“A Novel Method of Inverter Design in Grid Connected Photovoltaic System”

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In

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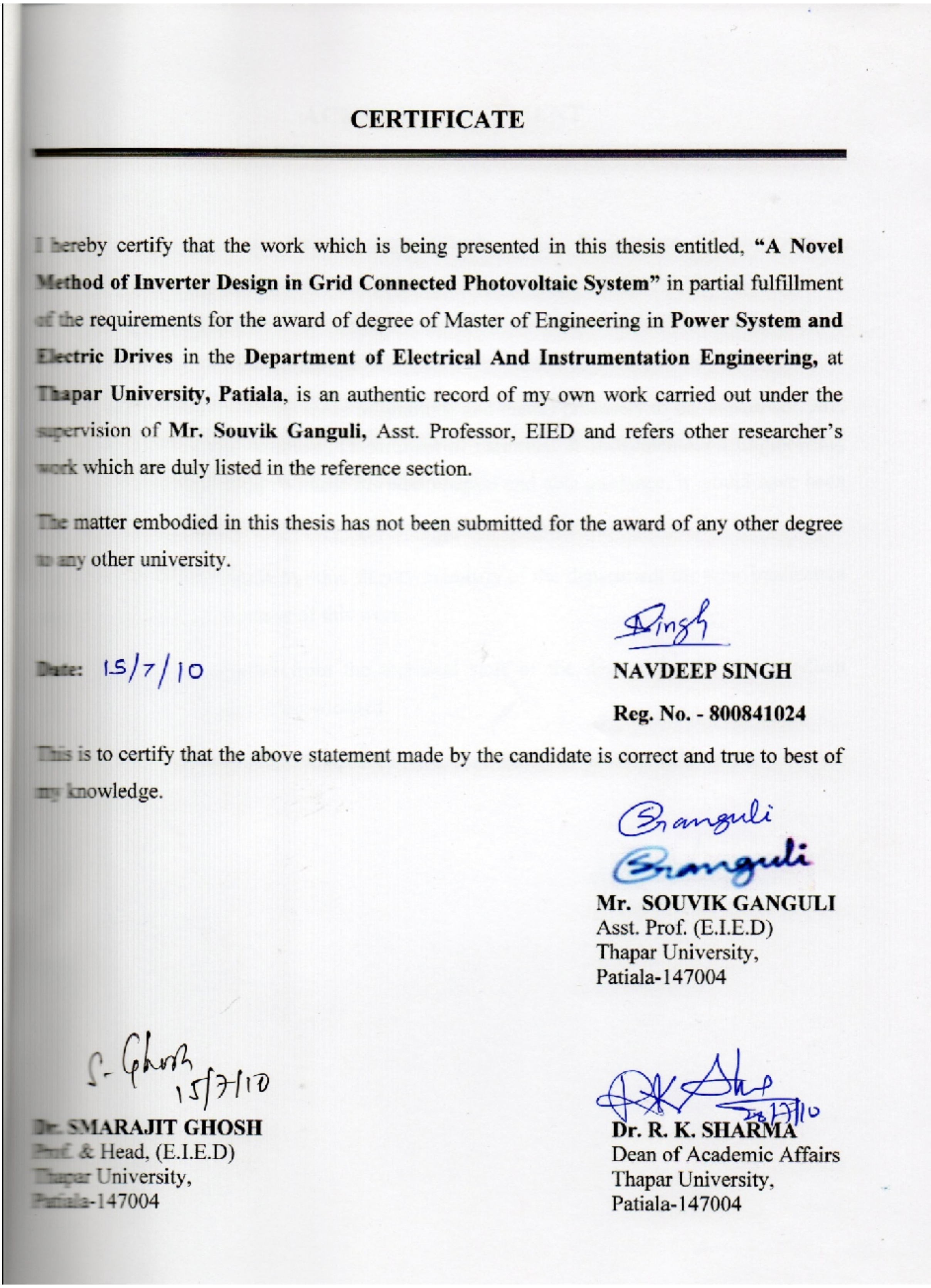

CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled, **"A Novel Method of Inverter Design in Grid Connected Photovoltaic System"** in partial fulfillment of the requirements for the award of degree of Master of Engineering in **Power System and Electric Drives** in the **Department of Electrical And Instrumentation Engineering,** at **Thapar University, Patiala**, is an authentic record of my own work carried out under the supervision of **Mr. Souvik Ganguli,** Asst. Professor, EIED and refers other researcher's work which are duly listed in the reference section.

The matter embodied in this thesis has not been submitted for the award of any other degree to any other university.

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This is to certify that the above statement made by the candidate is correct and true to best of my knowledge.

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ABSTRACT

World energy consumption and the resulting CO2 emissions are increasing substantially and this increase puts in danger the ecological stability of our Earth. Growing scarcity and rising prