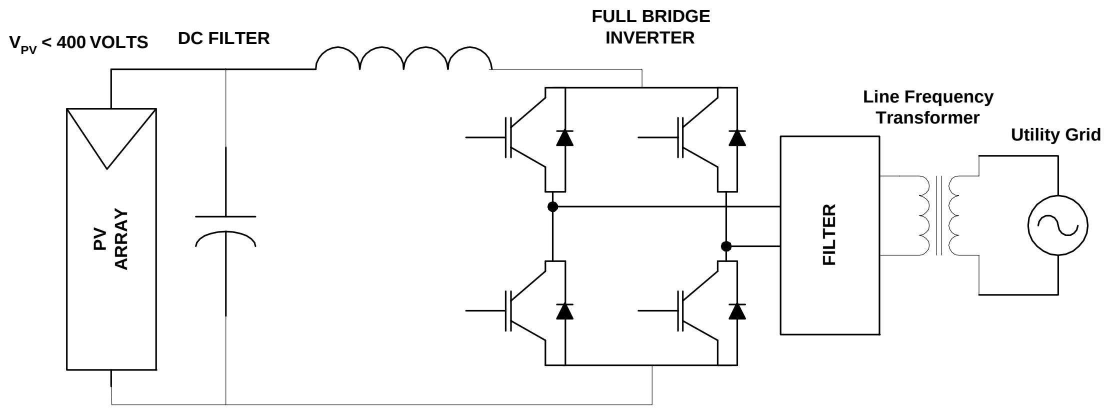


Figure (3.3): PV inverters with line frequency transformer

The disadvantages of all central inverter topologies are found in the system configuration:

1. The required DC wiring increases costs and decreases safety
2. There are no means of independently operating sections of the PV array at their maximum power point (MPP). Mismatch between sections (e.g. caused by partial shading) may therefore significantly reduce the overall system output.
3. Due to the high power range an extension or a flexible system design cannot be realized. These drawbacks can be overcome with module integrated or oriented inverters and with string inverters.

(b) Module integrated or module oriented inverters: These inverters are operating directly on one or several PV modules below 500 W. The PV array voltage is generally between 30 - 150 V. These low voltage levels require a voltage adjustment element, which allows for a variety of topologies. Topologies with transformer are shown in Fig. 3.4. Using a line frequency transformer is advantageous since low voltage MOSFET's can be used for the PWM high frequency switched bridge. Low voltage MOSFET's which are widely used in large quantities for automotive applications are cheap semiconductor devices. Furthermore the whole control system can be realized on the low voltage side and this topology is also suitable for high current PV modules. However, some inverter companies follow high-frequency transformer concepts in order to reduce the magnetic components and costs and an example topology is shown in Fig.6. In order to reduce the switching losses on the high voltage side the push-pull converter boosts the voltage to grid level and shapes the current waveform as well. A full bridge switched at line frequency is used in a second converter stage as an unfolding *I* inverting stage. Both converters in series reduce the efficiency and make the control more complex.

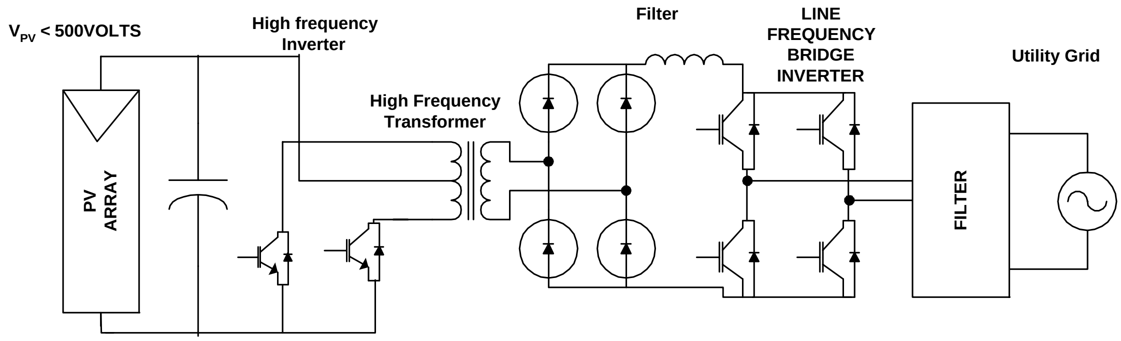


Fig: (3.4) PV inverter with several conversion stages and high frequency transformer

Fig. 3.5 shows a third topology available on the market, which avoids a transformer in order to reduce magnetic components and to increase efficiency. This topology can be used in several European countries e.g. Germany. Other countries require a transformer. While using a boost converter to boost the low PV voltage, shaping and inverting of the output current have to be done in the second converter stage at high voltage level.

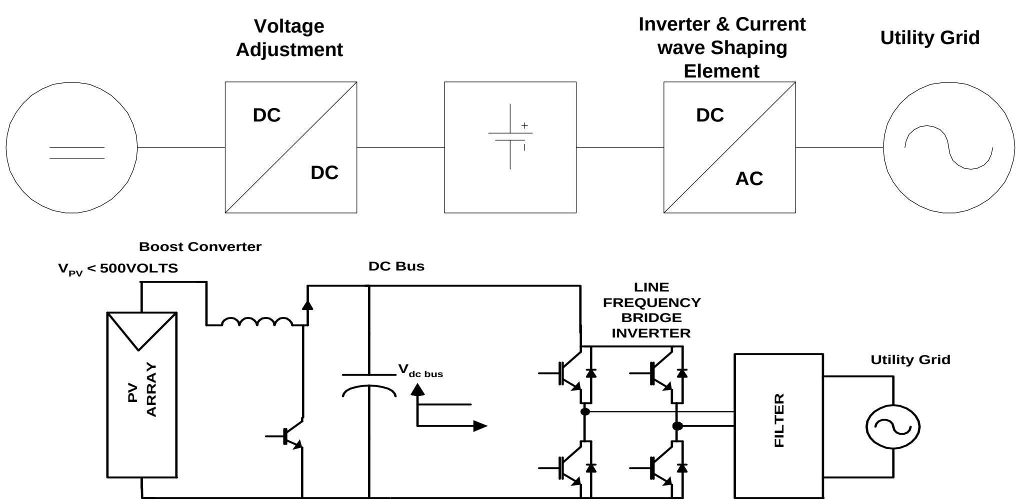


Fig. 3.5 Transformer less PV inverter with several conversion stages including boost stage

(c) String inverters: The string inverter is capable of combining the advantages of both central and module integrated inverter concepts with little tradeoffs. A number of PV modules connected in series form a string up to 2 kW. In this power range the PV array (string) voltage can be between 150-450V. Various topologies can be used for this concept. Depending on the power and voltage ratings, IGBT's and MOSFET's are used at switching frequencies between 16 and 32 kHz. The advantages are that these topologies are used in a higher power range, which decreases the price per watt and that the system efficiency is I-3% higher than in systems with central inverters. Figure (3.6) shows the structure of a string inverter.

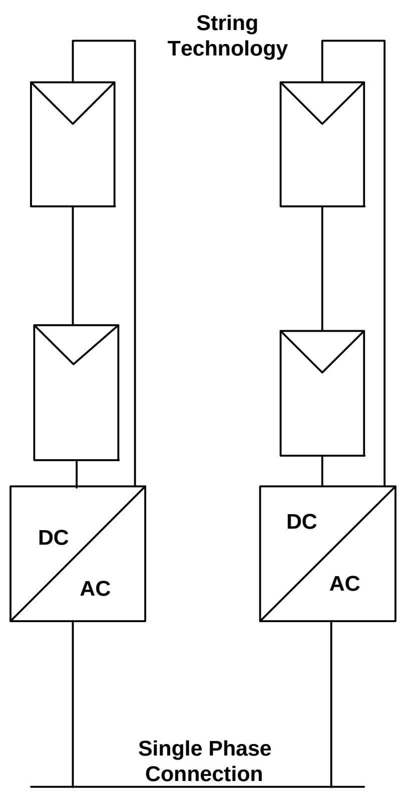


Figure (3.6) Structure of a string inverter

(d) Multi string inverters: Recent developments in subsidy programs by governments are forcing companies to reduce inverter costs by approximately 20% within 5 years. In order to achieve this goal a new inverter concept (see Fig. 3.7) has been developed to combine the advantage of higher energy yield of a string inverter with the lower costs of a central inverter. Lower power DC-DC converters are connected to individual PV strings. Each PV string has its own **MPP** tracker which independently optimizes the energy output from each PV string. To expand the system within a certain power range only a new string with a DC-DC converter has to be included. All DC-DC converters are connected via a DC bus through a central inverter to the grid. The central inverter is a PWM inverter based on the well-known and cheap IGBT technology already used in drive systems and includes all supervisory and protection functions. Depending on the size of the string the input voltage ranges between 125 and 750 V. The inverter has a maximum power rating of 5 kW.

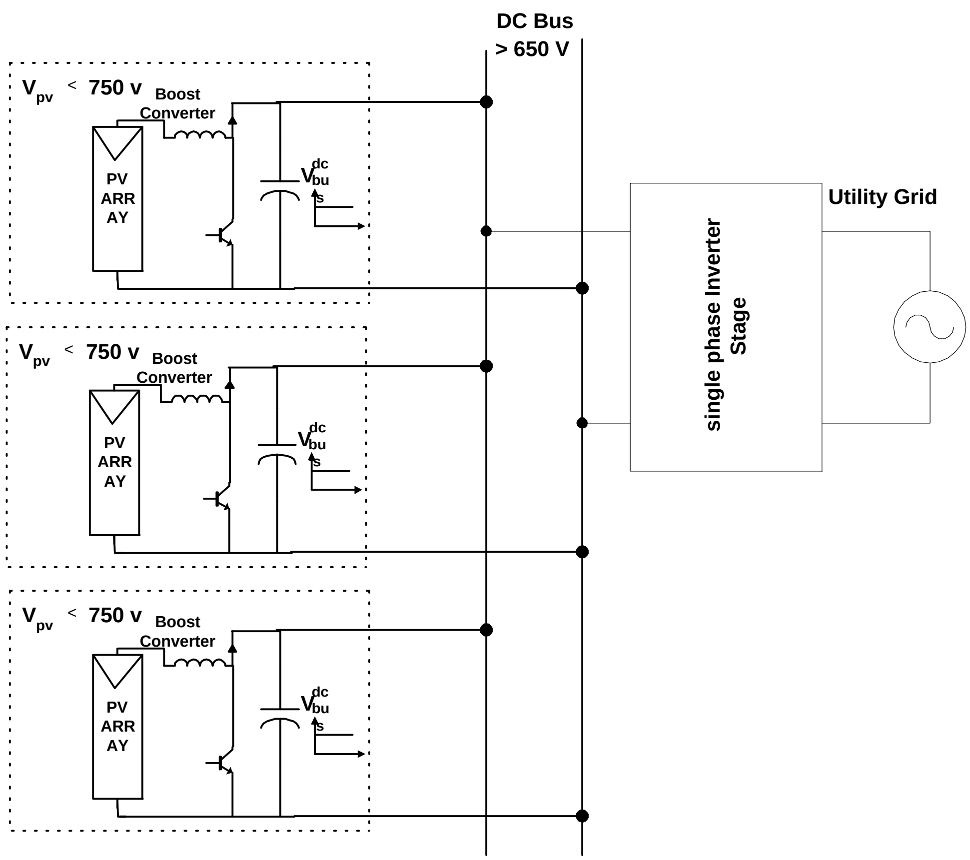


Fig.3.7 Multi string inverter

3.3 Inverter Topologies

Based on the electrical isolation between the input and output, inverters can be classified as isolated inverters or non-isolated inverters. While electrical isolation is normally achieved using transformers, a choice can be made between using line-frequency transformers or high-frequency transformers. The dc-link voltage of inverters for DG systems may vary over a wide range. Depending on the input dc voltage range in comparison to the output ac voltage, inverters can be buck inverters, boost inverters, or buck-boost inverters. It should be noted that although a full bridge inverters are buck inverters by themselves, the whole topologies eventually represent boost or buck-boost inverters due to PWM operations and voltage step-up in either low frequency or high frequency.

Traditional full-bridge buck inverters are used in many existing high power applications with bulky and heavy line-frequency transformers. However, modern power electronic converters tend to use "more silicon and less iron." This leads to the pursuance of compact designs with wide input voltage ranges and improved overall efficiency.

Broadly PV inverters are classified as

(i) single-stage and
(ii) multiple-stage power circuit topologies

(a) Single-Stage Inverters: The inverter in Fig. 3.8 has a simple circuit topology and low component counts, leading to low cost and high efficiency. Such a system also demonstrates robust performance and high reliability. This represents a preferred choice of topology as in [9] if performance requirements can be met. However, line-frequency transformers demand a premium in volume and weight, and thus are increasingly replaced by high-frequency transformers or transformer less designs.

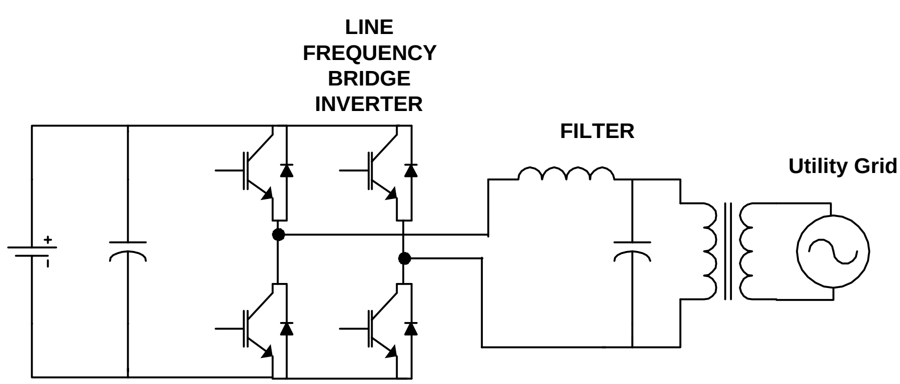


Figure 3.8 Single stage Inverter with line frequency transformer

Intended to both minimize the power components and step up voltage, single-stage boost or buck-boost inverters were proposed in [10]–[14]and [15] which accomplish boosting and inverting functions in a single power stage. Based on boost or buck-boost principles, as well known in dc–dc converters, these inverters use dc inductors for energy storage or fly back transformers for both energy storage and electrical isolation as required for safety reasons.

Single stage inverters may further classified as

1) four-switch topologies;

2) six-switch topologies.

Four-switch topologies: A non-isolated boost inverter by Cáceres and Barbi [10] is shown in Fig.3.9, where the dc inputs of two identical boost dc–dc converters are connected in parallel with a dc source and the load is across the two outputs. Each converter is modulated to produce a unipolar dc-biased sinusoidal output, 180 out of phase with the other. Thus the output across the load shows a pure sinusoidal waveform. Sliding

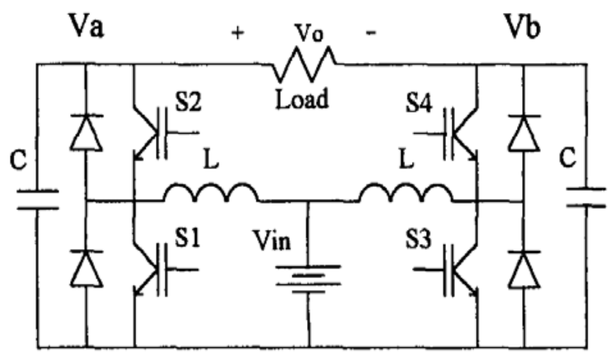


Figure (3.9): Four-switch boost inverter by Cáceres and Barbi [10].

Six-Switch Topologies: An isolated flyback buck-boost inverter by Nagao and Harada [13] in Fig.3.10 combines two buck-boost choppers in a four-switch bridge with two additional switches used for synchronous commutation in each half cycle of ac output. Advantages of this inverter include a desired output power regardless of the dc voltage and the electrical isolation between the PV and utility. Additional switches compared to four-switch topologies facilitate the grounding of both the grid and PV modules.

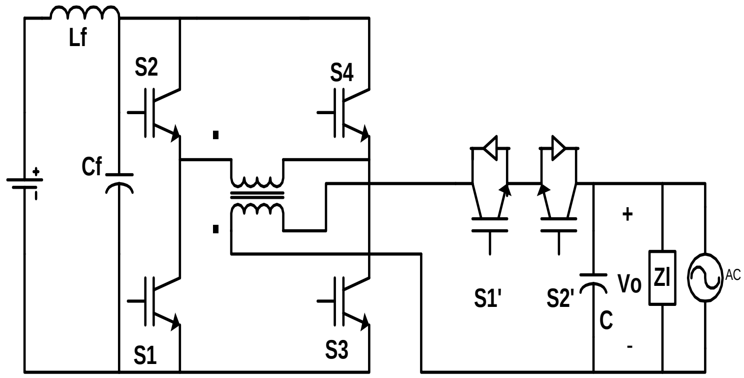


Figure (3.10): Six-switch isolated buck-boost inverter (isolated) by Nagao and Harada

A distinctive feature of single-stage buck-boost inverters is the elimination of low frequency transformers. Therefore they present a compact design with a good performance-cost ratio compared to conventional buck inverters with line-frequency transformers. Although single-stage inverters are generally high-efficient and low-cost, they usually suffer from

(i) limited power capacity,

(ii) compromised output quality,

(iii) Limited operation range imposed to dc sources.

It is observed, in such an inverter, the currents through main switches are usually discontinuous triangular pulses, and the output current cannot be controlled directly by the current through power switches even in the continuous conduction mode (CCM) operation. Increasing the power capacity will impose excessive peak current stresses on the power switches. Thus the power capacity of this type of inverters is limited due to cost and size considerations. Therefore, in certain applications where high power, high performance and wide input voltage range are required, multiple-stage inverters are often used.

(b) Multiple-Stage Inverters: In a multiple-stage power inverter, e.g., a two-stage inverter, boost and isolation (if necessary) are carried out in the first stage while the inversion is conducted in the second stage. Each stage can be controlled individually or synchronously. Various multiple- stage topologies are adopted to implement the buck-boost function of an inverter. For the buck or boost operation, either a dc–dc converter or dc–ac–dc converter can be used in the first stage. For the choice of dc-link, the system can be configured with a dc-link followed by a PWM inverter or a pseudo-dc-link followed by a line-frequency operated inverter.

DC-DC-AC Topologies: By adding a boost dc-dc converter in front of a buck inverter, a two-stage boost inverter is formed as depicted in Fig. 3.11, which is commonly used in small wind systems [9]. In this structure, an elevated dc voltage with tolerable ripple is obtained in the first stage; afterwards in the second stage, a high frequency PWM buck inverter is used to generate required ac waveforms. There is no need to synchronize between two stages and the output Power is usually controlled in the second stage.

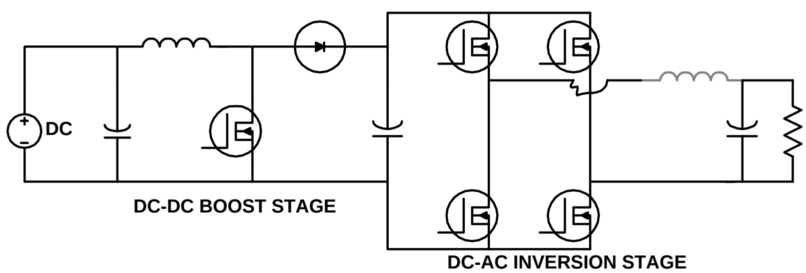


Figure (3.11): Two-stage boost inverter [9].

DC–AC–DC–AC Topologies: Multiple stage inverters with a high voltage boosting ratio normally consist of a high frequency DC-AC-DC converter to realize a controlled boosted DC voltage from a variable low DC voltage. The boosted DC voltage acts as in put for the inversion stage. Fig (3.4) shows a multi stage DC-AC-DC-AC topology.

DC–AC–AC Topologies: In DC-AC-AC topology the second stage is a bidirectional ac-ac converter, without an intermediate dc-link, in order to eliminate the bulky intermediate dc-link filter components as seen in most multiple-stage boost inverters. The topology also includes a high-frequency transformer for voltage level change and electrical isolation. Such a topology is proposed by Beristáin *et al.* [16] as shown in Fig. (3.12) Review of multiple-stage topologies for DG systems shows that it is desirable to use a high frequency transformer in front stages to increase the boosting ratio and provide necessary electrical isolation, and a line-frequency inverter in the last stage to reduce total switching losses.

However, as mentioned before, a multiple-stage inverter has two or more stages of power conversion to achieve a wide input voltage range and a large power capacity as compared to a single-stage inverter at the cost of additional power components and losses.

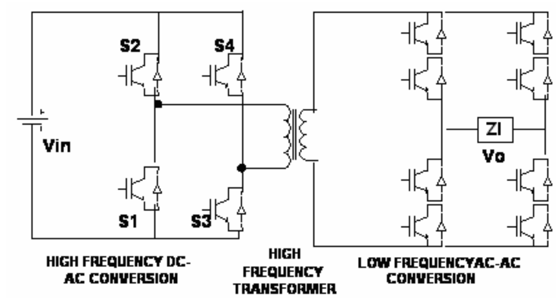


Figure (3.12) DC-AC-AC topology

3.4 Conclusion

In this chapter the development of PV inverter technology with larger and darker areas indicating increasing importance of the specific inverter type is described. Although the string and multi-string concept has established itself as a popular PV system concept there is no obvious trend noticeable towards a particular topology: The market share ratio of transformer less inverters versus inverters with transformer has remained constant over the last two years. Amongst the inverters with transformer, line frequency transformer topologies are far more common, but the number of manufacturers offering inverters with high frequency transformer has increased within the last three years and their market share is expected to rise. Developments in the area of standards, particularly in the requirements for safety in PV arrays will in the future affect decisions on preferred topologies.

CHAPTER 4

Components of an Inverter System

4.1 Introduction

Solar cells are photovoltaic (PV) cells directly converts solar energy in the form of DC voltage. A PV array is a series/parallel combination of PV cells depending on the voltage and current requirements of the load. But the consumer can use this energy only when it can be made to consumer requirements level (1/3phase, 230/400volts, 50/60Hz). Hence an energy conversion between the PV array and consumer is required, which should be cheap, simple, reliable and efficient. This energy conversion module needs

(i) To boost the low PV array voltage (DC-DC conversion)

(ii) To convert DC to sinusoidal AC (Inversion with minimum THD).

(iii) A technique to achieve efficient voltage regulation for any change in input (DC) voltage and change in load as the DC link voltage of the Inverters for DG system may vary in a wide range.

4.2 DC-DC converters

DC-DC conversion is one of the most important requirements for a practical inverter as the inverter gives an AC output from a regulated DC input. However the available DC is from a storage battery which is unregulated. Hence we need a regulated DC of required voltage from an unregulated DC using DC-DC converter.

A DC-DC converter also knows as "Switching Regulator". The basic principle of a switching regulator is that power switches (MOSFETs, IGBTs etc) are used for control/conversion the DC power. In result they are having an efficiency of 72 to 95% range which is more than double that of linear regulators.

In linear regulators the output (DC) is always less than the input (DC). But a switching regulator can provide the outputs that are greater than the input. One more advantages of switching regulator is that it can be operated at high frequency, resulting a lower magnetic as well as filtering requirement.

Broadly DC-DC converter can be classified as

1) outputs not isolated from inputs

2) outputs isolated from input

4.2.1 DC-DC Converter without Isolation

Under this category they further classified as

i) Buck converter

ii) Boost converter

iii) Buck-Boost converter

iv) Cuk converter

Buck, boost and buck-boost are the basic fundamental converters. In these topologies, the inductor is the element which transfers power from input to the output. The power switch is turned on and off by a pulse width modulator (PWM). All other converters are derived from these basic converters. For example, forward converter is a buck converter with input output isolation. A brief description of working of ach of the converter is given below.

i) *Buck converter:* As the name implies, a step-down converter produces a lower average output voltage than the DC input voltage V_{IN}. Its main application is in regulated DC power supplies and DC motor speed control. The average output voltage can be calculated in terms of the switch duty ratio is

$$V_{OUT} = D\, V_{IN}$$

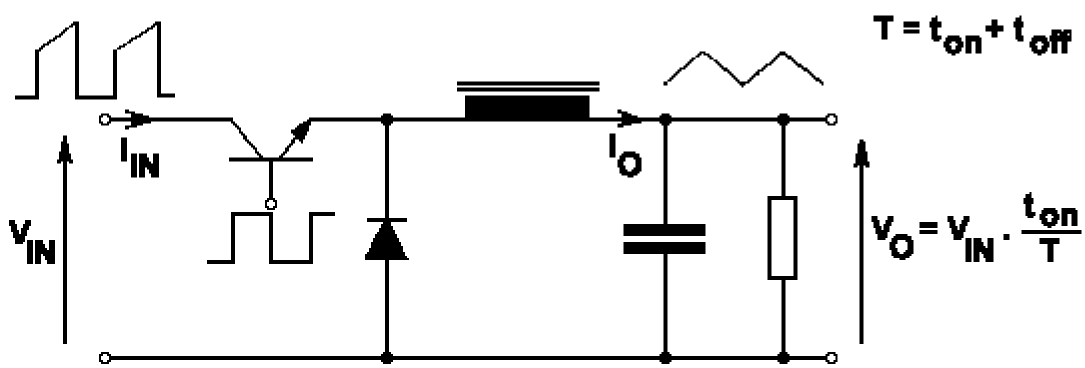


Figure (4.1): Buck Converter

During the interval when the switch is on, a diode becomes reverse biased and the input provides energy to the load as well as to the inductor. During the interval when the switch is off, the inductor current flows through the diode, transferring some of its stored energy to the load. In a steady state analysis, the filer capacitor at the output is assumed to be very large, as is normally the case in applications requiring a nearly constant instantaneous output voltage Vo(t)=Vo. In a step-down converter, the average inductor current is equal to the average output current Io, since the average capacitor current in steady state is zero.

Advantages of Buck converter:

1) It has high efficiency
2) The cost of the circuit, size and weight of the circuit is low.

Disadvantages: 1) In practice the load would be inductive. Even with a resistive load, there would be Always certain associated stray inductive. The switch would have to absorb the inductive energy and therefore it may be destroyed.

2) The output voltage fluctuate between zero and $V_{in,}$, which is not acceptable in most applications
3) There is no isolation between input and output
4) Only one output per circuit is possible
5) Output ripple is higher than linear circuit
6) Slow transient response compared to linear.

ii) *Boost Converter:* The boost converter is also called as step-up converter. Boost regulator produces a higher regulated voltage from a lower unregulated voltage. Its also known as a ringing-choke converter.

Its main application is in regulated Dc power supplies and the regenerative braking of DC motors.

As the name implies, the output voltage is always greater than the input voltage. When the switch is on, the diode is reversed biased, thus isolating the output stage. The input supplies energy to the inductor. When the switch is off, the output stage receives energy from the inductor as well as from the input. In the steady state analysis, the output filter is assumed to be very large to ensure a constant output voltage $V_0(t) = V_{0.}$

The average output voltage can be calculated in terms of the switch duty ratio is

$$V_{out} = \frac{V_{in}}{1-D}$$

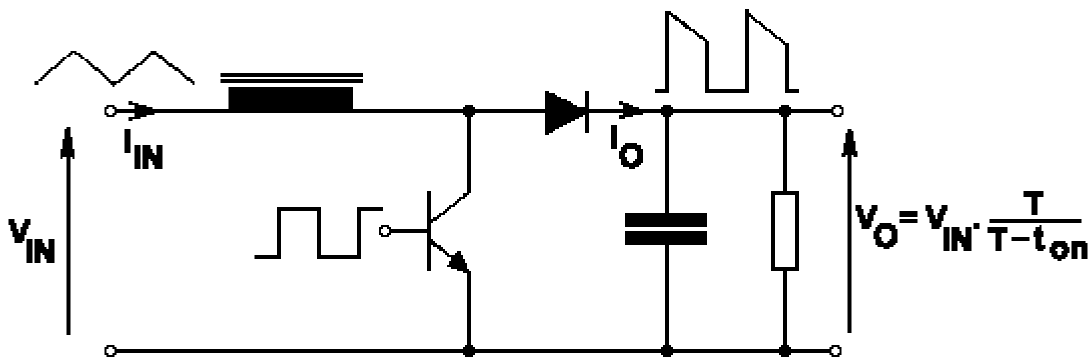


Fig (4.2): Boost Converter

Advantages of Boost Converter: 1) The main advantage of the boost regulator is that it can produce output voltage greater than input voltage.

Disadvantages: 1) The main draw back is that there is no isolation between input and output.

iii) Buck-Boost converter:

The main application of step-down/step-up or buck-boost converter is in regulated DC power supplies, where a negative polarity output may be desired with respect to the common terminal of the input voltage and the output voltage can be either higher or lower than the input voltage.

A buck-boost converter can be obtained by the cascade connection of the two basic converters, the step-down converter and the step-up converter. In steady state, the output to input voltage conversion ratio is the product of the conversion ratios of the two converters in cascade

$$V_{out} = \frac{DV_{in}}{1-D}$$

This allows the output voltage to be higher or lower than the input voltage, based on the duty ratio D.

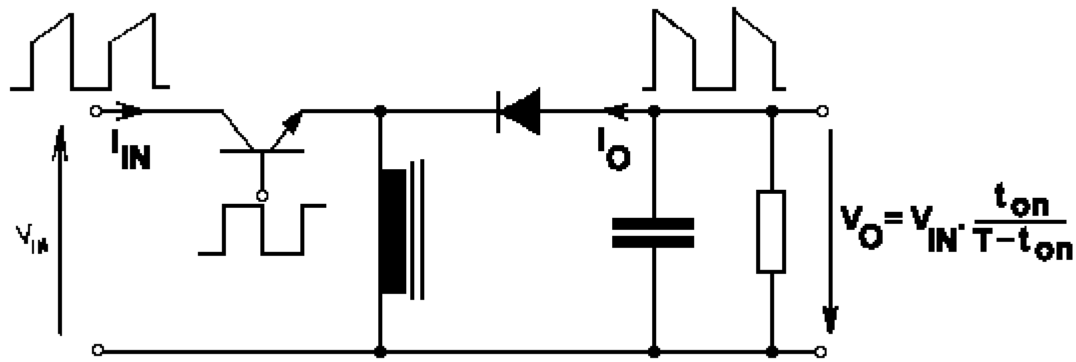


Fig (4.3): Buck-Boost Converter

The cascade connection of the step-down and the step-up converters can be combined into single buck-boost converter. When the switch is closed, the input provides energy to the inductor and the diode is reverse biased. When the switch is open, the energy stored in the inductor is transferred to the output. No energy is supplied by the input during this interval. In the steady-state analysis, the output capacitor is assumed to be very large, which results in a constant output voltage $V_0(t) = V_0$.

Advantages of Buck-Boost converter: 1) The main advantage of buck-boosting is that the output voltage can be either higher or lower than the input voltage

Disadvantages: 1) The main drawback of this regulator is that there is no isolation between input & output.

4.2.2 DC-DC Converter with Isolation

The second category is usually employed for higher power applications. Under this category we have

i) Fly-Back converter
ii) Forward converter
iii) Push-Pull converter
iv) Half-Bridge converter
v) Full-Bridge converter

All such converters use a transformer for isolation as well as increasing power level.

i) Fly-back converter:

Actually an isolated storage inductor known as a flyback transformer is a combination of an isolating transformer, output inductor, and a flywheel diode. These use a gapped core and have a power capability of 100 VA. Such transformers has capability of Storing energy in the air gap when the switch is on and delivering energy to the load when off. They do not perform like standard transformers. This is the simplest of all the transformer isolated regulators.

It has the following salient properties

a) It is very closely related to the boost regulator

b) More than one output is possible on one supply

c) These outputs can be positive or negative in voltage

d) The output voltage level is independent of the input voltage

e) The input voltage exhibits high dielectric isolation between the input and the Output.

f) There is a limitation for the switching frequency and duty cycle to use such Transformer without saturation.

The basic circuit topology is as shown below

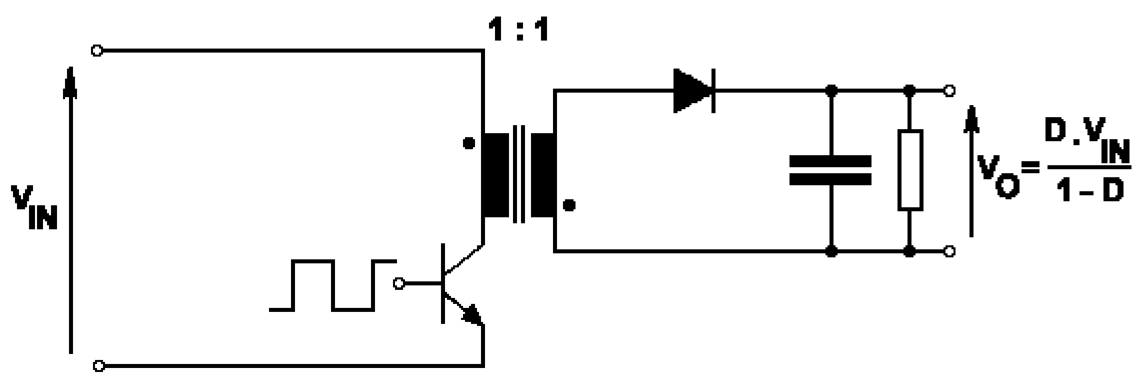


Fig (4.4): Fly Back Converter

ii) Forward converter:

The forward transformer operates by transferring the power to the load during the on-time and resetting in the off-time. A clamp diode and clamp winding are used in the off-time to reset the core. This transformer has a limitation of 500 VA.

The disadvantages of using the flyback or forward transformer are that a larger transformer is required since the power is only transferred during half of the input cycle.

These isolated DC-DC converters over comes the problems of a flyback converter (demagnetization of transformer core) by providing a tertiary winding in the transformer. This winding is connected to the input which returns back the stored energy in the magnetic field during off period of the switch.

This has the following salient features

a) Operates on buck converter principle

b) Can be operated at high switching frequency with greater efficiency

The basic circuit topology is has shown

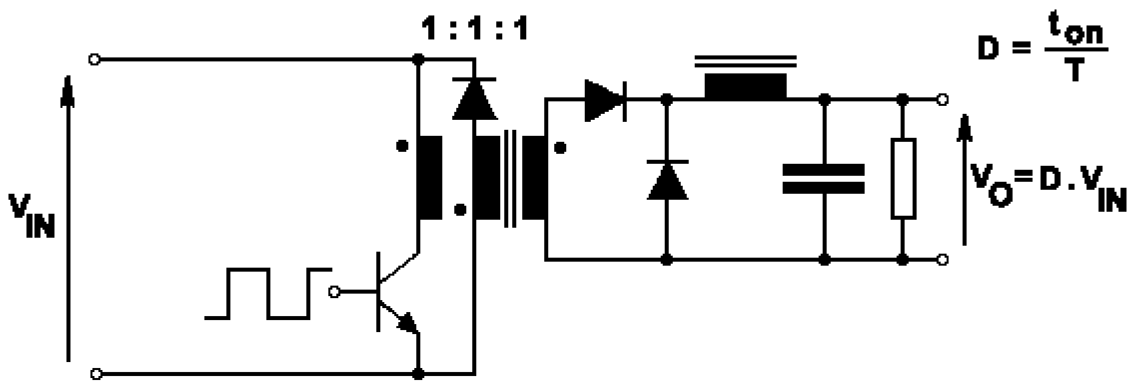


Figure (4.5): Forward Converter

iii) Push-pull converter:

Push-pull delivers power to the load during the whole input cycle. This transformer has a center tapped primary and secondary used alternatively with each input cycle. These can achieve power levels in excess of 1 KVA. Push-pull transformers are practical at low input voltages and higher output power. They are not advisable for off-line converters because the power switches operate at collector stress voltages of twice the supply voltage.

The push pull topology is a transformer isolated forward mode converter. The salient points of such converters are

a) It operates on buck principle

b) The push-pull regulator is called a double ended topology, where two power-switches Shares switching functions.

c) There is reversal of flux in the transformer core which results in an efficient transformer Operation

d) This topology can provide twice the output power of a single ended topology (forward converter) operating at same frequency.

The basic circuit topology is has shown

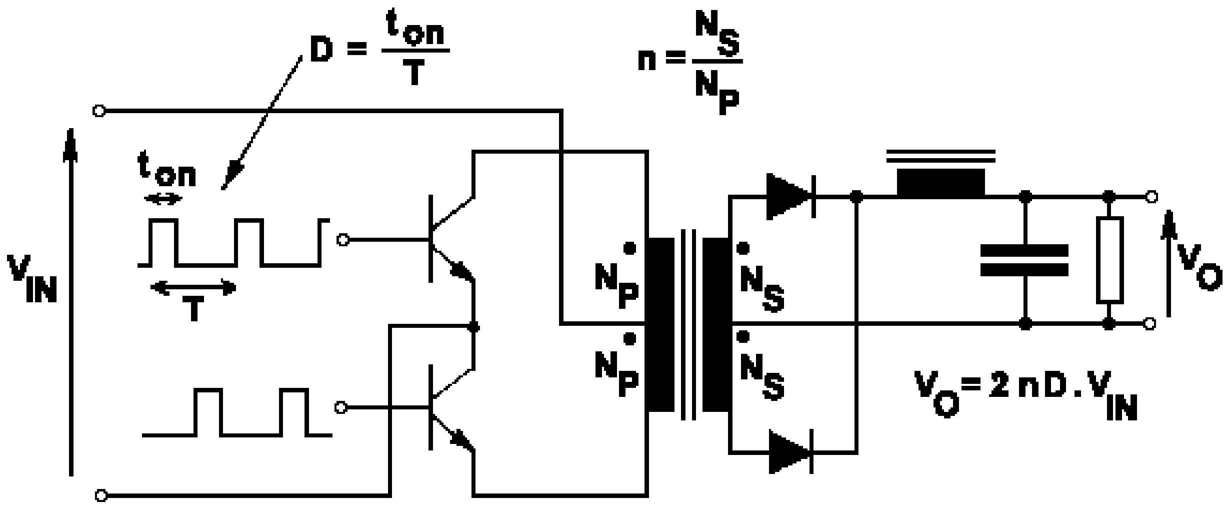


Figure (4.6): Push-Pull Converter

iv) Half-bridge topology:

A dual, forward-converter, using two power switches can also be called a half-bridge. Power, which does not exceed the supply voltage, is delivered to the load only during half the input cycle. This design permits the use of a smaller transformer.

In such DC-DC converter DC is converted to high frequency pulsed AC which is then stepped-up/down by using a pulsed-transformer. The output of the transformer is rectified and filtered to get a required level DC.

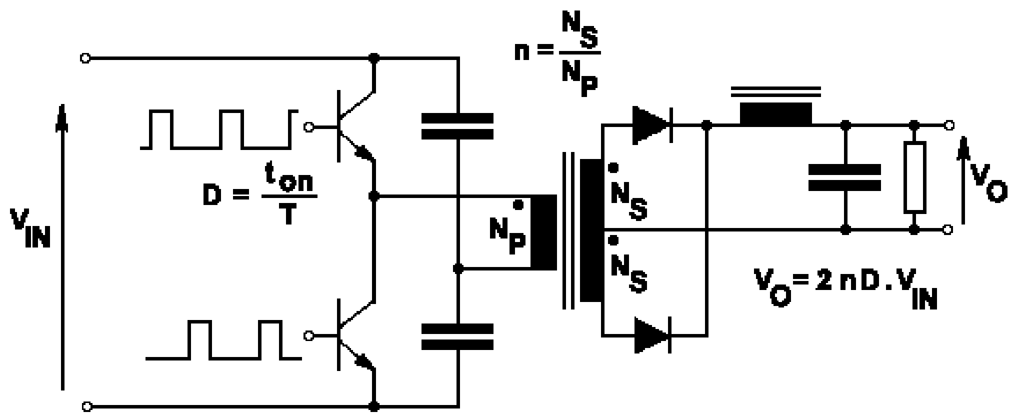


Figure (4.7): Half Bridge Converter

v) Full bridge topology:

Four power switches are used in a full-bridge and usually utilizes a single primary winding. Full supply voltage is obtained in both directions and utilizes the core and windings more effectively. Voltage on the switches does not exceed the supply voltage.

The full bridge converter is most popular transformer isolated converter. The PWM technique can efficiently be utilized for voltage regulation. Like the other double-ended regulators its transformer flux is driven in both positive and negative polarities. Its performance with respect to output power is significantly improved over that of half bridge converter. This is because the balancing capacitors are replaced with another pair of half bridge style power switches identical to the first pair.

The topology is as shown in figure (22).

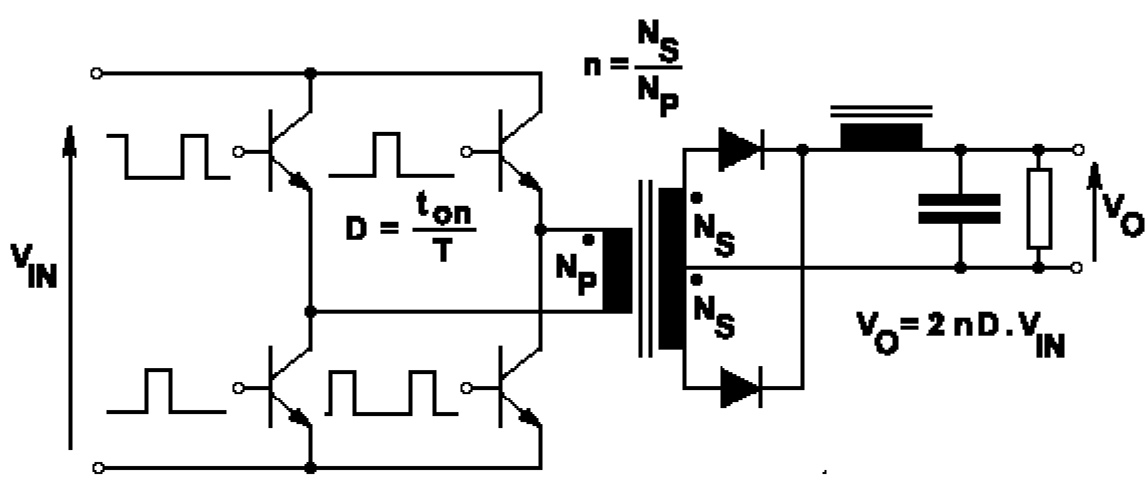


Figure (4.8): Full Bridge Converter

Basic operation: Like half bridge operation the DC is converted to high frequency square wave AC. It is then stepped up/down by a transformer and then rectified to get required level DC. The DC-AC conversion is done by a full bridge circuit consisting of four power switches S1, S2, S3 and S4 respectively. When S1 and S2 are turned on, V_{AB} become $+V_{dc}$. Similarly when S3 and S4 are turned on V_{AB} becomes $-V_{dc}$. Thus V_{AB} alters $+V_{dc}$ to $-V_{dc}$ at switching frequency of the power switches. The transformer (specially design to operate at high frequency) transfers the power to the secondary side at required voltage level. This is rectified and filtered to get desired DC output.

4.3 DC-AC conversion

An inverter is used to convert fixed DC to variable /fixed AC with/without changing magnitude. In earlier days power frequency inverters we were realized using power switches like SCRs, low efficiency requirement of commutation circuit, bulky magnetic restricted use of such inverters for large power applications. These are replaced by switch mode DC-AC inverters. In such inverters SCRs are replaced by self commutated power switches like MOSFETs, IGBTs, and GTO etc.

Classification: The classification of inverters can be made according to

1) Use of power switches
   a) Inverter with self commutated switch Transistor used inverters)
   b) Inverter without self commutated switch (Thyristorized inverters)
2) Modulation
   a) Square wave inverter
   b) PWM Inverter
3) Phases
   a) Single phase
   b) Three phase
   c) Multi phase
4) Type of modulation
   a) Equal pulse width modulation
   b) Single pulse width modulation
   c) Sine pulse width modulation

d) Trapezoidal modulation

e) Stair case modulation

f) Stepped modulation

g) Harmonic injection modulation

h) Delta modulation

5) Number of switches used

a) Half bridge inverter

b) Full bridge inverter

6) Depending on type of source

a) VSI-voltage source is constant

b) CSI-current source is constant

4.3.1 Basic Principle of operation of an inverter:

To understand the principle of operation of an inverter circuit let us consider a full bridge topology shown in the fig below

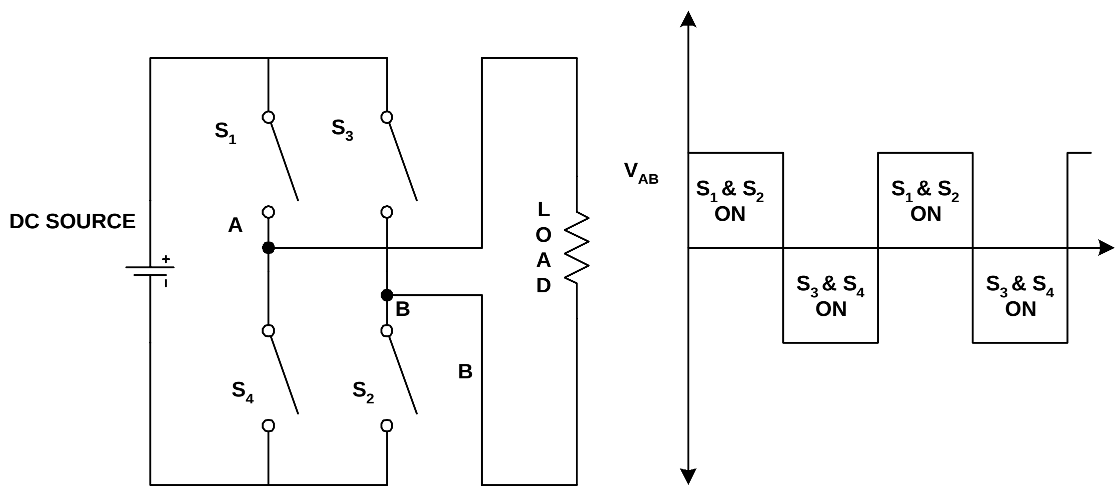


Figure (4.9): Principle of an Inverter Operation

This consists of four switches S1 to S4 in the form of a bridge. The DC supply is connected across the bridge while output is obtained across AB. By suitable circuitry gate pulses are provided to the switches S1, S2 simultaneously for half of the period while S3, S4 are provided with gate pulses for rest half of the period. When S1 and S2 are on the current in the load flows from A to B causing positive half cycle appear across the load. Similarly when S3 and S4 are on, the current in the load flow from B to A appearing negative half cycle across the load. As a whole a square wave AC output voltage appears across the load.

4.3.2 Performance parameters of inverter:

Besides other requirement an ideal inverter is supposed to supply sinusoidal AC but most of the practical inverter give either square wave or quasi-square wave output. By Fourier analysis we can see that these outputs contains large amount of higher harmonics voltages other than the fundamental. The quality of inverter output usually evaluated in terms of the following performance parameters

i) Harmonic Factor
ii) Total Harmonic Distortion
iii) Distortion factor

i) Harmonic Factor:

The harmonic factor of n[th] harmonic, which is measure of individual harmonic contribution, is defined as

$$HF_n = \frac{V_{n(rms)}}{V_{1(rms)}}$$

Where V_n= rms value of nth harmonic voltage

V_1= rms value of nth fundamental voltage

ii) Total Harmonic Distortion:

The total harmonic distortion is a measure of the closeness of the shape of the waveform to sinusoidal shape. This is defined as

$$THD = \frac{\sqrt{\sum_{n=2,3,4...}^{\infty} V^2{}_{n(rms)}}}{V_{1(rms)}}$$

Where $V_{n(rms)}$ = the rms value of the nth harmonic voltage

$V_{1(rms)=}$ the rms value of the fundamental component of the output voltage

iii) Distortion Factor:

This is a measure of the effectiveness of filtering the harmonics and defined as
The distortion factor of an individual or nth harmonic component is defined as

$$DF = \frac{1}{V_{1rms}}\left[\sum_{n=2,3,4...}^{\infty}\left(\frac{Vnrms}{n^2}\right)^2\right]^{1/2}$$

The distortion factor of an individual or nth harmonic component is defined as

$$DF_n = \frac{V_{nrms}}{V_{1rms}n^2} \; for \; n > 1$$

Lowest order harmonics:

The lowest order harmonics is that harmonic component whose frequency is the closest to the fundamental component and its amplitude is greater than or equal to 3% of the amplitude of fundamental component.

4.4 Voltage control of Single Phase Inverters:

In most of the inverter applications it is necessary to vary the ratio of the magnitude of the inverter output voltage to DC input voltage continuously. For example in inverters supplying induction motor drives employing well-known V/f control, to vary the speed, we need to vary the frequency f. This can be done by varying the frequency of switching. But correspondingly, we also need to vary the magnitude of the voltage V applied to the motor in order to maintain the ratio V/f constant. This is necessary to keep the air gap flux in the motor constant, so that the torque developed by the motor is not adversely affected by the variations in frequency. In battery fed inverters, the battery voltage drops due to usage. But still, the inverter should be able to maintain the required magnitude of output voltage.

The following two methods are available to vary the magnitude of the output voltage of an inverter

- By providing a variable DC input voltage
    a. With the help of a controlled rectifier at the input of the inverter if the supply is taken from an AC source

b. Or by using a chopper at the input if the supply is taken from a DC source such as battery.

- By adopting switching strategies with in the inverter by using one of the Methods given below
  a Single Pulse Width Modulation
  b Multiple Pulse Width Modulation
  c. Sinusoidal Pulse Width Modulation
  d. Modified Sinusoidal Pulse Width Modulation

The second of these two methods is more efficient. So this is employed in modern inverters. It can be shown that by adopting proper method of pulse width modulation [24], the lower order harmonics can be eliminated almost completely and harmonics, which can be eliminated easily by filtering.

4.4.1 Single Pulse Width Modulation:

In Single Pulse Width Modulation control there is only one pulse for half cycle and width of the pulse is varied to control the inverter output voltage. For such technique the gating signals are generated by comparing a rectangular reference signal of amplitude A_r with a triangular carrier wave of amplitude A_c. The ratio of A_r to A_c is the control variable known as modulation index.

The root mean square value of the output voltage by this technique given by

$$V_o = V_s \sqrt{\frac{\delta}{\pi}}$$

Where δ = width of each pulse. V_s= DC Source Voltage

One more advantage of such method is that due to symmetry of the output voltage along the x-axis, the even harmonics are absent. However the dominant harmonic is 3^{rd} and distortion factor increases significantly at low output voltage. The fig. below shows the waveforms for single PWM

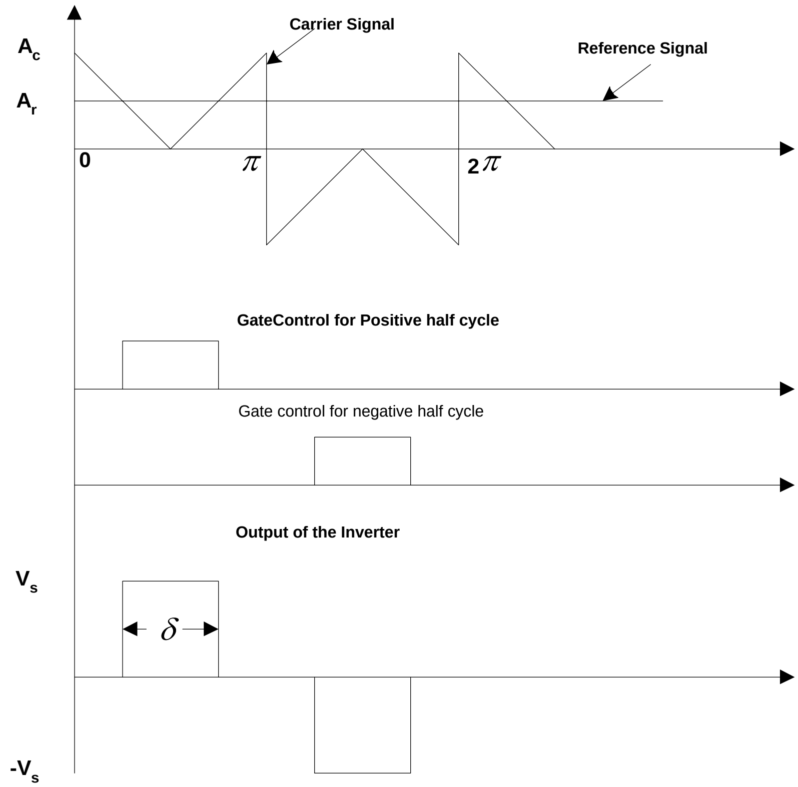


Figure (4.10): Scheme for Single Pulse Width Modulation

4.4.2 Multiple Pulse Width Modulation:

This is the technique where gating signals are generated by comparing a DC reference with high frequency triangular carrier wave. In this scheme there will be a number of smaller width pulses instead of a single pulse in each half cycle. If f_o is the output frequency and f_c is the carrier frequency then

$$P = \text{no. of pulses/half cycle} = f_c/2f_o$$

If δ = width of each pulse

Then the root mean square value of the output voltage by this technique is given by

$$V_o = V_s\sqrt{\frac{p\delta}{\pi}}$$

The harmonic content in the output is reduced by this technique with increase in no. of pulses in each half cycle. It can be noted that the amplitude of LOH (lower order harmonic) can be lowered, but the amplitude of some HOH (higher order harmonic) would increased. However such HOH produce negligible ripples are can easily be filtered out. The waveforms multiple PWM is as shown below

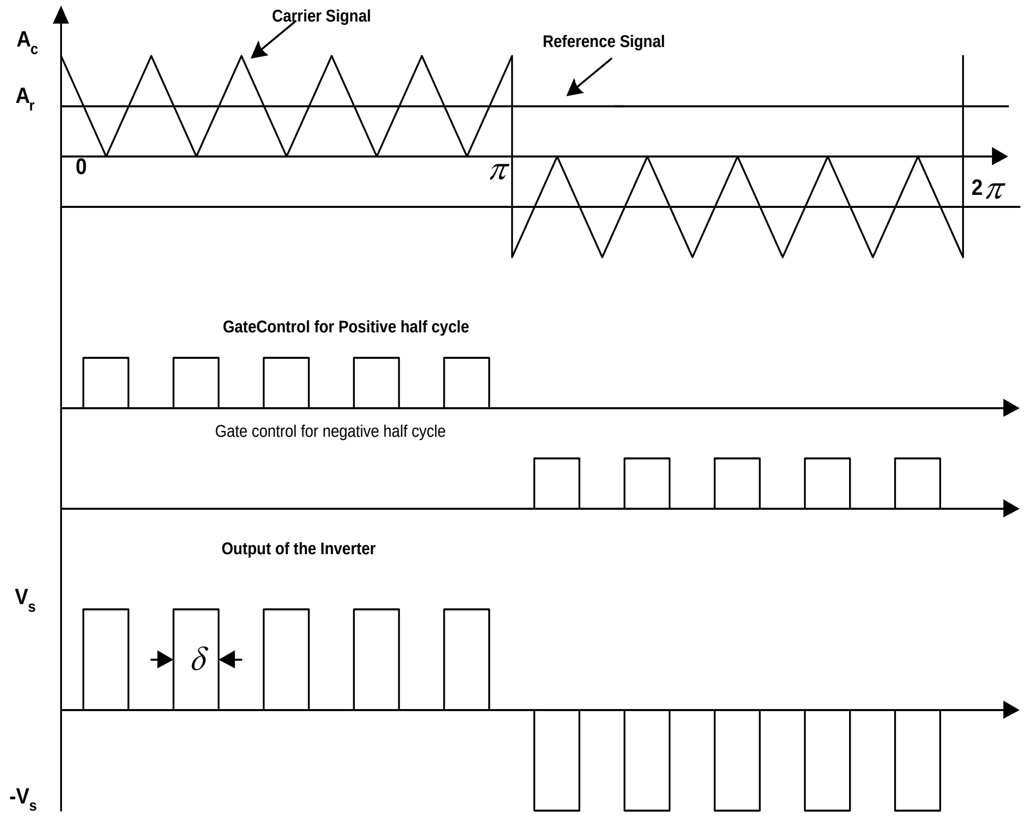


Figure (4.11): Scheme for multiple pulse width modulation

4.4.3 Sinusoidal Pulse Width Modulation:

Instead of maintaining the width of all pulses same as in the case of multiple pulse modulations, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the centre of the same pulse. The DF and LOH are reduced significantly by this technique. The gating signals are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency f_c. The output waveform corresponding gating signal for SPWM technique is as shown below

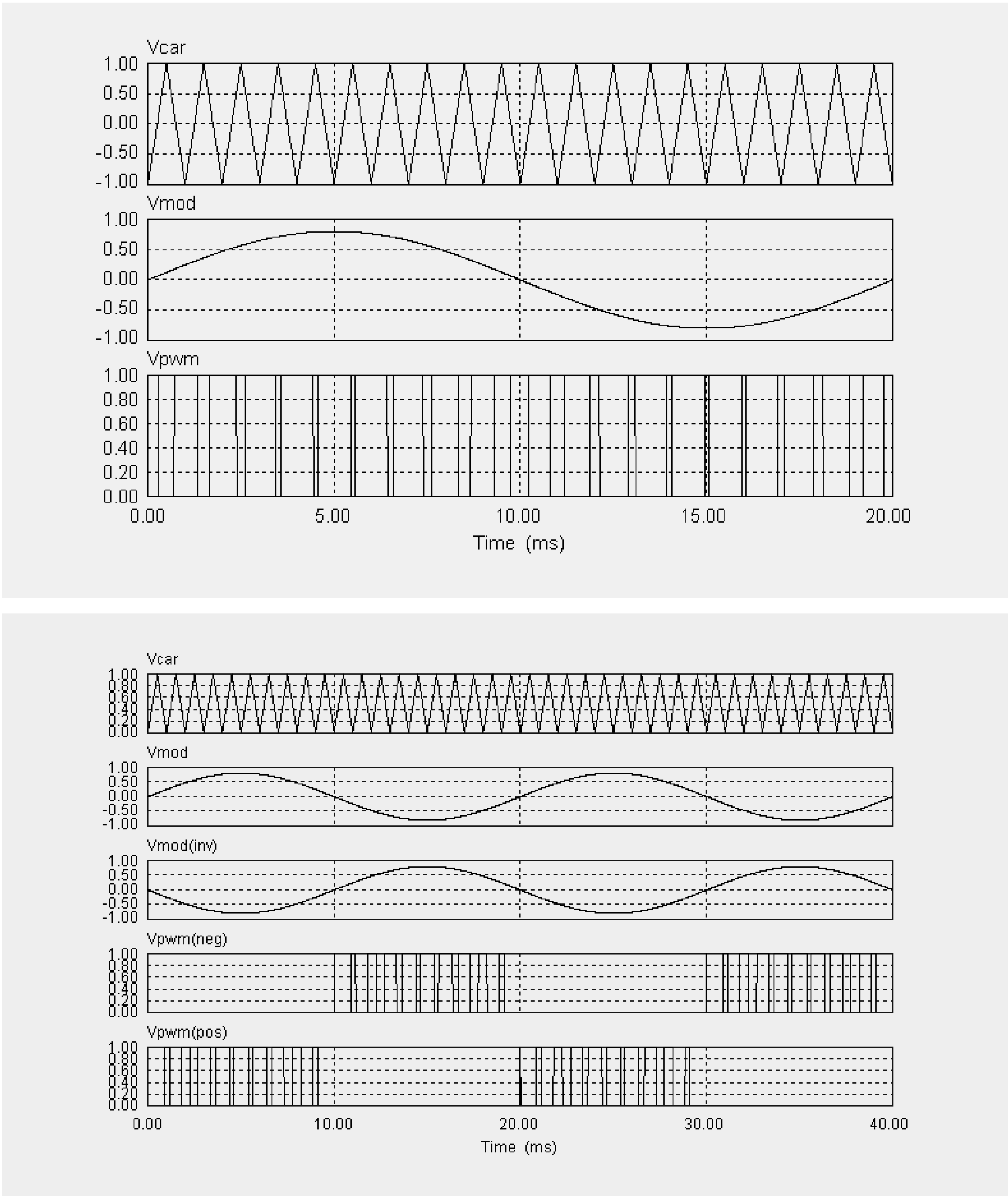


Figure (4.12): Scheme for bipolar & Uni-polar sine pulse width modulation

4.4.4 Modified Sinusoidal Pulse Width Modulation:

One major draw back with SPWM is that it contains a lower fundamental component. Hence modified SPWM technique is employed so that the fundamental component is increased as well as its harmonic characteristic are improved. It reduces the number of switching power devices resulting a reduced switching loss.

This technique involves in generating gating signals by comparing a reference sine wave with a triangular wave of duration 0 to 60^o and 120^o to 180^o in each half cycle. The output waveform for the gate signal as shown below

4.4.5Advanced Modulation Technique:

Even though SPWM technique is the best method for producing sinusoidal AC, it suffers from drawback of getting lower fundamental output voltage. To overcome such problems advanced modulation technique such as

Trapezoidal modulation

Staircase modulation

Stepped modulation

Harmonic injection modulation

Delta injection modulations are employed.

The details of these switching techniques are described in [23].

-

4.5 Methods to improve the Efficiency of the Inverter

Efficiency is an area of concern for an Inverter as the power level increases. The losses that take place in Inverter is mainly due to

1. Switching losses at the Switches
2. losses due to conduction drop across the switches

For low frequency inverters such as square wave inverters and quasi square wave inverters the switching losses are considerably low. But it needs bulky filters to attenuate lower order harmonics which increases the losses at the filter components. Switches with low conduction drop such as SCR's can be used in such inverters but need of additional commutation circuit which makes the overall circuitry complex. Hence the only option available is the use of self commutated switches such as MOSFET's, IGBT's, and Power Transistors etc. in place of SCR's.

Among all above switches MOSFET's have the highest operating frequency at the cost of higher conduction drop. To reduce the size of filter components and improve the harmonic characteristics of inverters, higher switching frequency is preferred. However, a drawback of higher switching frequency is the increase of switching losses. Switching losses are due to diode reverse recovery and hard turn off and turn on of active switches. As a result, the system efficiency is reduced. Various soil switching techniques (zero voltage switching (ZVS) and zero current switching (ZCS)) have been proposed to reduce the switching losses and improve the efficiency in inverters [I7]-[18].

Besides soft switching one method known as Hybrid Pulse Width Modulated Switching [19] is an efficient method of switching for full-bridge inverters. In HPWM control, only two of the four switches in the full bridge inverter are pulse width modulated at high frequency, while the other two switches are commutated at line (low) frequency. Compared to the case when all four switches are pulse width modulated, the switching loss of the inverter is reduced to one half.

Although total switching loss reduced in HPWM switching technique, the switching losses of all switches are not equal, especially at higher load with high switching frequency. The switches driven with high frequency signal dissipate more heat in comparison to the switches driven with low frequency signals leading to unequal rise of temperature at the switches. This reduces reliability of the system. This thesis proposes a symmetrical hybrid PWM switching method for a full bridge inverter which equalizes switching loss of all the switches resulting uniform temperature rise. Thus efficiency as well system reliability is improved. In [20] a random switching method for HPWM full bridge inverter is proposed in which the authors have experimentally proved that when each switch gets high and low gating signals alternatively instead of conventional hybrid PWM signals, switching loss of all the switches are equalized and provides good out put performance.

CHAPTER: 5

Novel SHSPWM Inverter

This chapter describes overview of the proposed Inverter system in which a novel switching technique is proposed at the inversion stage for higher efficiency and grater reliability.

5.1 Block Diagram

The inverter developed in this thesis is intended for a stand alone operation. Although it is designed for stand alone operation this inverter may be arranged to operate in parallel with power lines. The block diagram of the whole system is shown in figure (5.1).

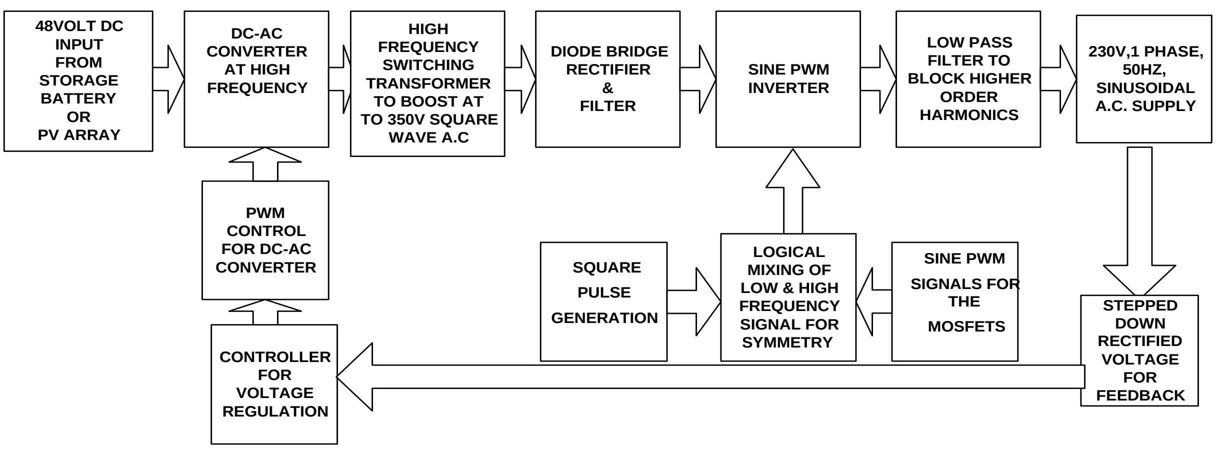


Fig (5.1): Block diagram for the developed inverter

This comes under multistage (DC-AC-DC-AC) topology category. In the first stage (DC-AC), 48 volt DC is inverted at high frequency (>20 KHZ) to get PWM controlled square wave AC which is stepped up to the required voltage level by a high frequency transformer. In the second stage this boosted ac is rectified and filtered by a diode bridge rectifier and passive L-C filters respectively. As the switching frequency is very high the size of transformer is very small as well the filtering components are small. The boosted DC acts as input to the proposed novel SHSPWM inverter.

In the inversion stage the boosted DC is converted to sinusoidal AC voltage .The inverter is of a full bridge topology. Here two set of gating signals are generated for the inverter. In each half cycle one switch is provided with high frequency sine PWM signals, while the other switch is provided with simple rectangle pulses of low frequency (line frequency). This pattern is reversed in alternate cycle. This reduces the overall switching loss resulting better efficiency and reliability. As dead time is essential between the two half cycles to avoid short circuit of DC link as well as over heating of the switches, many methods are proposed [21] for providing the dead time. In this circuit the dead time can be provided between two square pulses by comparing the modulated sine wave with a small DC voltage.

The out put of the inverter contains higher order switching harmonics which are attenuated by providing a passive low pass filter.

To take care of the voltage regulation the out put ac voltage is scaled down and then rectified to compare with reference voltage. The error signal generated is fed to PWM controller at the 1st stage (DC-AC) through PI controller.

5.2 Power Circuit

Broadly the whole module is divided as

(1) DC-DC converter (to boost low DC voltage to the required level)
(2) DC-AC inverter (to get utility level sinusoidal AC voltage)
(3) Low pass filter

5.2.1 DC-DC Converter: The 48 volt DC input is inverted by a full bridge circuit. Here the switches used are IGBTs but not MOSFETs. The reasons are being, when MOSFETs are used, due to low gate capacitance it causes high voltage spikes across the switches when connected to a high frequency transformer. This is avoided when the MOSFETs are replaced by IGBTs.

The IGBTs are triggered at high frequency (20 KHz) by help of a PWM generating IC through proper signal conditioning and isolation. The PWM IC is capable of controlling the width of out put pulses which provides a controllable high frequency square wave AC. This high frequency square wave AC is stepped up to 350 volts (peak to peak) by a high frequency transformer [22], whose core is made of ferrite (al 5000 87/70) for 1 KVA out put. Out put of the transformer is then rectified by full bridge diode rectifier made of fast recovery high speed diodes. An L-C filter is used to eliminate the voltage ripples. One of the important requirements for the high frequency pulse transformer is to avoid core saturation. This can be achieved by connecting a small non-polarized blocking capacitor in series with the transformer. This avoids flux imbalance problem responsible for core saturation. Schematic diagram of DC-DC converter is as shown in fig (5.2)

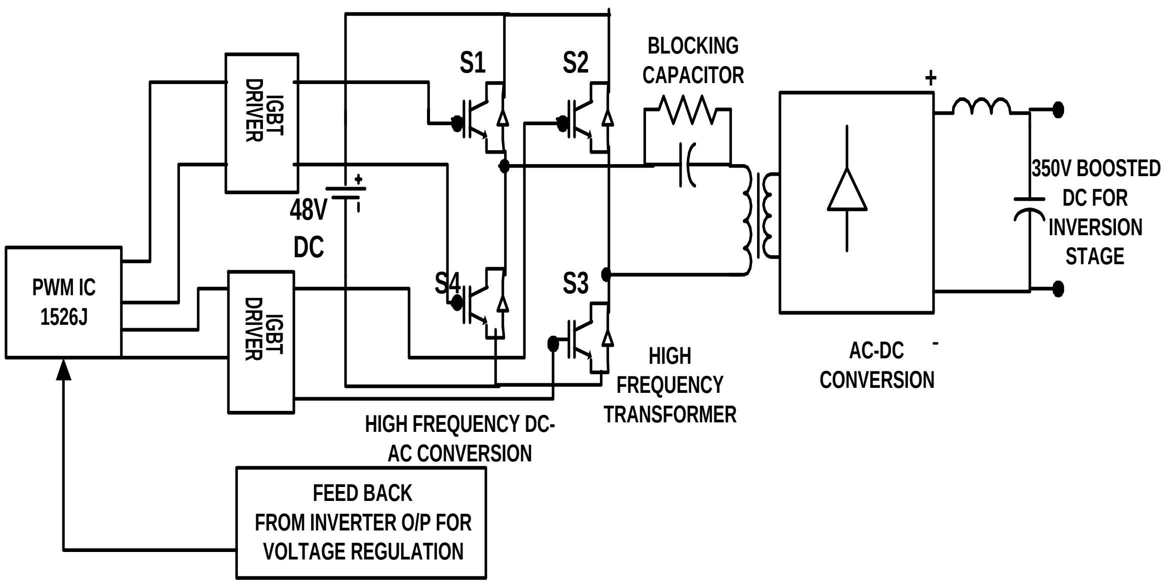


Fig (5.2): schematic for DC-DC converter

5.2.2 DC-AC Inverter*:* This is further divided as power circuit and control circuit. The power circuit consists of a bridge topology with 4 power MOSFETS as switches. Boosted DC is used as input while a novel Symmetrical Hybrid Sine PWM technique is adopted to drive the inverter.

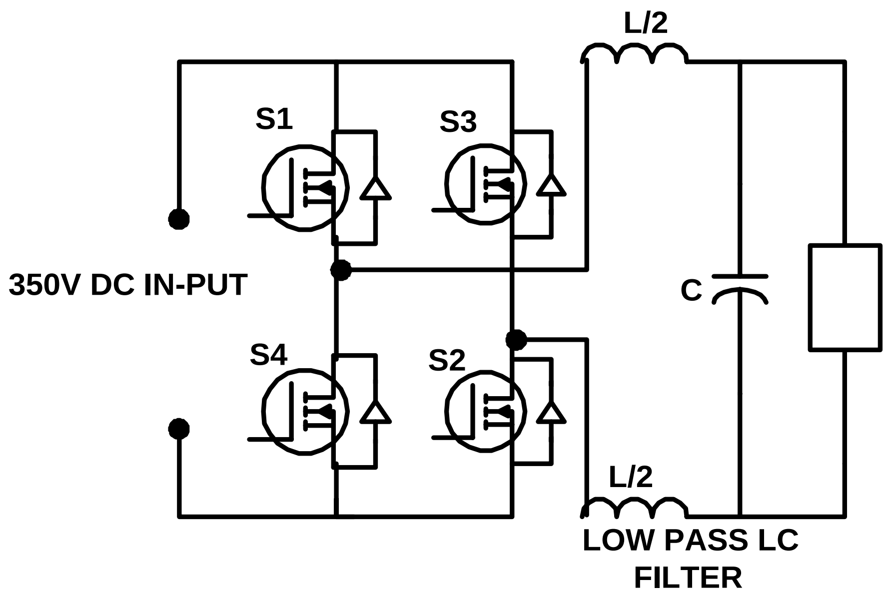


Figure (5.3): basic full bridge topology inverter

Generation of HSPWM Signal: The first set of switching signals are high frequency sin PWM signals which are generated by comparing the modulating sine wave of power frequency with a high frequency unipolar triangular wave signal. Unipolar sin PWM techniques are employed for lower distortion in the output. The second set of low frequency switching pulses are generated, by comparing the same modulating sine wave with a small DC voltage which will provide the necessary dead time between two half cycle to avoid short circuit of DC link and overheating of switches. Figure (5.4) shows the technique for generation of HSPWM signals where S_1, S_4 are sine PWM signals while S_2, S_3 are square wave signal at output frequency with suitable dead time between them.

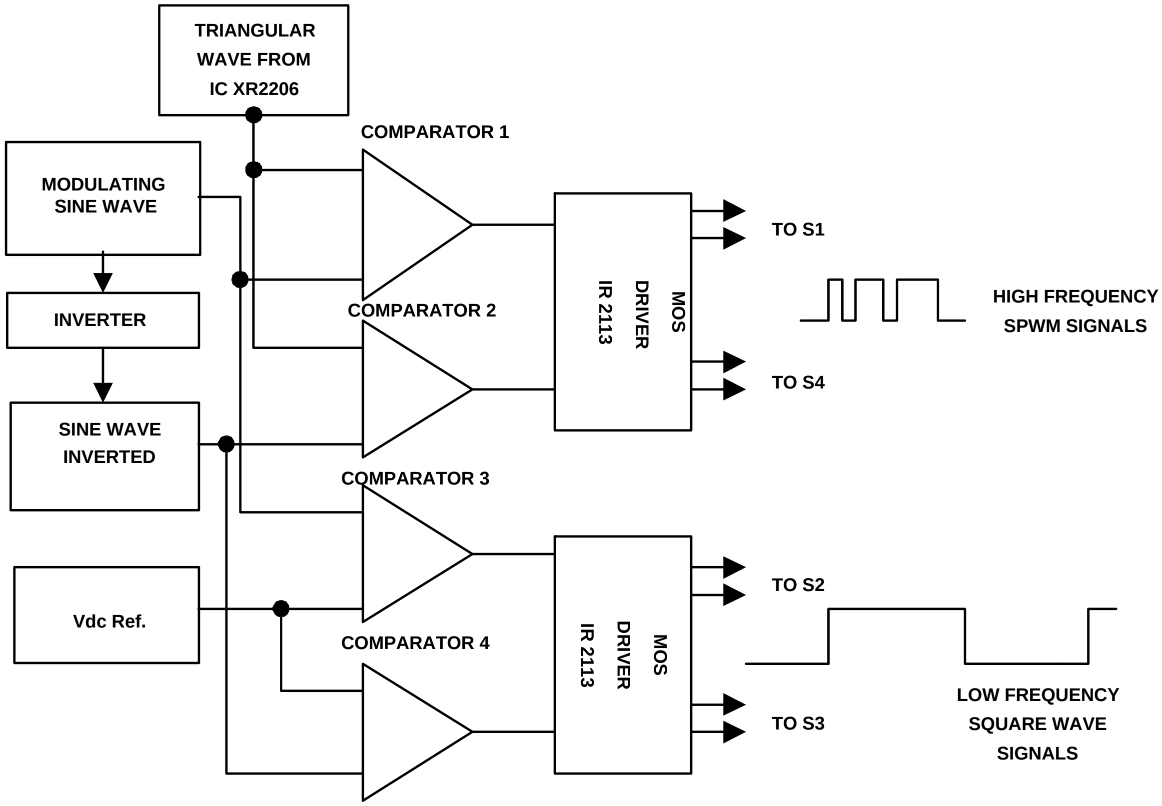


Figure: (5.4) Generation of HSPWM signal

Combinational Logic Operation: The HSPWM gate signals generated is processed through a logic circuit consisting of one D-flip-flop, four AND gates and four OR gates, shown in figure (5.5) which makes all gate signals symmetrical i.e. each gate signal is composed of both low and high frequency signals alternatively. In one cycle S_1, S_4 are commutated at high frequency and S_2, S_3 are commutated at low frequency while in the next cycle the pattern reverses. i.e. S_2, S_3 are commutated at high frequency while S_1, S_4 are commutated at low frequency. This makes the switching stress of all the switches equal.

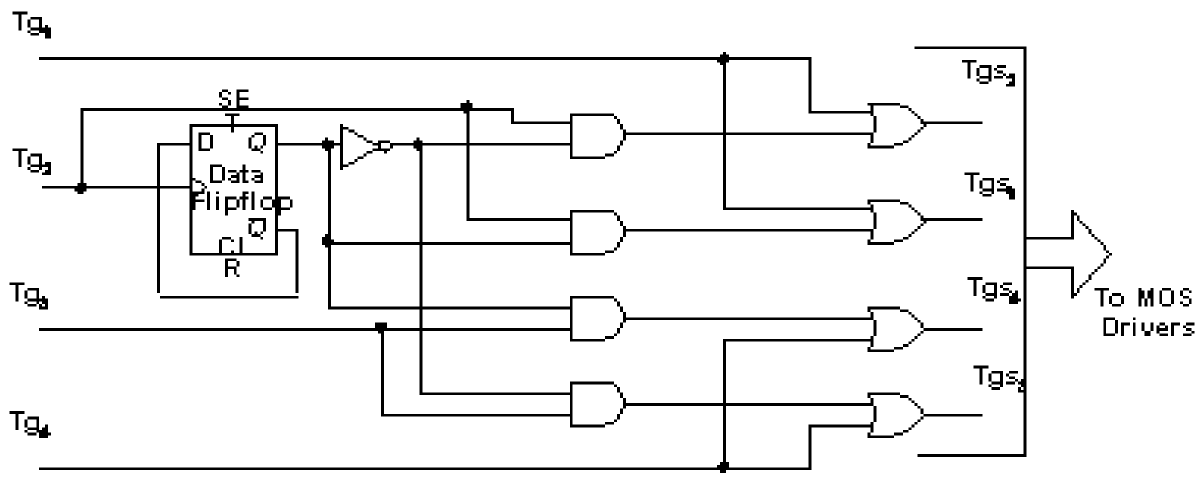


Figure: (5.5) logic circuit for SHSPWM gate signals

Hardware Implementation of the SHSPWM Inverter: Circuit given in figure (5.6) shows the practical circuit for the Novel switching technique at the Inversion stage. In this circuit unipolar triangular carrier is generated by a op-amp circuit while 50 Hz modulating signal is taken from a signal generator. The DC link voltage is applied from a regulated power supply with 0-60 V, 2 amp output.

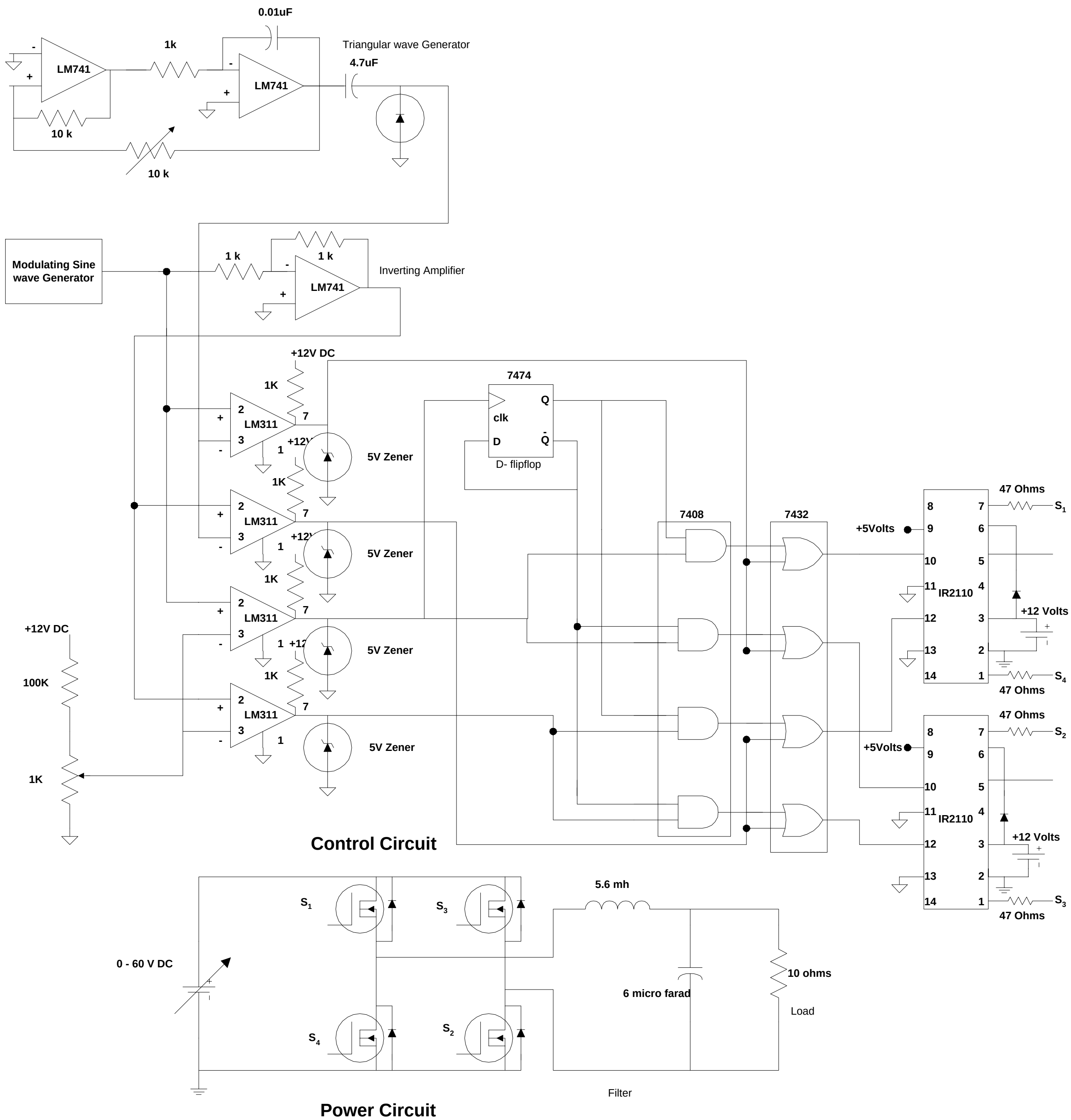


Figure (5.6): Hardware Implementation of the proposed Inverter

5.3 Feed Back Arrangement for Line Regulation

To get the constant AC, a constant DC is needed. Hence to maintain the output of the DC-DC converter constant a suitable feedback arrangement is provided from output the inverter to the PWM IC 3526. An error amplifier allows reference voltage at pin1 to be compared with output voltage feedback at pin 2 of the amplifier. For stability of the system an appropriate feed back network is provided. This provides necessary compensation as well loop gain for the error amplifier.

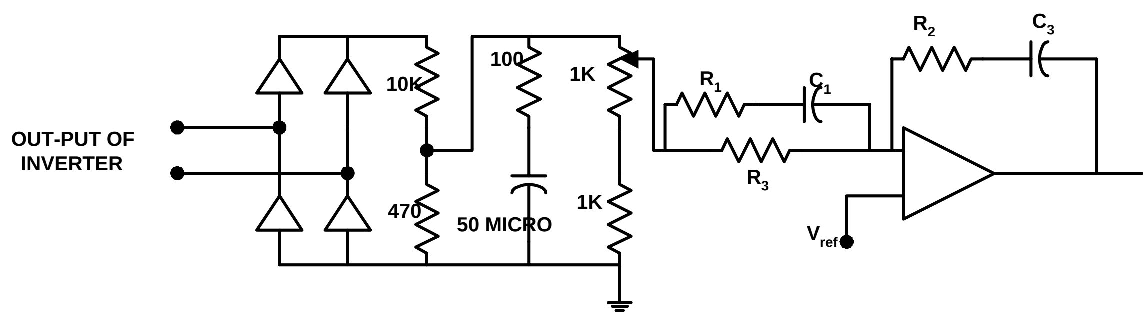


Figure (5.7): Feed Back Circuit & error amplifier for line regulation

CHAPTER: 6
Design

6.1 Technical Specification

The proposed Inverter is designed with the following technical specification.

1. Nominal DC Input : 48V (45-60V)
2. DC Input Range : 45V-60V DC
3. Nominal A C Output Voltage : 230V, 50 Hz Single Phase, Sinusoidal
4. Output Voltage Range : 230V (±10V) 50Hz (±2Hz)
5. Output Waveform : Sine Wave
6. Control Method : Soft-Starting Voltage Source
7. Efficiency (Full Load) : ≥80%
8. Regulation : 6% (Maximum) against input Voltage and load variation
9. Total Harmonic Distortion (THD) : 8% (Max)
10. Maximum Continuous Output : 1KVA
11. Surge current : 2KVA for 10 seconds
12. Cooling : Forced Air with Fan

N.B: As about 200 watt of power is to be dissipated in the whole inverter module due to loss, to keep the temperature rise with in limit forced cooling should be employed by using a fan.

6.2 DC- DC Converter

This converter has an input voltage of 48V DC. The output voltage of the inverter is 220V AC.

Output Power= 1KW, Overall Efficiency =0.8

Input Power = $\frac{1000}{0.8}$ = 1250 watts at unity power factor (UPF)

Input average current = $\frac{1250}{48}$ =26.04A

The current drawn from DC input source V_{dc} is in the form of pulses. For simple calculation these pulses are assumed to have an equivalent flat-topped wave shapes whose amplitude I_{pft} is given by

$$I_{pft} = 1.56 \times (P_o/V_{dc}) = 1.56 \times (1000/48) = 32.5A$$

6.2.1 Selection of Devices

a) Power Devices:

As the maximum average input current is 26A and I_{pft} is 32.5A, the selected power devices are IGBTs BSM 100 GB 170 DLC whose standard ratings are V_{cemax}=1200V and I_{cmax}=100A at 125^0 C.It may be noted that intentionally a high rated device is selected so that the power dissipation in the device will not to lead temperature rise. The details datasheet of IGBTs are given in last chapter.

b) PWM IC:

For generating gating pulses IC SG 3526 can be used which has the provision for control pulse width, so that suitable voltage regulation can be implemented. Detailed description of of the IC SG 3526 is given in appendix with its data sheet.

c) MOS Driver:

As the power switches (IGBTs) needs higher gating requirements the PWM IC cannot provide the same. Hence a driver which acts as a buffer for the gating pulses are used. In this project driver IXDD414YI could be used which has the following standard ratings

i) Vcc = supply voltage = 4.5V to 25V

ii) Max. Junction temperature = 125c

iii) Operating tempt rang e= - 40c to 85c

iv) Storage tempt range = - 65c to 150c

v) Peak output current with Vcc is 18V = 14A

vi) Continuous output current = 3A

d) Base or Gate Drive Transformer:

The purpose of gate drive transformer is to provide isolation between the controller section and floating power switch. Their design is relatively easy, but it's important to the reliable operation of the switching power supply.

There are several important factors to be considered during the design of the gate or base drive transformer

a) The dielectric isolation between each of the windings should be greater than twice the input voltage. This dielectric failure would cause a catastrophic failure in the control circuitry and the power switch.
b) A turns ratio should be chosen so as not to cause avalanche of the gate for this during the "off state" or to over stress the gate or base during the "on state".
c) The winding techniques that exhibit primary to secondary coupling should be used. Any degradation in good coupling causes the isolated power switches to switch more slowly than the grounded power switches.

The design of the base or gate drive transformer is similar to that of the forward mode power transformer. The designer must assure that the transformer core is not driven into saturation during its operation. A small bobbin core or a torroid may be used for a drive transformer. An air gap is not needed if the transformer in a bipolar fashion, that is when there is a totem pole driven on each end of the primary winding.

One area of concern in the design of the drive transformer is that the secondary waveforms of centre point voltage is the DC average of the drive waveform times the turns ratio. This results in the waveform DC zero point shifting with varying drive duty cycles.

To start a drive transformer design, one needs a fairly stable controller IC bias supply voltage that is typically in the range of 10 to 16V. Next, the designer should decide at what voltage levels the power switch should be driven. For power MOSFETs and IGBTs the voltage range should not exceed 18V-15V and is typically driven from –5V to +12V. The secondary voltage limits dictate the turns ratio of the drive transformer. The equation to determine this turns ratio is

$$\text{Ratio} = V_{PP(sec)}/V_{PP(pri)}$$

Select the desired core style and material. Since the transformer is coupling very little power, core loss is not a concern. The maximum flux density (B_{max}) should be approximately one-half of the saturation flux density at 100°C. MPP cores saturates above 6000G (0.6T). So a choice of a B_{max} of 2500G is satisfactory. Ferrite typically saturates at 3500G (0.35T) So a B_{max} of 1800G is good. To determine the number of turns, use

$$N_{pri} = \frac{V_{CE}}{4 f B_{max} A_c}$$

d) Power Diodes:

The four power diodes to be used in bridge topology for rectifying the pulsed AC obtained from output of the pulse transformer. The diodes used may be DSEP 2X61, This has the following ratings.

i) $V_{rm\,s}$= 1200V

ii) Maximum forward current = 60A

iii) Average forward current = 12A

6.2.2 Design of switching transformer:

Design of high frequency switching transformer is the most important design in a DC-DC converter. It consists of a ferrite made pot core and windings. Because of high frequency operation the size of core and windings are small in comparison to a power frequency transformer.

Recommended Core = Pot core AL 5000 87/70 ferrite

Make-siemens

Type-B65713-A5000-L27

Material-N27

Ac=area of core=9.15cm^2

B_{sat}= 3kgauss

Length of the core (L_c) =15.3cm^2

Design input

Primary voltage = ±50V (±20%) @ 30A

Secondary voltage = ±350V @ 3A

Transformer equation:

$E=4.44 \times f \times N \times B \times A\times10^{-8}$ (rms value for sine wave)

$E=4 f \times N\times B \times A\times10^{-8}$ (peak value for square wave)

E=Applied Voltage

f= Switching Frequency

N= no of turns

B=Flux Density in gauss

A= Cross Sectional Area in cm^2

We have E=50+20% (50) =60V

$F_{osc}= 2 \times f_{switching} = 30$ KHz

B=0.4Kgauss

Ac=9.15cm2

$$\therefore N_p = \frac{60}{4\times0.4\times10^3\times9.15\times10^{-8}\times30\times10^3} = 13.66 \approx 14$$

Secondary DC voltage = 350V

Max. Duty ratio = 80%

Min. Duty ratio = 70%

Hence secondary peak voltage = 350/0.5 = 500V

The primary peak voltage (min) = (50-20% (50) = 40V

Turns ratio = 500/40 = 12.5 ≈ 12

The no. of turns in the secondary = 12×14 = 168

Selection of core:

The core used has an effective area Ac

$A_c = 915\ mm^2 = 9.15\ cm^2$

Area of the bobbin winding $A_e = 657\ mm^2$

$= 6.57\ cm^2$

We have P_o=1000W

B_{max} = 0.5Kguass where B_{max} = peak operating flux density in gauss

D = current density of wire = 400A/m^2

f = switching frequency in Hz = 20 KHz

Then $A_cA_e = (0.68 \times P_o \times D \times 10^3)/(f \times B_{max}) = 34cm^4$

In our case $A_cA_e = 60cm^4$

Since practical value is nearly two times that of theoretical value. This transformer can effectively handle 1000watts at 20 KHz.

6.2.3 Design of output Filter:

During maximum knock period turn off time

$$T_{off} = \frac{1-(E_{out}/E_{in})}{2f}\ where (E_{out}/E_{in}) = 0.8,\ f = 20KHz$$

$$\Rightarrow T_{off} = 6.25\mu s$$

Let us assume the ripple current in the o/p be 50% of the output current. Then

$$L = \frac{E_{out} \times T_{off}}{0.5 \times I_{out}} = \frac{350 \times 6.25 \times 10^{-6}}{0.5 \times 3} = 1.458mH$$

The output capacitance is given by

$$C_{out} = \frac{\delta \times I_{out}}{8 \times f \times \delta V_{out}} = \frac{3 \times 0.5}{8 \times 20 \times 10^{3} \times 7 \times 10^{-3}} = 1674\mu F$$

$$where \delta V_{out} = 7mV$$

The nearest available capacitor is of 1800uf

Design of filter inductor:

The recommended Core to be used MPP core Arnold type-W107156-4.

Number of cores is three. (To avoid core saturation three cores should be used)

AL=156nH/T^2

L=3×A_L×N^2 where N= no. of turns

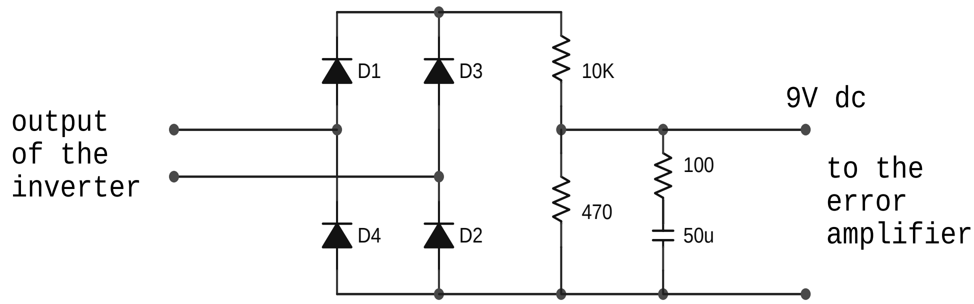
N=√ L/3×AL= {(√1.45×10^{-3}) /3} × (156×10^{-9}) =55.8=56

6.2.4 Design of blocking capacitor:

Unlike incase of half bridge converter, the chances of flux unbalancing in the transformer core for a full bridge DC-DC Converter is less. However a flux imbalanced may be caused due to unequal voltage drop across the IGBTs in one half cycles. Hence a small non-polarized blocking capacitor of 5uF in parallel a 1KΩ resistor is connected in series with the primary side of the pulse transformer.

6.2.5 Design of error amplifier:

For regulation purpose feedback to PWM IC3526 is fed from the output of the inverter. This output is rectified and stepped down by potential divider method. The schematic for the feed back circuit is as shown below.



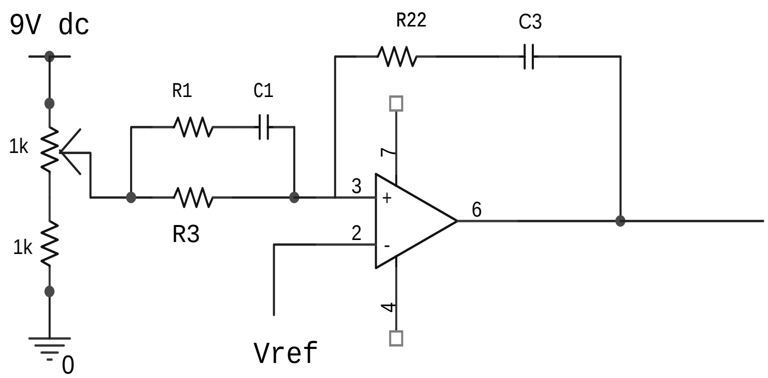


Figure (6.1): Feed Back Circuit

Design:

R_T=1KΩ

R_1=3R_T=3KΩ (used 3.3K)

L=1.46mH

C=1800uF

Corner frequency $f = \dfrac{1}{2\pi\sqrt{LC}} = 98Hz$

20 times LC corner frequency introduce a pole

f_1 = 20 f × B_{max} 98 = 1.96 KHz

$$f_1 = \frac{1}{2\pi R_1 C_1} \Rightarrow C_1 = \frac{1}{2\times\pi\times1.96\times10^3\times3\times10^3} = 27nf \approx 1\mu F$$

Pole at a frequency equation LC zero

$$f = \frac{1}{2\pi(R_1 + R_{22})C_1} \Rightarrow R_1 + R_{22} = 60K\Omega$$

$$\Rightarrow R_{22} = 60 - 3 = 57K\Omega$$

$$f = \frac{1}{2\pi R_3 C_3} \quad \text{Let } R3 = 22K\Omega$$

$$C_3 = \frac{1}{2\pi R_3 f} = \frac{1}{2\pi\ f \times B_{max}\ 22\ f \times B_{max}\ 103\ f \times B_{max}\ 98} = 73.8\text{nf (used 47nf)}$$

6.3 Inverter

Under steady condition the input to the inverter is 350V DC and output is 220VAC. Therefore the peak voltage across switching device 22 under steady condition the input to the inverter is 350V DC and output is 220VAC. Therefore the peak voltage across switching device 22 Under steady condition the input to the inverter is 350V DC and output is 220VAC. Therefore the peak voltage across switching device 2×√2×220 = 622V.The rms value of the o/p current under full load condition 1000/220 = 4.545A

The peak current = 4.54×√2 = 6.43A

6.3.1 Selection of Device

The full bridge inverter can be used using four power MOSFETs (IXFE 36N100). These MOSFETs are capable of operating at 1000V, 33A (rms) at 25˚C. The data sheets are given in the last chapter.

Selection of switch

The power MOSFETs promises exciting performance advantages over the more conventional bipolar transistor. It becoming more and more popular in many applications due to its inherent features such as

1) Extremely fast switching characteristics

A power MOSFET is capable of switching rapidly, because it is a majority carrier device. The speed at which it can switch depends upon the rate at which gate charge is supplied and removed by the gate-driving source. In a practical application the MOSFET can be made to switch in less than 10ns. This feature allows operation at higher frequency than with bipolar devices, resulting in improved electrical performance, reduced size and cost of the magnetic components and decreased weight of the overall system

Other advantages derived from fast switching times are:

- The switching times of power MOSFET are independent of load and temperature variation
- The losses in the Snubber circuit if employed are minimized
- The cross conduction problem in a switch mode converter reduced, because powers MOSFET have no storage time.
- The problem of core saturation due to asymmetrical volt-seconds in circuits using a transformer is minimized because the major cause of this effect is differences in storage time is negligible for MOSFETs.
-

2) High gate input impedance

The gate input impedance is a high resistance shunted by a capacitance. At high frequencies the capacitance completely dominates. This fact allows the design of simple and efficient gate drive circuit.

3) No forward or reverse biased second breakdown

Because of the positive temperature co-efficient of channel resistance power MOSFETs do not have forward or reverse biased second breakdown characteristic like bipolar devices. Thus power MOSFETs improves the overall reliability of systems.

4) Current sharing capability

Since the channel resistance of a power MOSFETs has a positive temperature co-efficient of channel resistance, many devices can be parallel with much less special design attenuation than with bipolar transistors. Hence output power capacity can, thus be extended.

5) Integral diode

There is a built-in diode across source to drain. The reverse recovery time of the diode depends upon the drain to source breakdown voltage. The low voltage devices have reverse recovery times as low as 200ns, while high voltage device have recovery times of about 600-700ns.

Main parameters considered in selecting the power MOSFET are

1) ***Drain current:***

The drain current does not begin to turn on until the gate to source voltage reaches about 2.5V. Thus positive noise pick up spikes at the gate terminal cannot falsely turn drain current ON until the 2,5V threshold is reached.

The drain current for SMPS is given by $I_d=3.13P_o/P_{dc}$

Hence a power MOSFET with drain current of at least 2.7A or greater than that is to be selected.

2) ***Maximum reverse voltage it can withstand***

For a switch employed in D.C-D.C converter, the maximum reverse voltage to which the switch is subjected as $V_m=1.3\ (2V_{dc})$

Therefore power MOSFET which has reverse voltage of greater than or equal to -910 Volts is to be selected

3) Drain source resistance R_{ds}(ON)

Normally a power MOSFET with low $R_{ds(ON)}$ is to be selected since it affects the on state voltage drop. Therefore power MOSFET IXFE 36N100 was selected.

It has $I_d = 33$ amps

$R_{ds(ON)} = 0.24$ ohms

6.3.2 Generation of Triangular Wave:

The triangular carrier wave can be generated by using a signal generating IC XR-2206 whose frequency is set at 10 KHz by suitable selection of R and C values.

$f=1/RC=10\text{x}10^3$

Choose R=5.9K

$$C = \frac{1}{5.9\times10^3\times10\times10^3} = 16.9nF \text{ (15nF is chosen)}$$

6.3.3 Generation of Sinusoidal Wave

By suitable modification in circuiting the same IC-XR2206 is used to generate the reference sinusoidal voltage whose frequency is set to be 50HZ

f=1/RC = 50HZ

Choosing R=23.5K

$$C = \frac{1}{23.5 \times 10^3 \times 50} = 0.85 \mu F$$

Buffer and Inversion for reference Sine Wave

As the generated ref sine wave signal is required to be inverted as well as buffered for this purpose an IC OP271 is used which has 16 pins. Pin1 given inverted sine wave while pin 7 given non-inverted sine wave.

Comparator

For comparing sine wave with the triangular carrier LM311 is used.

MOS Driver

For signal conditioning and isolation of the comparator output the driver IC IR-2110 can be used for each leg. The data sheets are given in the last chapter.

6.3.4 Design of Snubber Circuit

To calculate peak current available to charge capacitor

I_{PK}=3.13× (P_0/V_{dc})

I_{PK}=3.13× (1000/350) = 8.94A

From datasheet, MOSFET, rise time and fall time

t_r = 27ns t_f = 300ns

C_{snub}=I_{PK} x t_f /2Vdc

= (8.94/2) ×300×10^{-9}/(2x350)

C_{snub} chosen is 2nF

$$R_{snub} = \frac{T_{on}(\min)}{3 \times C_{snub}} = \frac{0.6 \times 10^{-6}}{3 \times 2 \times 10^{-9}} = 100\Omega$$

C_{snub}= 2nF

R_{snub} = 100Ω

6.3.5 Inverter Output Filter Calculation:

Since the output of this inverter have significant presence of higher order harmonic, a low pass filter is used to attenuate the higher order harmonic components we have fundamental frequency is equal to 50HZ.

Assuming the 3db corner frequency to be 1000HZ

We have $F_c = \dfrac{1}{2\pi\sqrt{LC}} = 1000Hz \Rightarrow LC = 2.533\times10^{-8}$

L=4.91mH

C=5.16μF (6μF)

Here instead of taking single section of inductor we can take two sections each of 2.45mH. This is done for symmetry in output waveform.

The filter section is as shown below

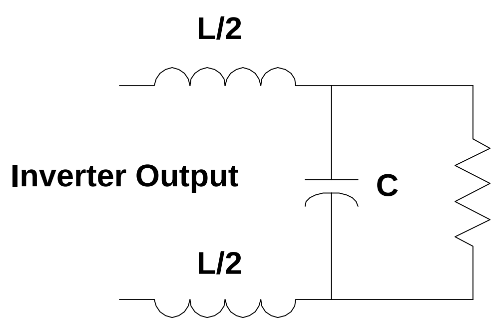


Figure (6.2): Low pass filter for the Inverter

$V_o/V_i=1/\sqrt{1+w^2LC}$ with f = 50Hz

$V_o/V_{in}=1$

i.e. a 50Hz component is passed completely

For f=10 KHz

$$\frac{V_o}{V_{in}} = \frac{1}{\sqrt{\{1+(2\times\pi\times10\times10^3)^2\times4.91\times10^{-3}\times6\times10^{-6}\}}} = \frac{1}{10}$$

i.e. the switching frequency component is attenuates more than 10 times as compared to desired modulating signal.

CHAPTER: 7

Simulation and Experimental Results

7.1 Simulation Results

The whole Inverter module was simulated using the software P-SIM with the following specifications.

DC Input to the Inverter = 48 Volts

Switching frequency for the DC-DC converter = 20 KHz

Frequency of Modulating signal = 50Hz

Frequency of Carrier Signal for the Inverter = 10 KHz

Filters used: Passive L-C Filter.

The Wave forms at different stages are as shown below

DC-DC Converter

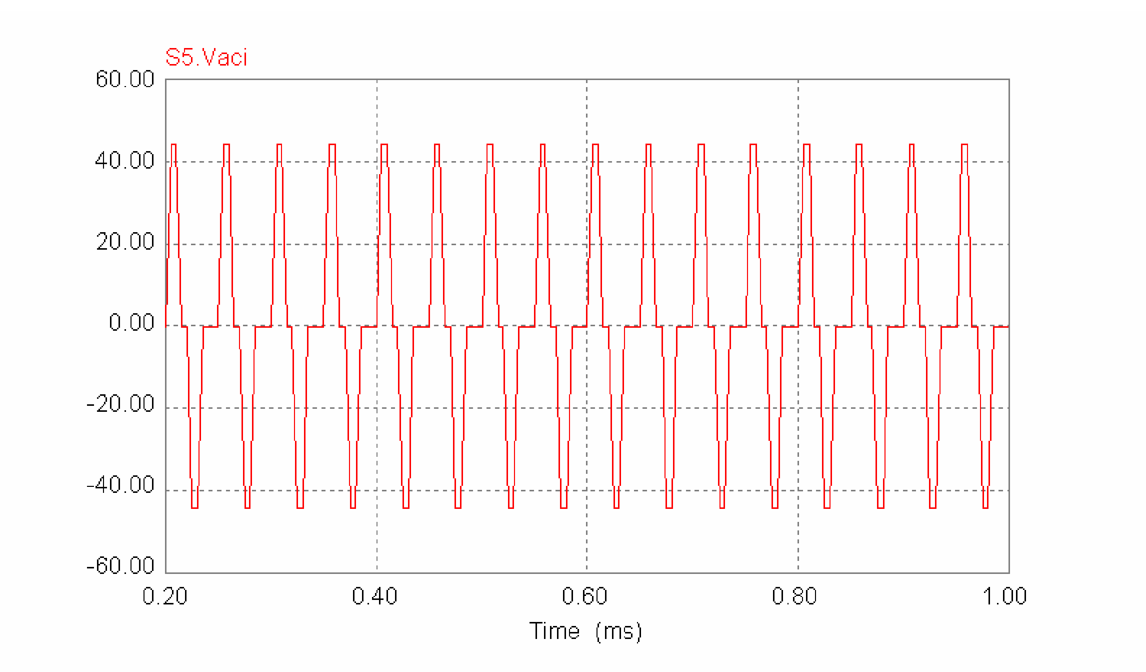


Figure (7.1): Out put of the High frequency Inverter

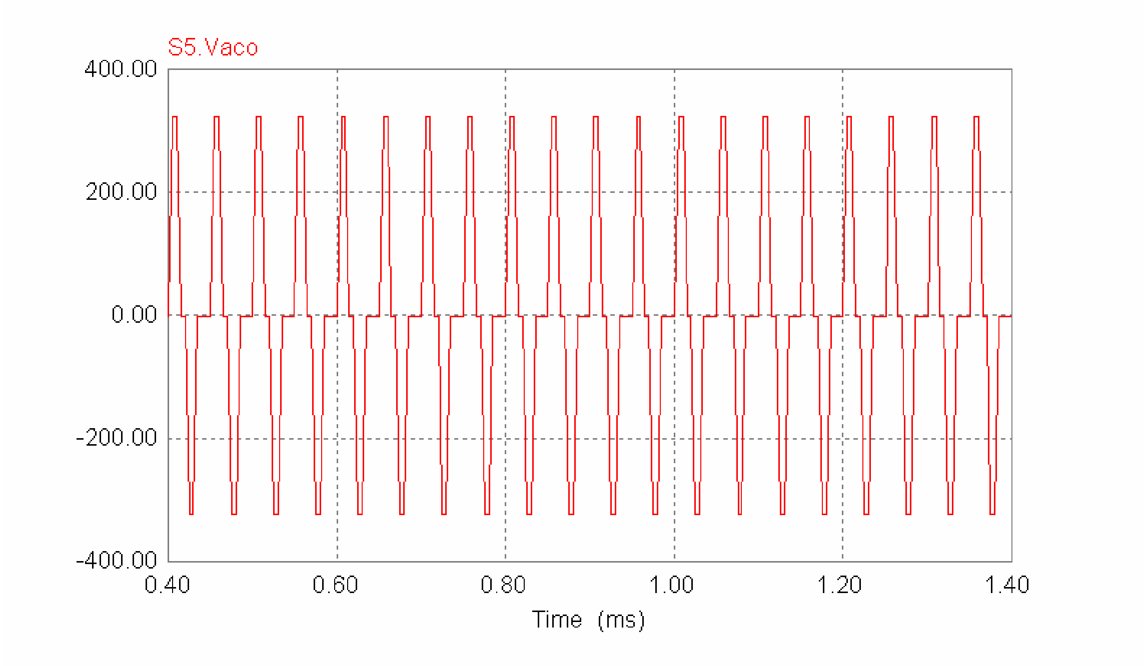


Figure (7.2): Out put of the High frequency switching Transformer

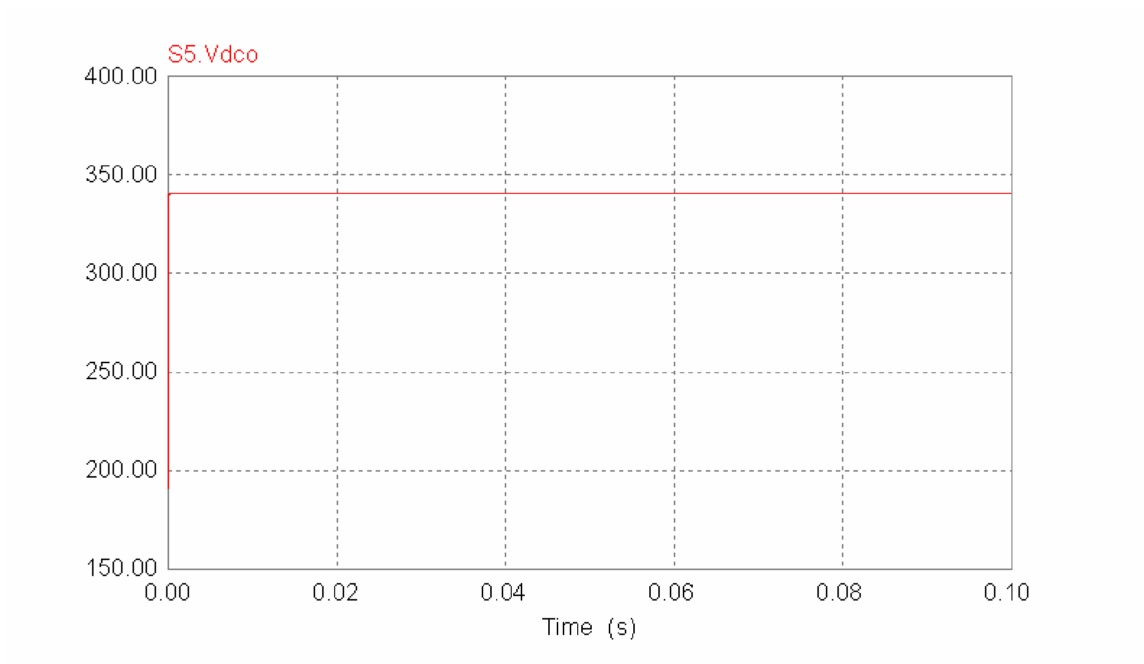


Figure (7.3): Output of DC-DC Converter after rectification

Symmetrical Hybrid Sine PWM Inverter

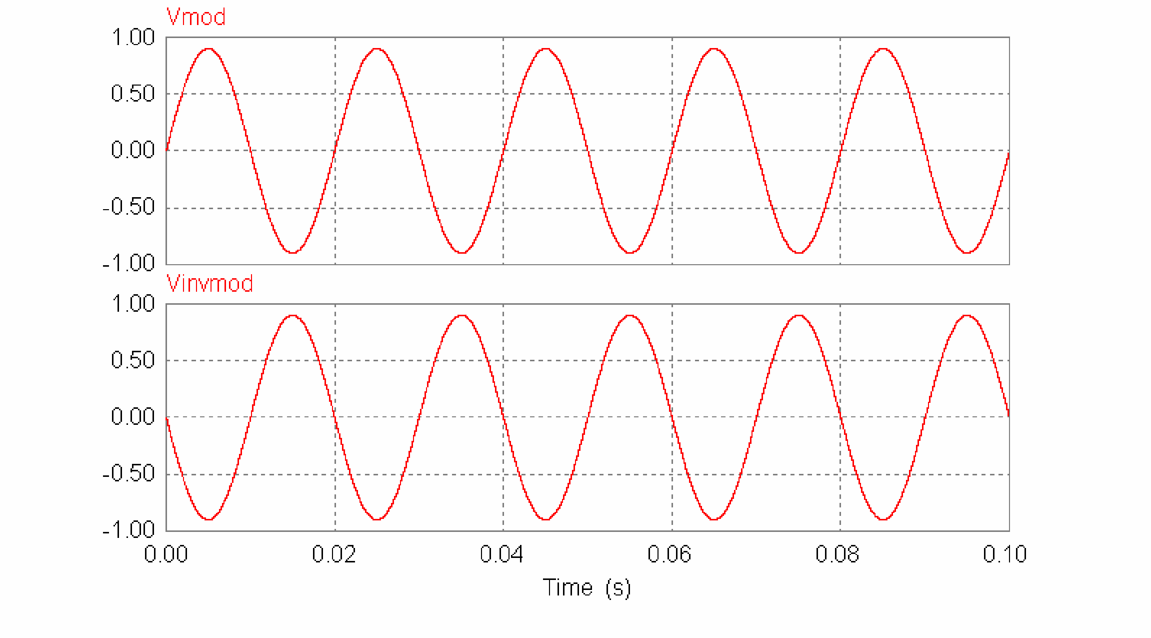


Figure (7.4): Modulating Sine Wave and its Inversion

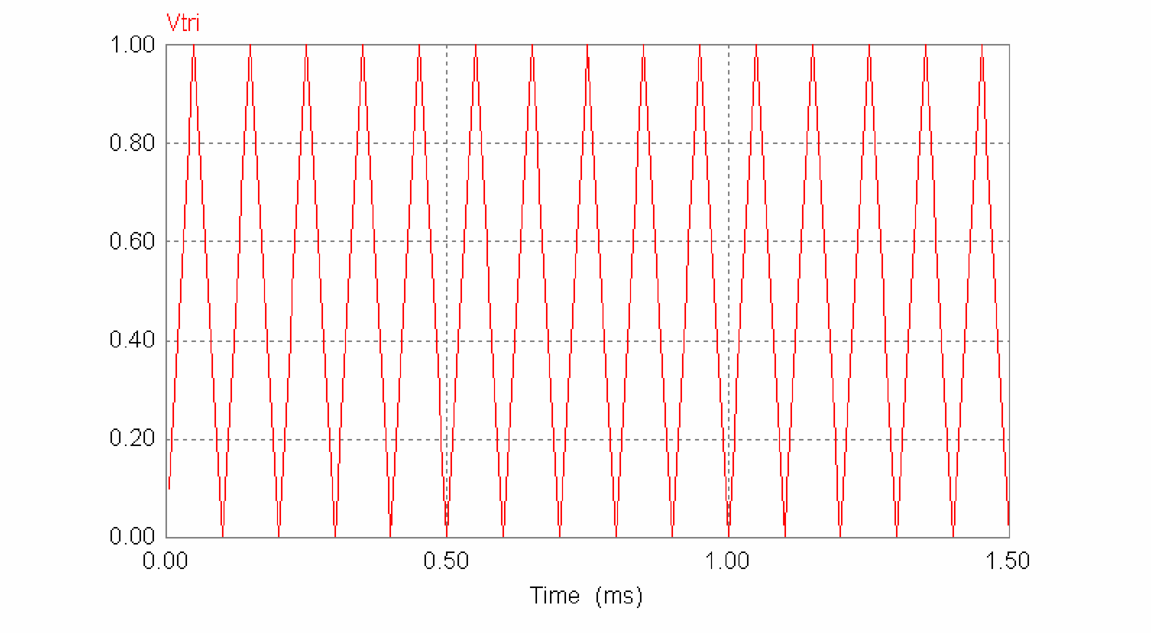


Figure (7.5): Unipolar triangular carrier wave signal

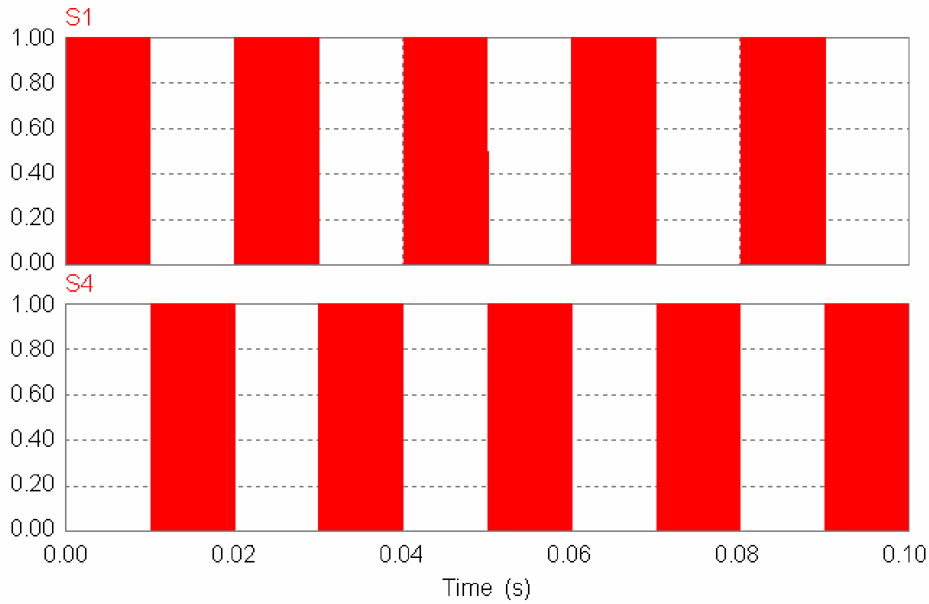


Figure (7.6): Generation of Sine PWM signals

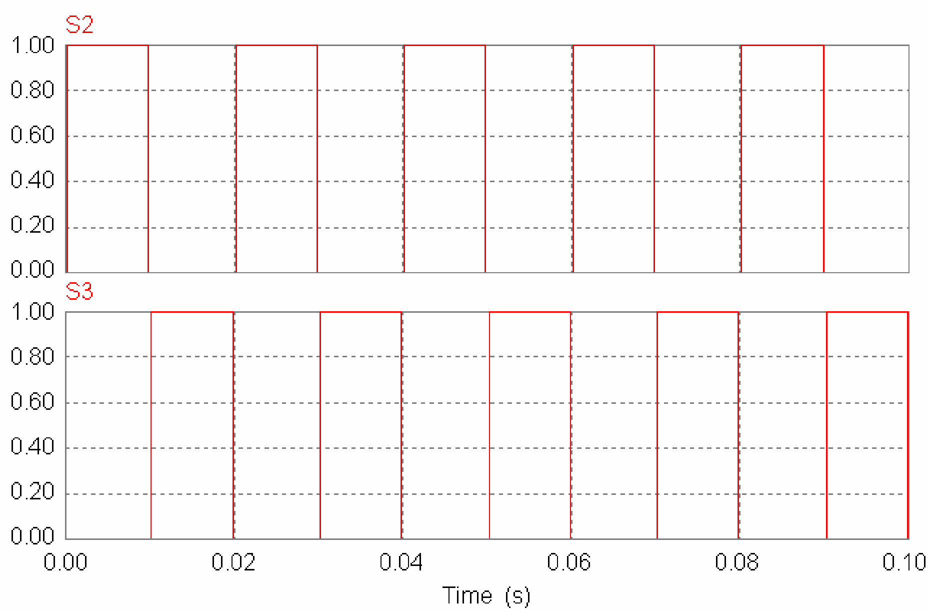


Figure (7.7): Generation of low frequency square wave signals

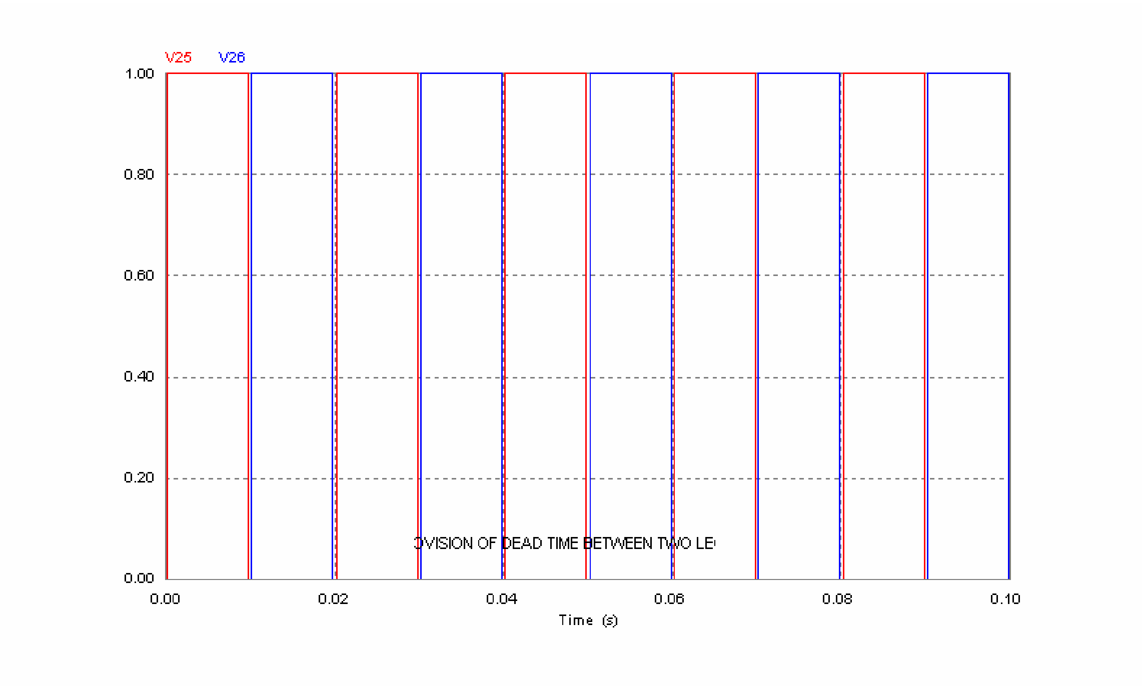


Figure (7.8): Provision of dead time between two switches in each leg.

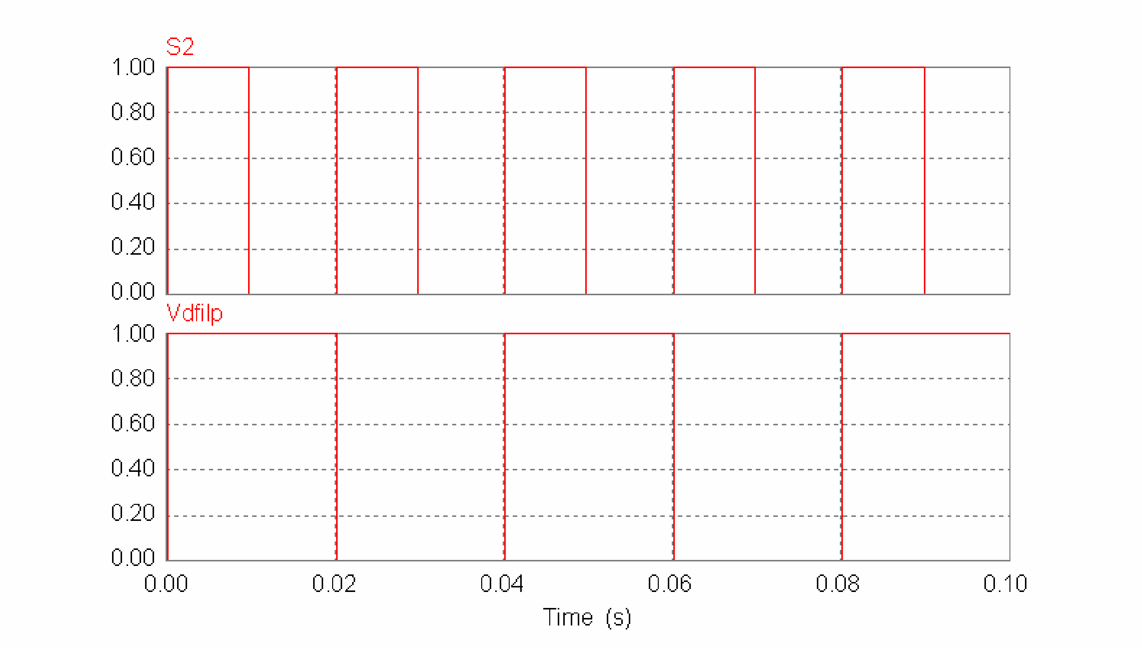


Figure (7.9): Output of the D-Flip-flop (Frequency Divider)

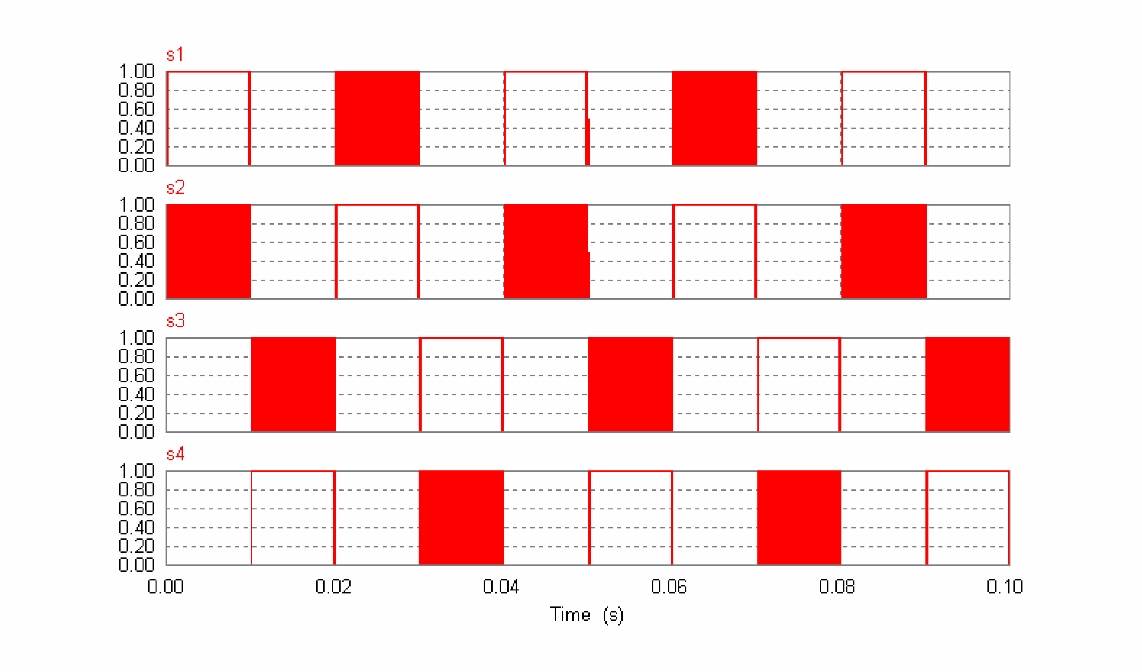


Figure (7.10): Generation of Symmetrical Hybrid Sine PWM signals for the Inverter Switches

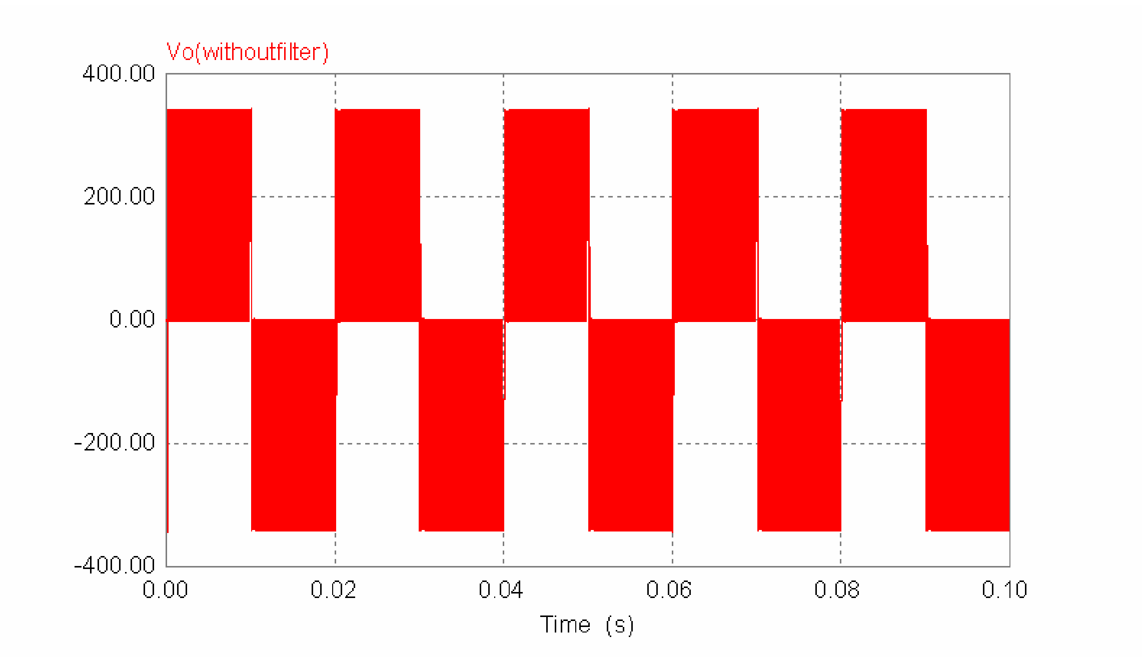


Figure (7.11): Output of the Inverter Without low pass Filter

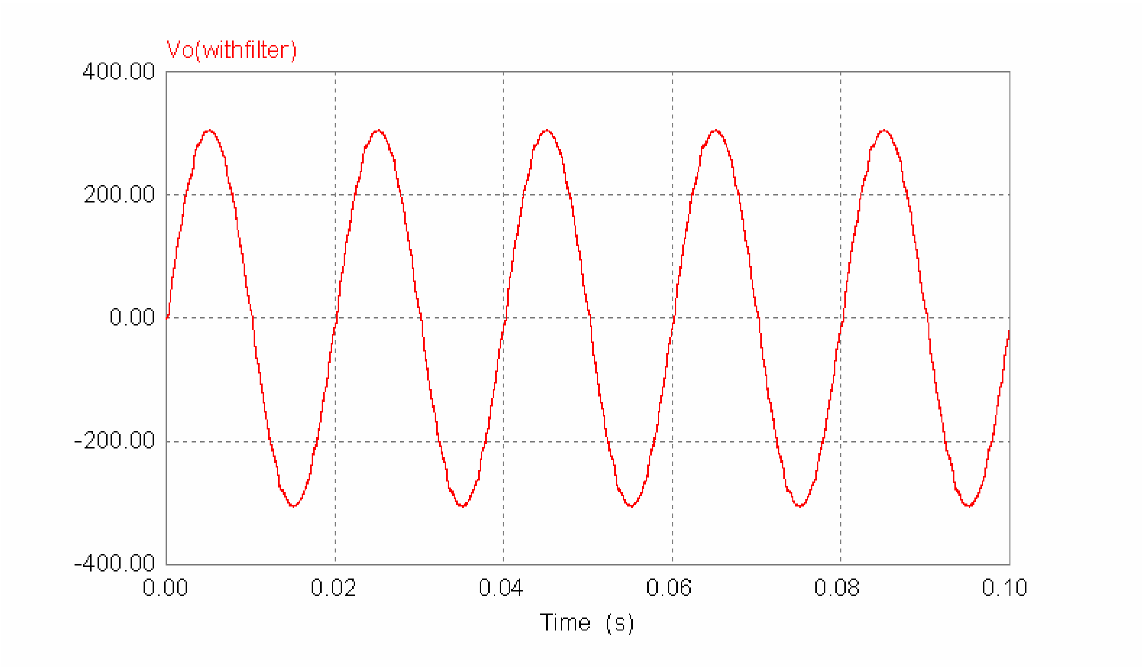


Figure (7.12): Output of the Inverter With low pass Filter at full load

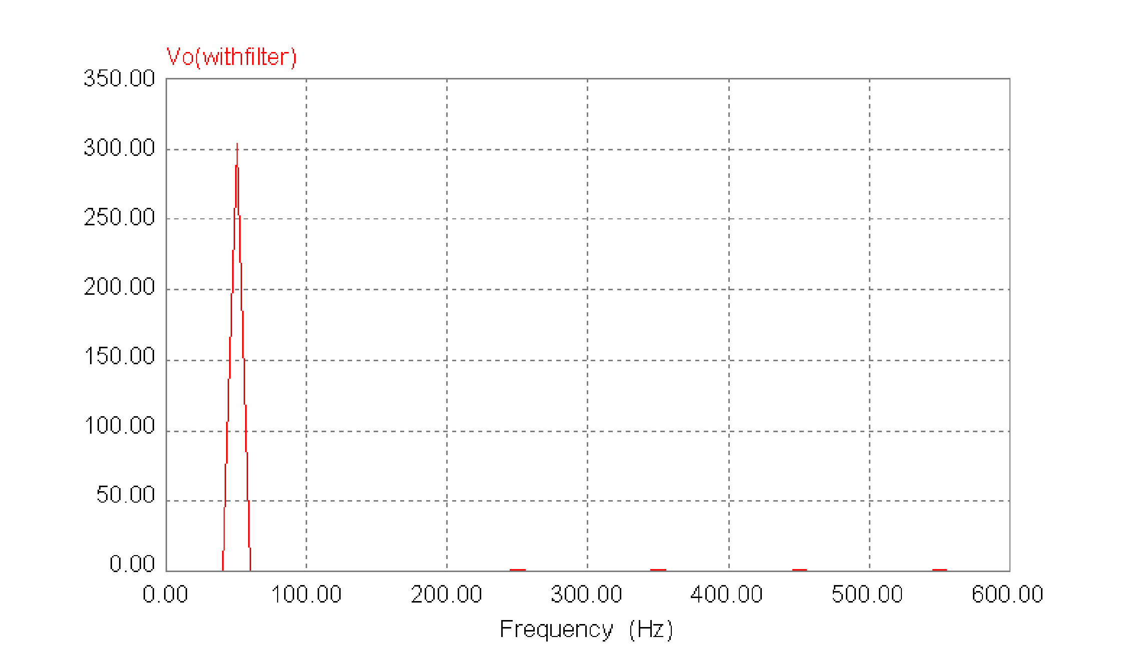


Figure (7.13): FFT for the Inverter output at full load

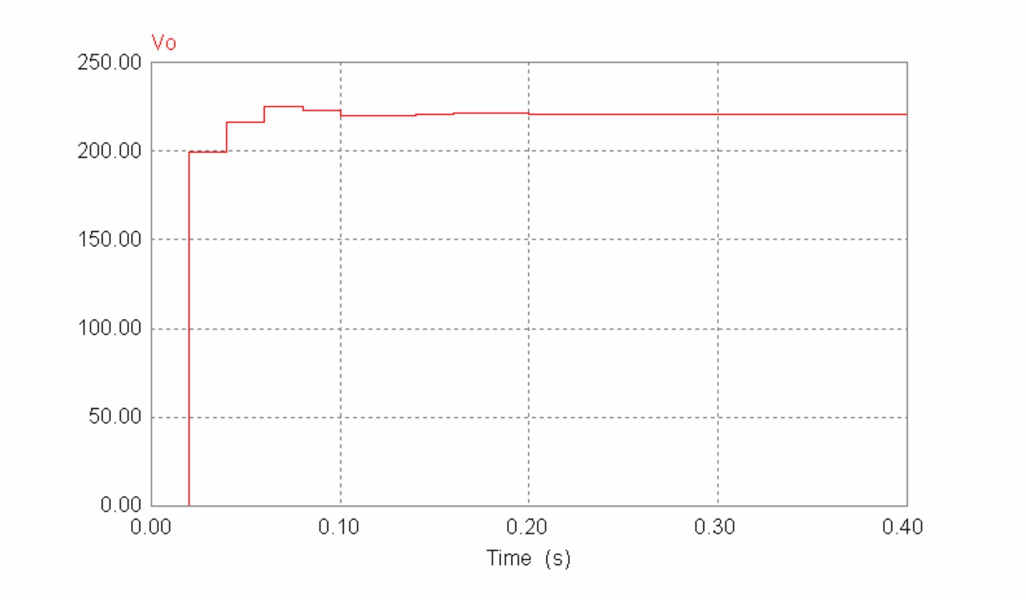


Figure (7.14): Output voltage (RMS) of the Inverter at full load

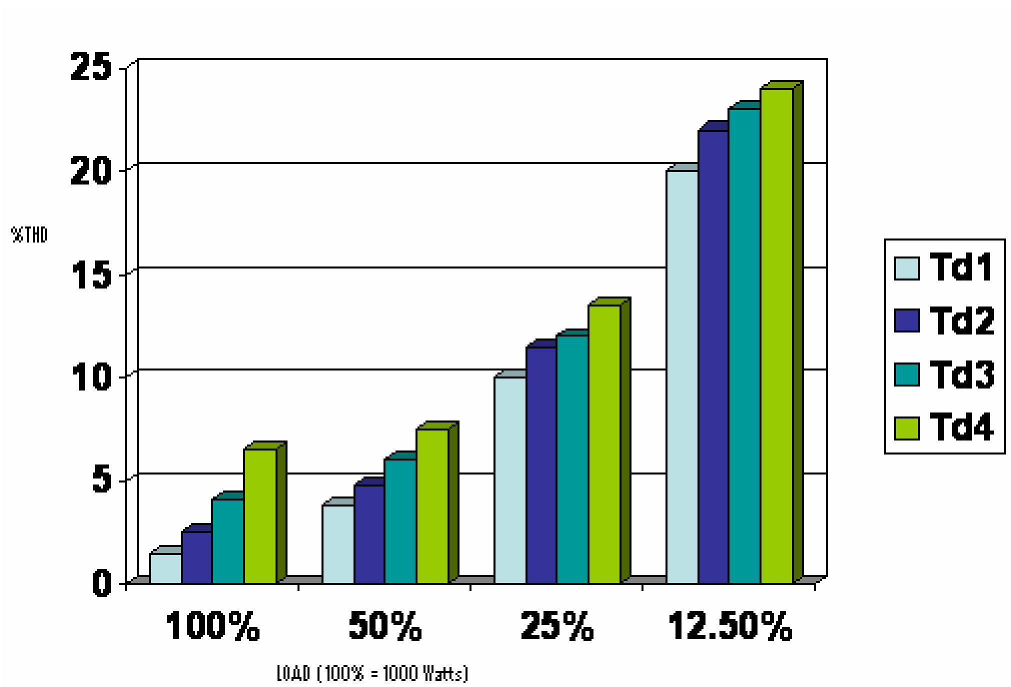


Figure (7.15): THD Verses Load [Td1=0.159ms, Td2=0.318ms, Td3=0.479, Td4=0.641ms]

The Inverter was tested with variable resistive loads. The DC input to the DC-DC converter is varied. The output voltage, efficiency and amount of distortion are measured for different input voltage at various loads.

Table: 1

P_{out}= 1000 watts (R_L = 50 ohms)

V_{DC} in volts	I_{DC} in Amps	V_{ORMS} in volts	% Efficiency
46.2	27.6	220.5	76.26
47.0	26.9	221.5	77.6
48.0	26.3	221.6	77.8

Distortion = 4%

Table: 2

P_{out}= 500 watts (R_{LOAD}=100Ω)

V_{DC} in volts	I_{DC} in Amps	V_{ORMS} in volts	% Efficiency
44.0	13.16	218.9	82.75
45.0	13.0	219.0	81.98
48.0	12.5	219.1	79.37

Distortion = 6%

Table: 3

P_{out}= 250 watts (R_{LOAD}=200Ω)

V_{DC} in volts	I_{DC} in Amps	V_{ORMS} in volts	% Efficiency
40.0	6.9	212.6	81.88
45.0	6.6	212.7	76.16
48.0	6.2	212.7	76.0

Distortion = 8%

Table: 4

P_{out}= 125 watts (R_{LOAD}=400Ω)

V_{DC} in volts	I_{DC} in Amps	V_{ORMS} in volts	% Efficiency
40.0	3.93	206.4	67.75
45.0	3.53	206.8	67.31
48.0	3.13	207.0	71.3

Distortion =14%

7.2 Experimental Results

In the proposed Inverter module a Novel switching technique, Symmetrical Hybrid Sine PWM (SHSPWM) is employed in the front end Inverter. To test the feasibility of such technique a prototype model of this technique is developed to drive a single phase full-bridge Inverter, with following specification. The wave forms at different stages are observed and recorded.

Input DC Link Voltage = 12-40 V,

Frequency of modulating Signal = 50Hz,

Frequency of carrier signal= 10 KHz (Unipolar Triangular wave),

Modulation Index= 0.8.

Filters used: Passive L-C Filter.

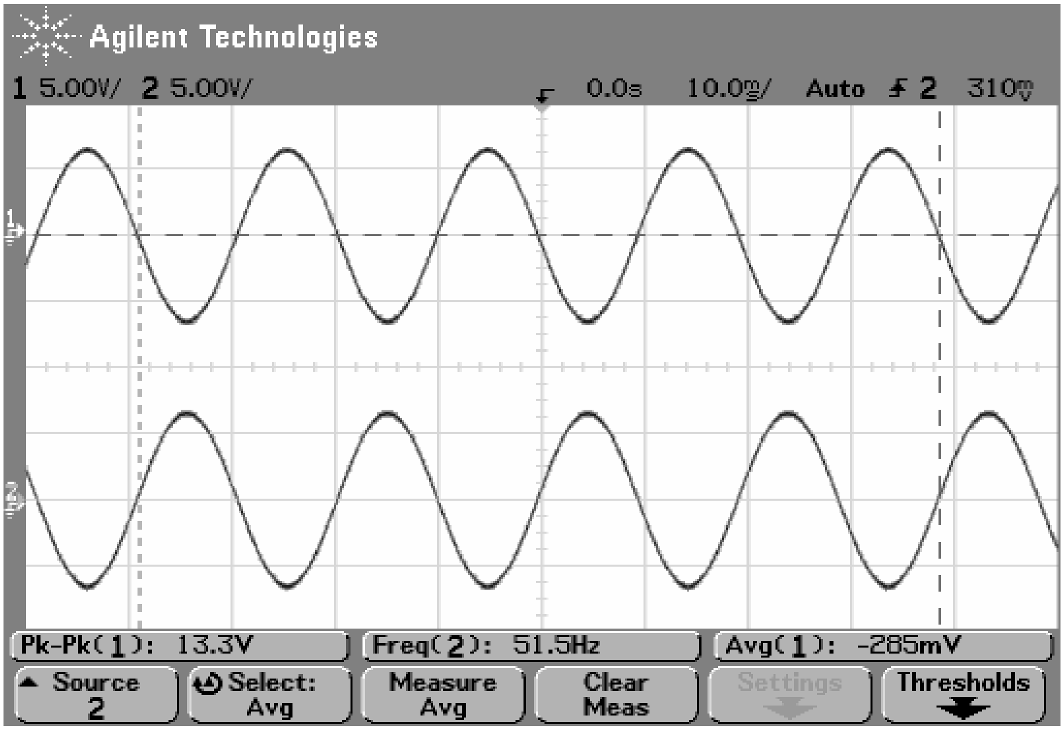


Figure (7.16): Modulating Sine & Inverted Sine Wave

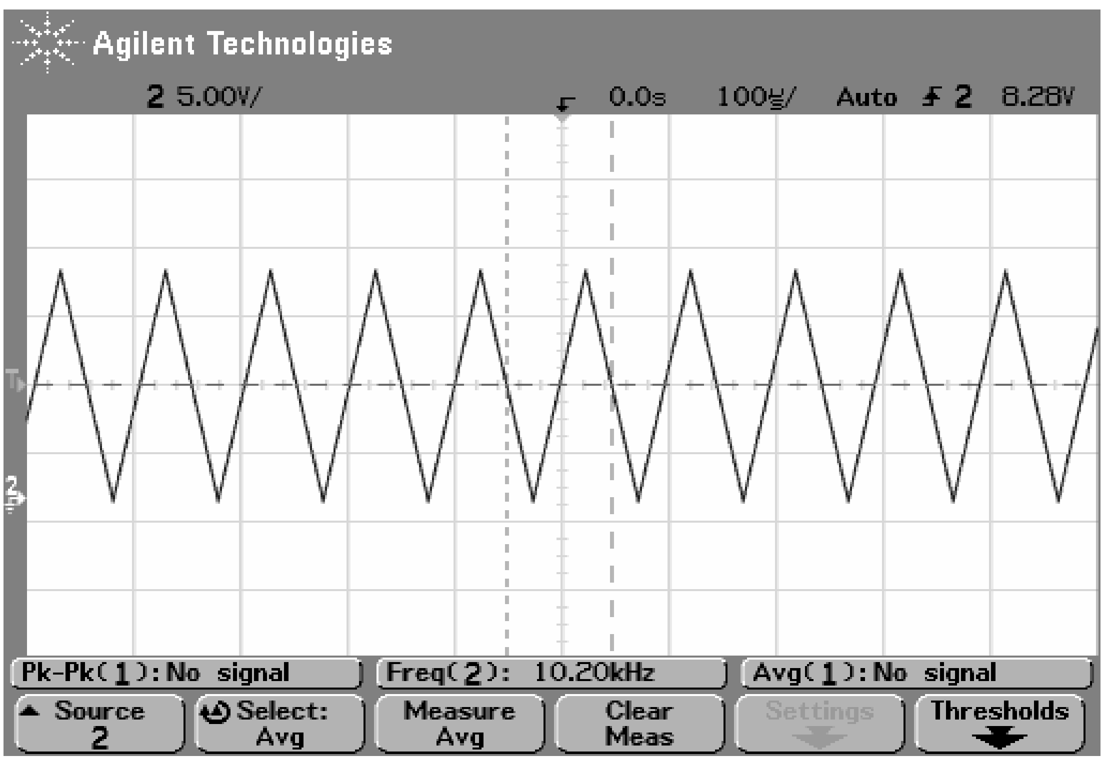


Figure (7.17): Unipolar Triangular Carrier wave

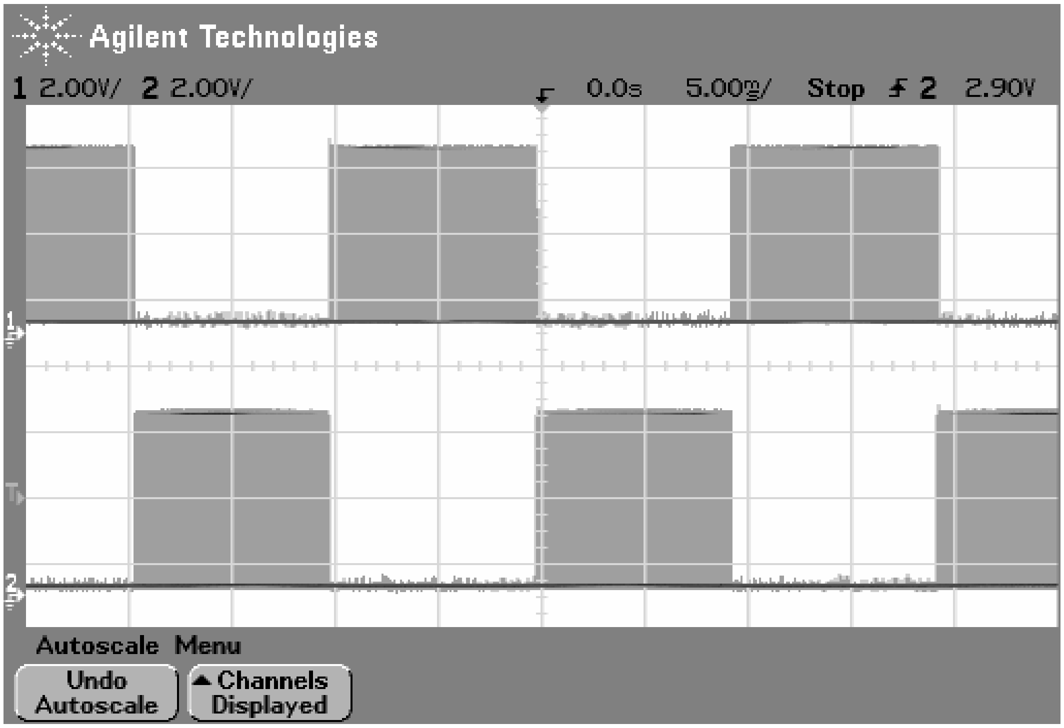


Figure (7.18): Sine PWM Signals

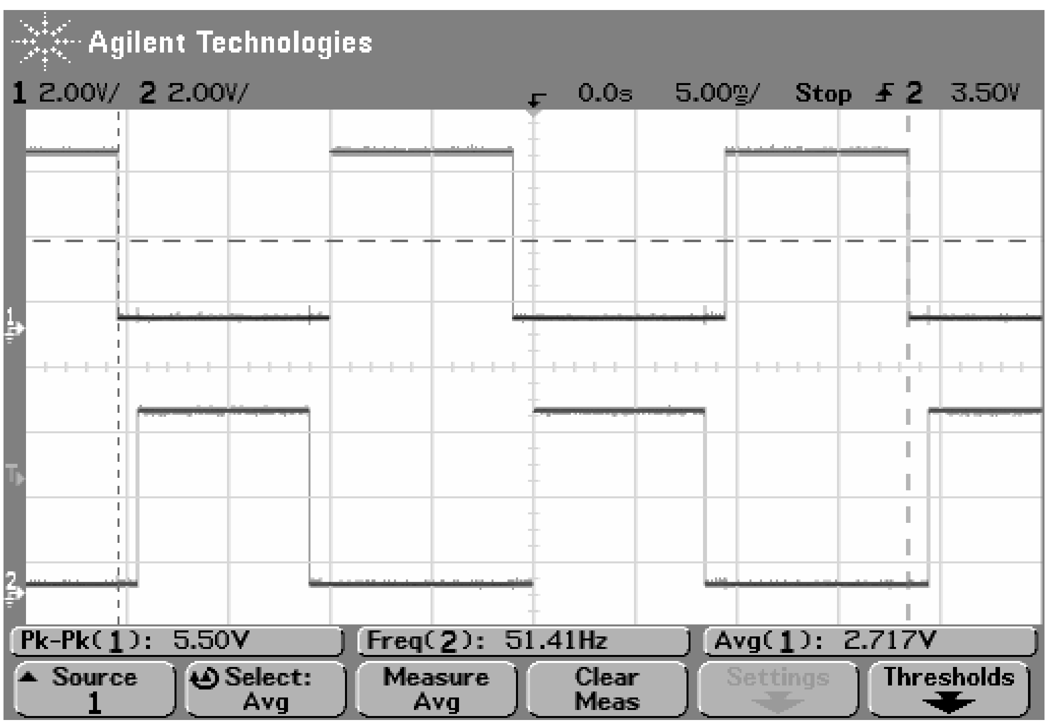


Figure (7.19): Square Wave Signals at line frequency.

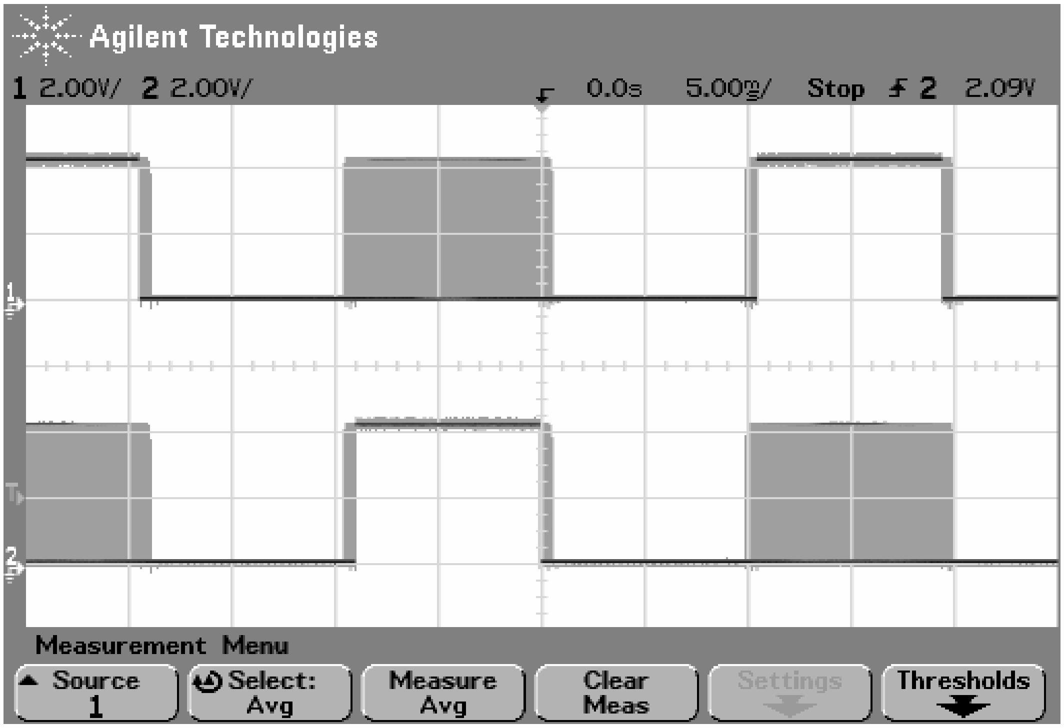


Figure (7.20): Symmetrical HSPWM signals for S_1 & S_2

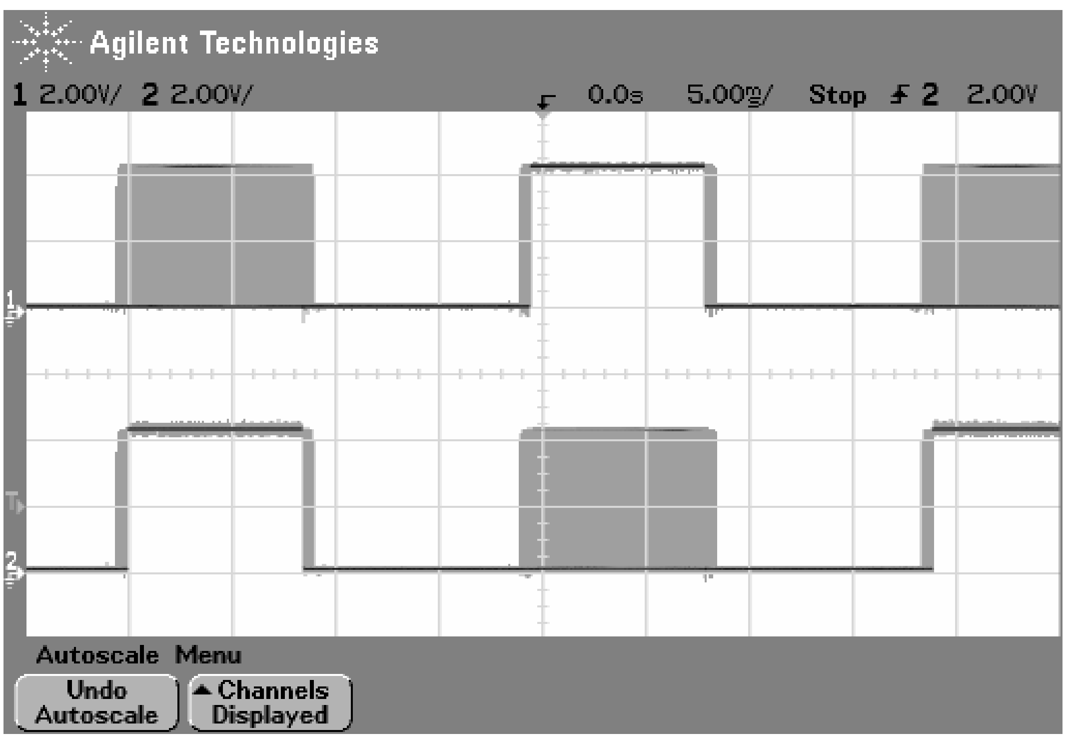


Figure (7.21): Symmetrical HSPWM signals for S_3 & S_4

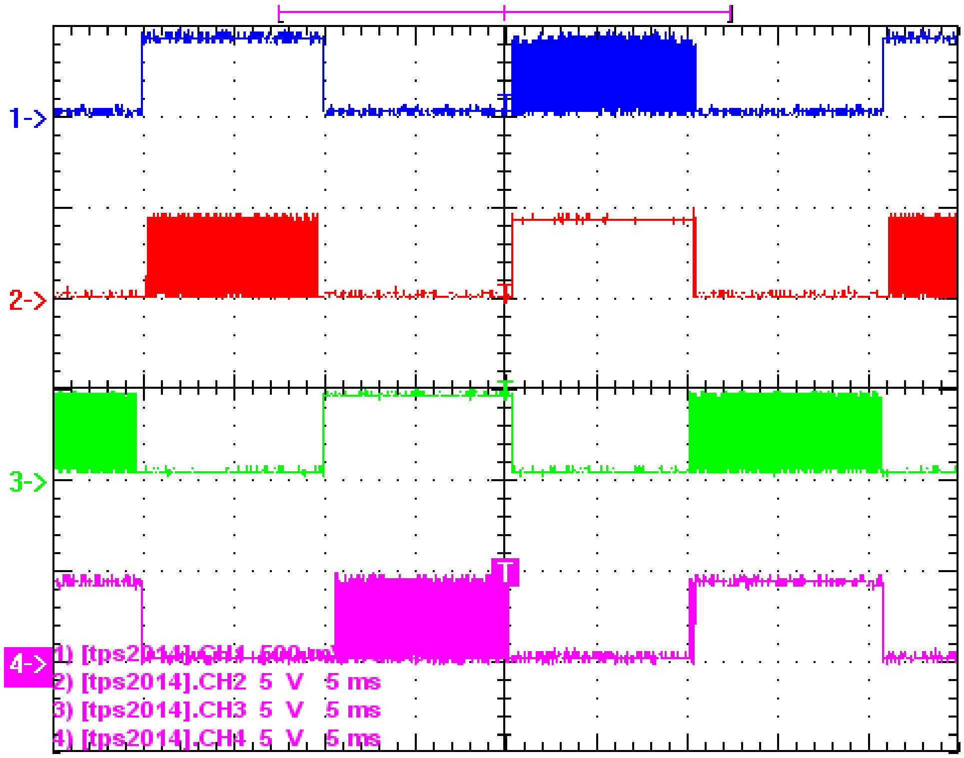


Figure (7.22): SHPWM pulses for switches S_1, S_2, S_3, and S_4 respectively (Driver o/p)

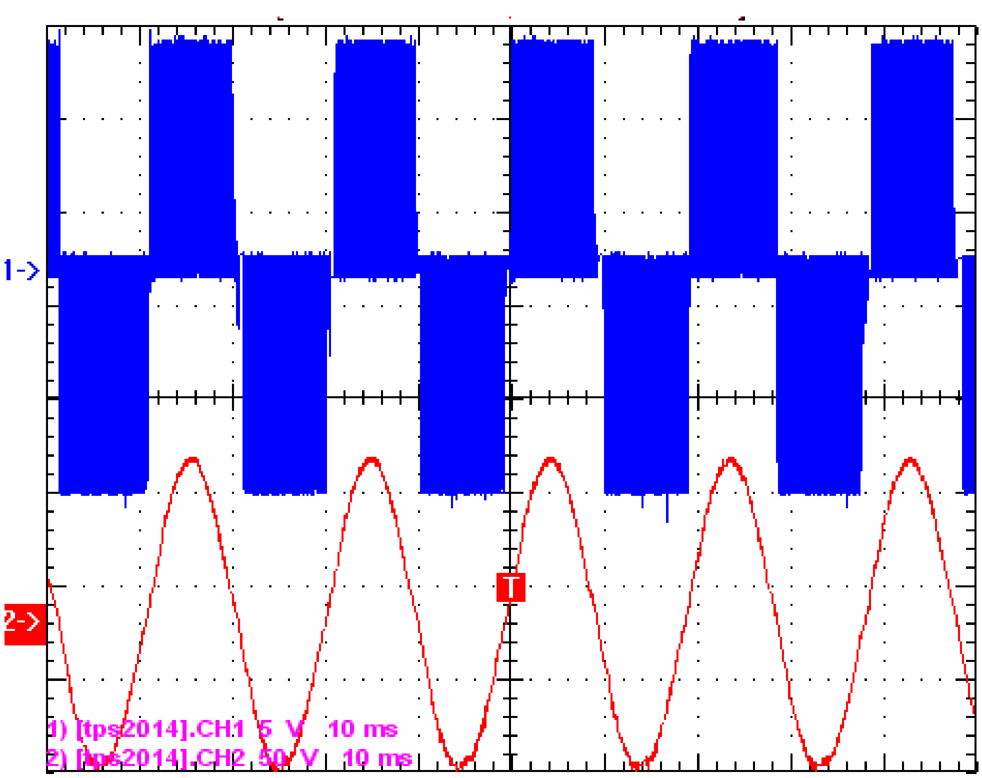


Figure (7.23): Out put of Inverter with and with out low pass filter

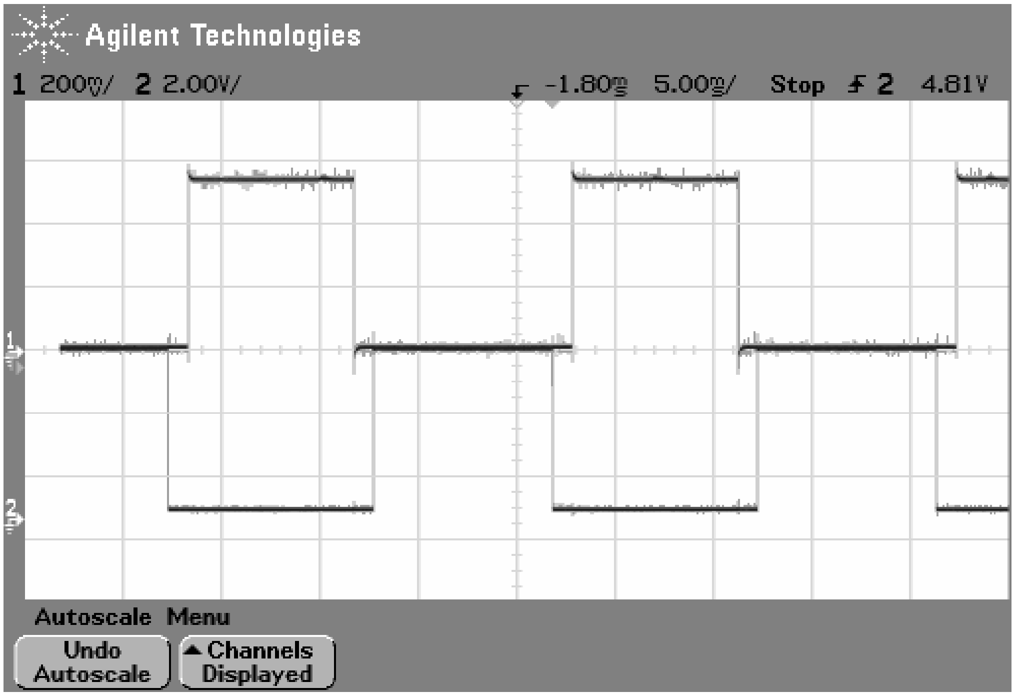


Figure (7.24): Provision of Dead time between two Switches In each leg of the Inverter

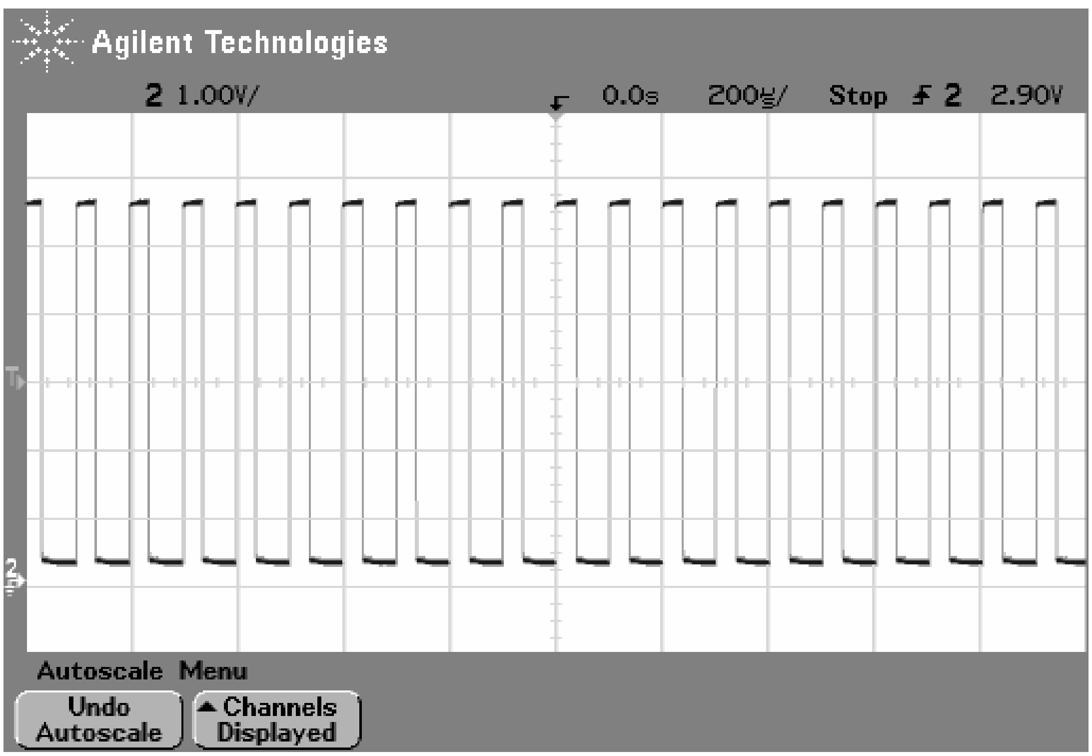


Figure (7.25): Zoomed Sine PWM Signals

F.F.T Analysis

Table: 5

For M= 0.9

Voltage = 7.9655 V

Current = n/a

Power = n/a

Voltage THD = 2.922 %
Power Factor = n/a
Instantaneous Power = n/a VA

Current THD = n/a
Displacement Power Factor = n/a Degrees
Reactive Power = n/a VAR

	Frequency	Voltage RMS	Voltage % of Fund.	Voltage Phase	Current RMS	Current % of Fund.	Current Phase
Fundamental	51.125 Hz	7.9353 V	100.000 %	0.0000			
Harmonic 2	102.25 Hz	124.75m V	1.572 %	93.633			
Harmonic 3	153.37 Hz	45.782m V	0.577 %	-58.430			
Harmonic 4	204.50 Hz	97.831m V	1.233 %	-75.046			
Harmonic 5	255.62 Hz	126.20m V	1.590 %	501.36m			
Harmonic 6	306.75 Hz	50.805m V	0.640 %	126.08			
Harmonic 7	357.87 Hz	25.837m V	0.326 %	6.5308			
Harmonic 8	409.00 Hz	52.888m V	0.666 %	-52.300			
Harmonic 9	460.12 Hz	53.114m V	0.669 %	61.748			
Harmonic 10	511.25 Hz	9.1247m V	0.115 %	132.53			
Harmonic 11	562.37 Hz	22.749m V	0.287 %	131.70			
Harmonic 12	613.50 Hz	17.774m V	0.224 %	68.322			
Harmonic 13	664.62 Hz	25.707m V	0.324 %	157.67			

Table: 6

For M= 0.8

Voltage = 7.2772 V

Current = n/a

Power = n/a

Voltage THD = 1.551 %
Power Factor = n/a
Instantaneous Power = n/a VA

Current THD = n/a
Displacement Power Factor = n/a Degrees
Reactive Power = n/a VAR

	Frequency	Voltage RMS	Voltage % of Fund.	Voltage Phase	Current RMS	Current % of Fund.	Current Phase
Fundamental	50.327 Hz	7.2734 V	100.000 %	0.0000			
Harmonic 2	100.65 Hz	42.974m V	0.591 %	112.70			
Harmonic 3	150.98 Hz	66.114m V	0.909 %	-108.61			
Harmonic 4	201.31 Hz	7.3270m V	0.101 %	-168.30			
Harmonic 5	251.64 Hz	68.015m V	0.935 %	-84.539			
Harmonic 6	301.96 Hz	13.752m V	0.189 %	-144.04			
Harmonic 7	352.29 Hz	30.584m V	0.420 %	-27.679			
Harmonic 8	402.62 Hz	12.493m V	0.172 %	-114.48			
Harmonic 9	452.94 Hz	15.455m V	0.212 %	-88.028			
Harmonic 10	503.27 Hz	6.3510m V	0.087 %	-169.86			
Harmonic 11	553.60 Hz	11.121m V	0.153 %	-13.252			
Harmonic 12	603.93 Hz	5.7776m V	0.079 %	-140.60			
Harmonic 13	654.25 Hz	3.8603m V	0.053 %	-8.6027			

Table: 7

For M= 0.7

Voltage = 6.2425 V

Current = n/a

Power = n/a

Voltage THD = 1.710 %
Power Factor = n/a
Instantaneous Power = n/a VA

Current THD = n/a
Displacement Power Factor = n/a Degrees
Reactive Power = n/a VAR

	Frequency	Voltage RMS	Voltage % of Fund.	Voltage Phase	Current RMS	Current % of Fund.	Current Phase
Fundamental	49.801 Hz	6.2502 V	100.000 %	0.0000			
Harmonic 2	99.602 Hz	48.014m V	0.768 %	96.097			
Harmonic 3	149.40 Hz	61.326m V	0.981 %	-103.27			
Harmonic 4	199.20 Hz	16.448m V	0.263 %	-137.35			
Harmonic 5	249.00 Hz	60.667m V	0.971 %	-92.058			
Harmonic 6	298.80 Hz	13.193m V	0.211 %	-160.57			
Harmonic 7	348.61 Hz	20.489m V	0.328 %	-45.679			
Harmonic 8	398.41 Hz	9.4838m V	0.152 %	-154.62			
Harmonic 9	448.21 Hz	16.002m V	0.256 %	-73.130			
Harmonic 10	498.01 Hz	9.9989m V	0.160 %	-176.92			
Harmonic 11	547.81 Hz	7.0502m V	0.113 %	-61.218			
Harmonic 12	597.61 Hz	9.5974m V	0.154 %	159.55			
Harmonic 13	647.41 Hz	5.4111m V	0.087 %	-42.481			

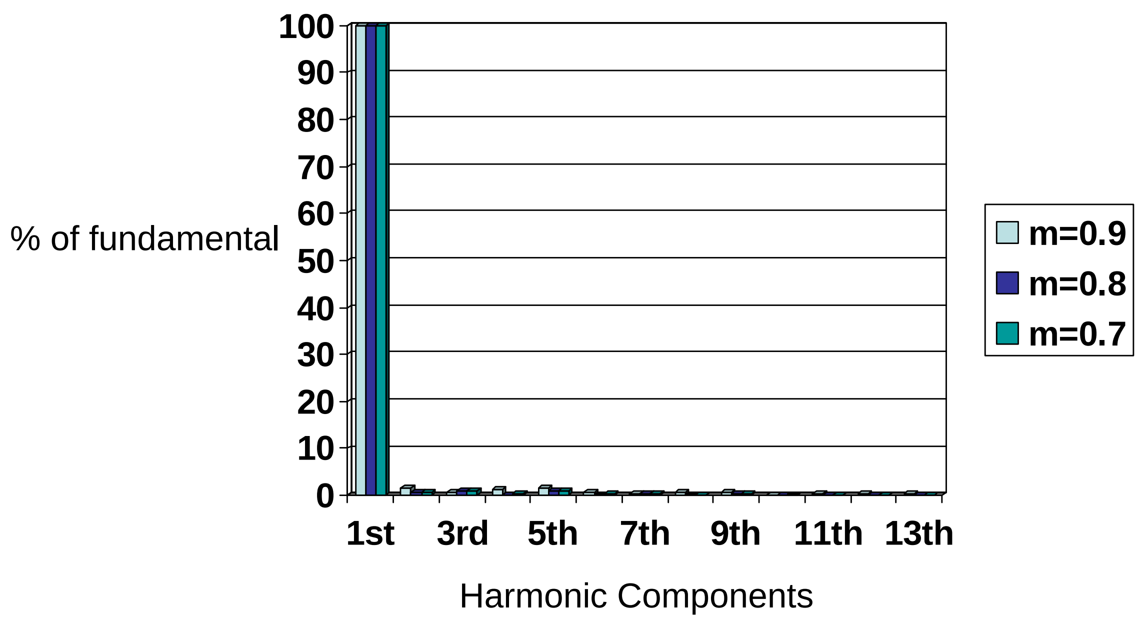


Figure (7.26): % Fundamental Vs Harmonic component for different ‘m’.

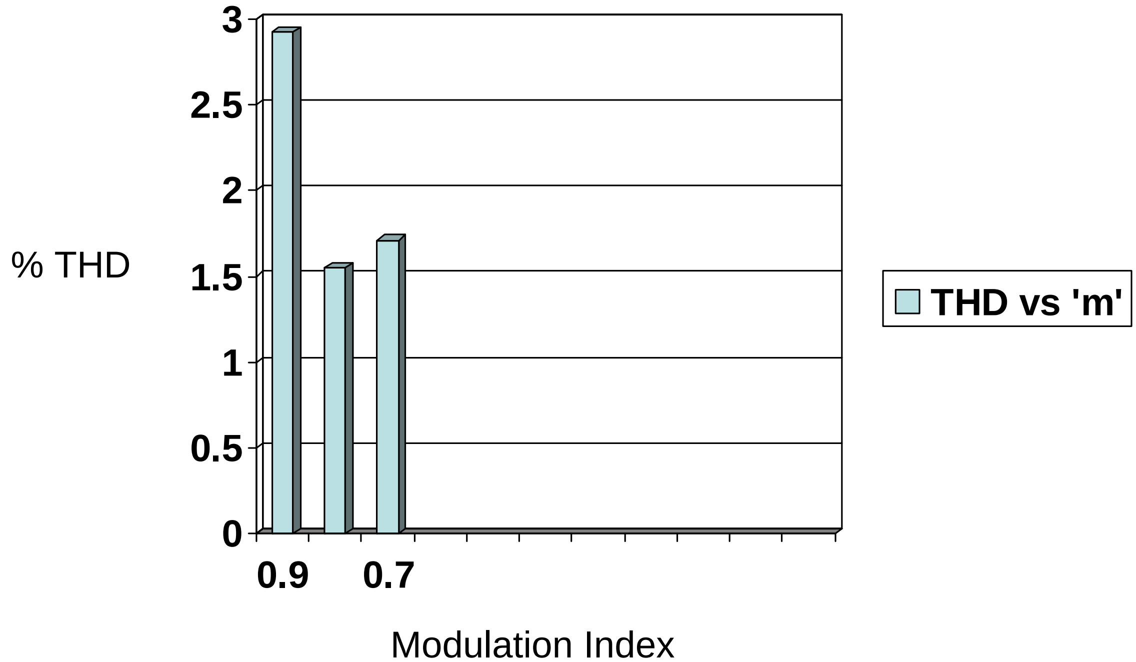


Figure (7.27): % THD Vs Modulation Index ‘m’

Experimental observations

The Proto type Inverter was tested with resistive loads. The DC input is varied. The output voltage, efficiency and amount of distortion are measured for different input voltage with 10 ohm resistive load.

Table: 8

Sl. No.	V_{dc} in volts	I_{dc} in amps	V_{out} in volts	I_o in amps	P_{in} in watts	P_o in watts	% Efficiency
1	40	1.74	23	2.3	69.6	52.9	76
2	38	1.7	21.5	2.2	64.6	47.3	73.21
3	35	1.5	20.1	2	52.5	40.2	76.51
4	30	1.3	17	1.7	39.0	28.9	74.1
5	25	1.1	14	1.4	27.5	19.6	71.2
6	20	0.9	11.5	1.15	18	13.23	73.4

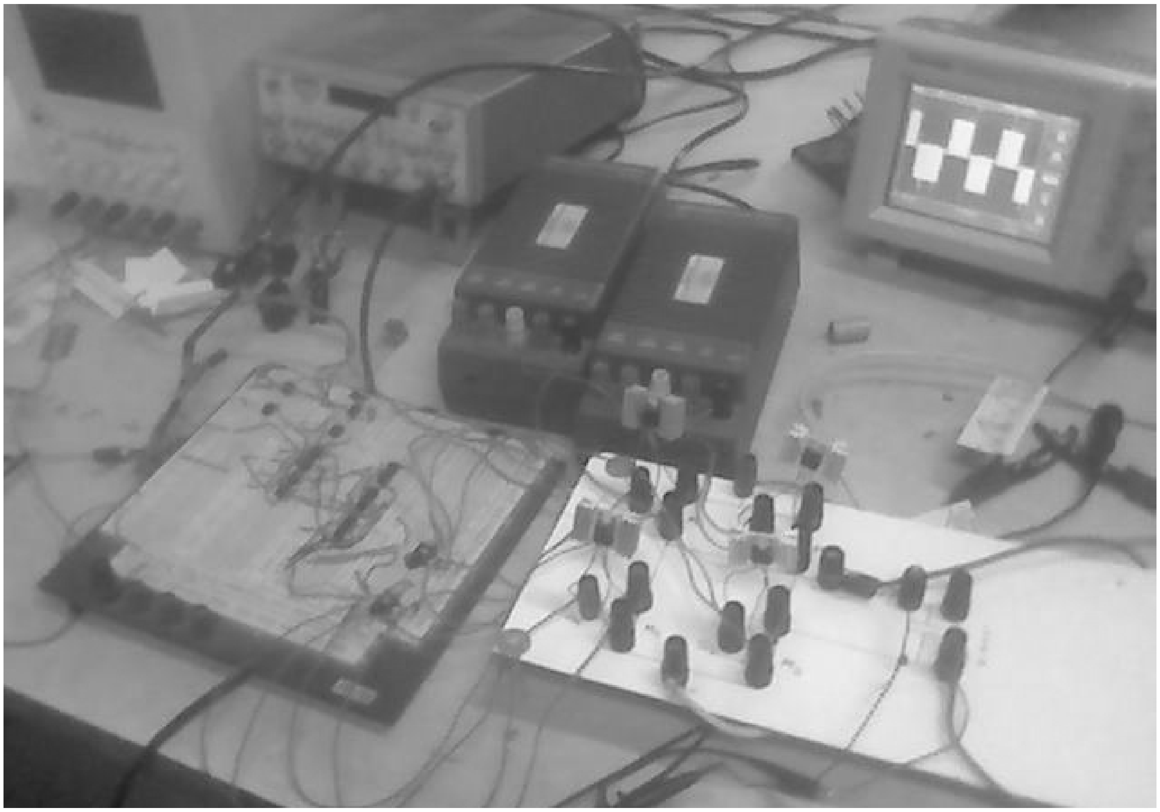


Figure (7.28): Experimental setup for prototype SHSPWM Inverter

CHAPTER: 8

Conclusion

In this dissertation a novel Symmetrical Hybrid Sine PWM switching technique for single phase Inverters has been developed. This switching technique is simulated using P-SIM software. A laboratory prototype model of single phase bridge inverter is developed to implement the proposed SHSPWM switching technique and to validate the simulated performance of the Inverter.

The proposed inverter module using SHSPWM switching technique has the following advantages over the existing conventional inverters.

1. Most of commercial inverters available in the market are of square wave output. Resulting a higher chunk of 3^{rd} harmonic voltage in the o/p. this will result higher iron losses, larger EMI reducing the efficiency of the electrical appliances, but the sine wave inverter contains no lower order harmonic and a very little amount of higher order harmonic which proves its superiority over a square wave inverter.
2. Because of the higher switching frequency the magnetic requirement such as inductors, transformers capacitors are less. Which reduces the size of whole unit
3. The dc-dc converter (48v-400v) has high efficiency due to use of high frequency switching transformer. Efficiency of the PWM inverter is also very high making overall efficiency of the system is very compatible, in comparison to conventional square wave inverters.
4. The same technique can be used with a changed reference voltage for harmonic injection in active filter circuit.
5. Use of Symmetrical Hybrid Sine PWM technique in the Inversion stage not only reduces the switching loss but also equalizes the switching loss among all four switches.

Applications of proposed inverter with SHSPWM switching technique***:***

1. Presently this inverter is designed to operate for a solar power supply where solar energy is converted to electrical energy by help of an array of solar cells and stored in storage batteries (4x12V lead acid cells). This provides 48V dc input to the inverter.
2. It can be used to generate backup power supply from storage batteries in commercial and domestic use.
3. A little modification in the circuitry can generate variable frequency and variable voltage AC used for speed control of induction motor.
4. Opting for higher switching frequency in both inverter and dc-dc converter, they can be used in satellite and air-craft power supplies.
5. High frequencies sinusoidal AC can be generated by this method which has a large scope for industrial applications such as induction heating, fluorescent lighting, air conditioner etc.

Scope for future work:

1) Presently this inverter is designed for 1KW load. By increasing capacity of switching transformer in dc-dc converter and with higher rating MOSFETs used in inverter circuit, the rating of the device can be increased up to 2Kw. Of course a suitable cooling arrangement is necessary for the IGBTs used in DC-DC Converter.

2) The content of distortion varies with different loads which may be highly objectionable for certain sophisticated loads. Hence suitable feedback circuit may be designed to have a least and uniform distortion in the o/p for varied loads.

3) The same technique can be extended for a 3 phase sine PWM inverter. This is achieved by generating three set of SPWM gating signals by comparing 3 phase sinusoidal reference signal with high frequency triangular carrier wave.

4) In this thesis analog method of generating SPWM signal are used. However same signals can be generated digitally which will have higher control compatibility.

5) High speed microcontroller and microprocessor can be used for generation of PWM signals which are more flexible and have a stable source of modulation, free from problems of drift.

6) With suitable control technique this inverter module can be used to be part of a grid connected DG system.

DC-AC PWM inverter has good potential as alternative energy source from the solar photovoltaic cells. They are useful in remote villages, forest, and hilly areas etc. world over conventional energy sources are getting replaced by non-conventional solar energy which is available in abundance and at no cost. Thus inverter holds good promise in future energy source.

The technique of PWM inversion used for VSI and CSI can be extended for series and shunt compensation in transmission (FACT) and distribution system. Of course suitable control technique with feedback is necessary for this.

References

[1]. "*International Energy Outlook 2005"*, [Online] Available: http://www.eia.doe.gov/oiaf/ieo/electricity.html.

[2]. B. K. Bose, "*Energy, environment, and advances in power electronics*," IEEE Trans. Power Electronics, vol. 15, pp. 688–701, July 2000.

[3]. Dale, L.; "*Distributed generation and transmission*", Power Engineering Society Winter Meeting, 2002. IEEE Volume 1, 27-31 Jan. 2002 Page(s):132 - 134 vol.1

[4]. "MPPT of photovoltaic systems using extremum-seeking control" Leyva, R.; Alonso, C.; Queinnec, I.; Cid-Pastor, A.; Lagrange, D.; Martinez-Salamero, L.; Aerospace and Electronic Systems, IEEE Transactions on Volume 42, Issue 1, Jan. 2006 Page(s):249 – 258.

[5]. T. Shimizu, M. Hirakata, T. Kamezawa, H. Watanabe, "Generation control circuit for photovoltaic modules", IEEE trans. on power electronics, vol. 16, no. 3, pp. 293-300, May 2001.

[6]. M. Calais, V. G. Agelidis, "Multilevel converters for single-phase grid connected photovoltaic systems – an overview", IEEE proc. Of ISIE'98, vol. 1, pp. 224-229, July 1998, South Africa

[7]. M. Meinhardt, T. O'Donnell, H. Schneider, J. Flannery, C. O. Mathuna, P. Zacharias, T. Krieger, "Miniaturised "low profile" module integrated converter for photovoltaic applications with integrated magnetic components", IEEE proc. of APEC'99, vol. 1, pp. 305-311, March 1999, USA.

[8]. M. Wuest, P. Toggweiler, J. Riatsch, "Single cell converter system (SCCS)", IEEE proc. of 1st WCPEC, vol. 1, pp. 813-815, December 1994, USA.

[9]. T. Boutot and L. Chang, "Development of a single-phase inverter for small wind turbines," in Proc. IEEE Electrical and Computer Engineering Canadien Conf. (CCECE'98), Waterloo, ON, Canada, May 24–28, 1998, pp. 305–308

[10]. R. O. Cáceres and I. Barbi, "A boost dc-ac converter: analysis, design, and experimentation," IEEE Trans. Power Electron., vol. 14, pp. 134–141, Jan. 1999.

[11]. N. Vázquez, J. Almazan, J. Álvarez, C. Aguilar, and J. Arau, "Analysis and experimental study of the buck, boost and buck-boost inverters," in Proc. IEEE PESC'99, Charleston, SC, June 27–July 1 1999, pp. 801–806

[12]. N. Kasa, T. Iida, and H. Iwamoto, "An inverter using buck-boost type chopper circuits for popular small-scale photovoltaic power system," in *Proc. IEEE IECON'99*, San Jose, CA, Nov./Dec. 1999, pp. 185–190.

[13]. M. Nagao and K. Harada, "Power flow of photovoltaic system using buck-boost PWM power inverter," in *Proc. IEEE PEDS'97*, Singapore, May 26–29, 1997, pp. 144–149.

[14]. M. Kusakawa, H. Nagayoshi, K. Kamisako, and K. Kurokawa, "Further improvement of a transformerless, voltage-boosting inverter for ac modules," *Solar Energy Mater. Solar Cells*, vol. 67, pp. 379–387, Mar. 2001.

[15]. J. M. A. Myrzik, "Novel inverter topologies for single-phase stand-alone or grid-connected photovoltaic systems," in *Proc. IEEE PEDS'01*, Oct. 22–25, 2001, pp. 103–108.

[16]. A. Beristáin, J. Bordonau, A. Gilabert, and G. Velasco, "Synthesis and modulation of a single phase dc/ac converter with high frequency isolation in photovoltaic energy applications," in *Proc. IEEE PESC'03*, Acapulco, México, June 15–19, 2003, pp. 1191–1196.

[17]. R.Guruna!han and A.K.S Bhat, "Zero Voltage Switching DC Link Single-Phase Pulse Width Modulated Voltage *Source* Inverter," IEEE Applied Power Electronics Conference. 2002, pp.519-524.

[18]. M.D. Bellar. *T.S* Wu, A Tchamdjou, J. Mahdavi, and M. Ehsani. "A Review of Soft switched DC-AC Converters", IEEE Trans. On Industry Applications, Vol. 34, No. 4, pp. 847-860, JulyIAugust 1998

[19]. R.-S. Lai and K. D. T. Ngo, *"A PWM method for reduction of switching loss in a Full-bridge inverter,"* IEEE Trans. Power Electronics., vol. 10, pp. 326-332, May 1995

[20]. Tsu-Hua Ai, Jiann-Fuh Chen , Tsorng-Juu Liang;*"A Random Switching Method for HPWM Full-Bridge Inverter"*; IEEE transactions on industrial electronics, vol. 49, no. 3, june 2002; pp.595-597.

[21]. David Leggate, and Russel J. Kerkman, "Pulse-Based Dead-Time Compensator for PWM Voltage Inverters" IEEE transactions on industrial electronics, vol. 44, no. 2, april 1997, PP 191 197.

[22]. George C.Chryssis, “High-Frequency Switching Power Supplies Theory and Design”, McGraw Hill International Edition

[23]. [23] M.H Rashid, Power Electronics: circuits, devices, and Applications, Pearson Education, 2004, pp. 248-264.

[24]. N. Mohan, T. M. Undeland, and W. P. Robbins, “*Power Electronics; Converter, Applications and Design”* John Wiley and Sons, 2003, pp. 211–218.

[25]. “Photovoltaic Fundamentals” [online] available at www.fsec.ucf.edu/pvt/pvbasics

[26]. “Photovoltaic: Basic Design Principles and Components” [online] available at “www.toolbase.org/docs/MainNav/Energy/3209_pvbasics”

[27]. Maycock, P.D.; “International photovoltaic markets, developments and trends forecast to 2010” ; Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth ; IEEE Photovoltaic Specialists Conference - 1994, 1994 IEEE First World Conference on; Volume 1, 5-9 Dec. 1994 Page(s):694 - 699 vol.1

Publication work related to this thesis

[1]. Ramaprasad Panda and R. K. Tripathi, **“*Development of a Simple and Efficient Hybrid Sine PWM Inverter for PV Power Cells*”** in proceeding of All India seminar in Advances in Product Development 2006”, 17-18 feb. 06, jointly organized by Motilal Nehru national institute of technology (MNNIT), Allahabad and the Institution Of Engineers (India)

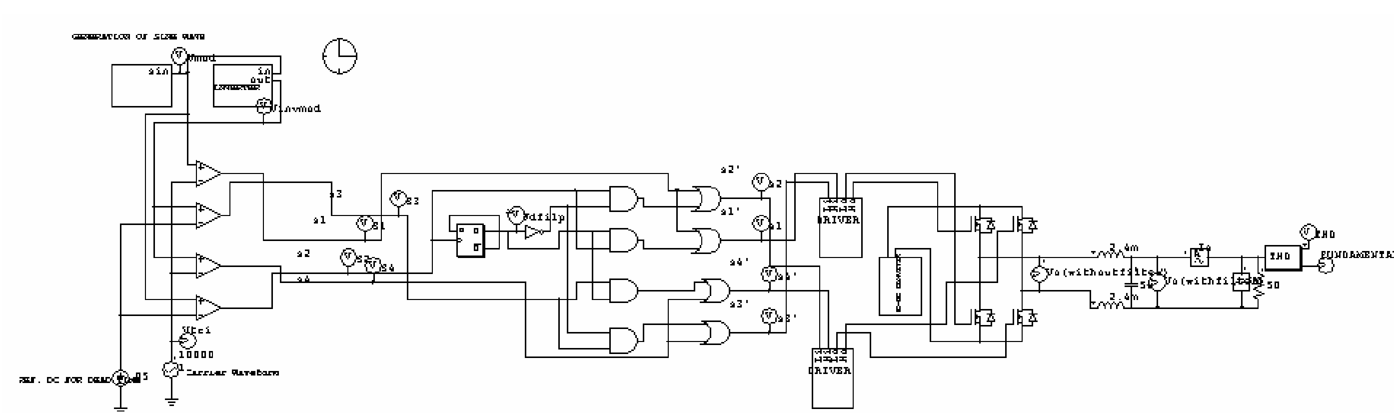
[2]. Ramaprasad Panda and R. K. Tripathi, ***“A Symmetrical Hybrid Sine PWM Switching Technique for Full Bridge Inverters”*** submitted for publication in proceeding of India International conference on Power Electronics, 19-21, Dec. 06, Chennai.

Appendix

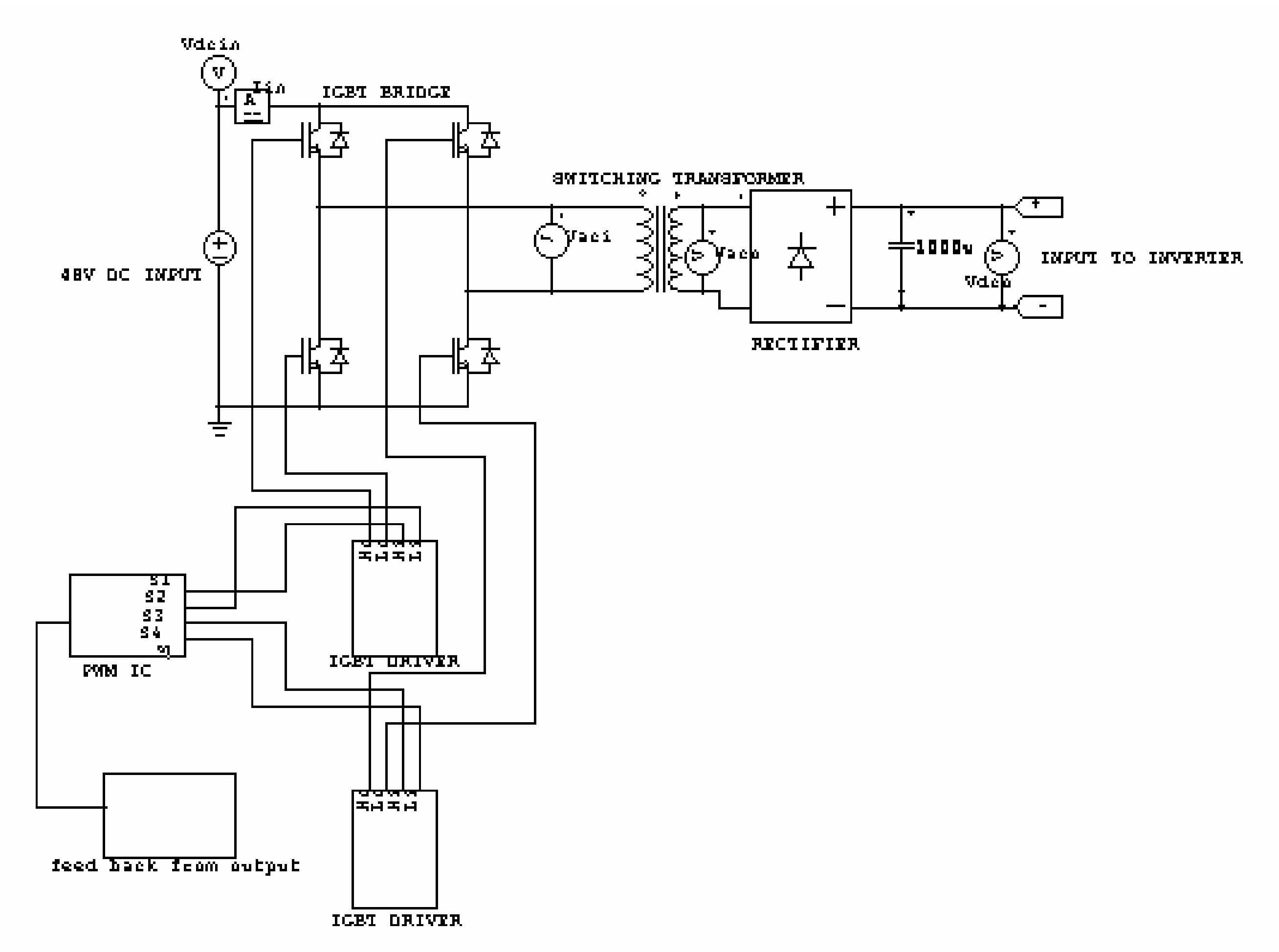
1. List of Components Used

Sl. No.	Name of Components	Part No.	Important Specifications	Quantity
1	Op-Amps	LM 741	1.7mA, 10-44 Volts, Offset: 5 Volts, Gain bandwidth= 1 MHz	2
2	Op-Amps	LM 311	5-15 Volts, I/P current = 150nA, offset current = 20nA	4
3	Zener Diode	1N 751A	5.1 Volts, 20mA	4
4	D- flip-flop	MM74HT74	Supply Voltage (VCC) 4.5-5.5Volts Dual flip-flop	1
5	AND gate	SN74LS08N	quad 2 input AND gate	1
6	OR gate	74LS32PC	quad 2 input OR gate	1
7	NOT gate	HD74LS04P	hex inverter	1
8	MOS Driver	IR 2110	VOFFSET (IR2110) = 500V max. I_O (+/-) = 2A / 2A,V_{OUT} = 10 - 20V	2
9	MOSFET	IRF 540	28A, 100V, 0.077 Ohm, N-Channel Power MOSFETs	4
10	Diode	1N4003	200V,1Amps	20
11	Torroidal core	-		1
12	Non polarized capacitor	-	1 micro farad, 400V	6
13	Load	-	10 ohms, 500 Watts,	1
14	Transformer	-	230:12 V, 500 mA, 50Hz	4
15	Capacitor	-	2200 µf, 50V, Electrolytic	4
16	Capacitor	-	220µf, 50V, Electrolytic	4
17	Regulating IC	IC 7812	12V, 200mA	4

2. Simulation Circuit for Inverter



4. Simulation Circuit for DC-DC Converter



5. Data sheet of

(i) IC SG 3526
(ii) IC XR 2206
(iii) IC IXDD414YI
(iv) IC IR 2110
(v) DIODE DSEP 2x 61-03A
(vi) IGBT IXGR 60N60C2
(vii) POWER MOSFET IXFE 36N100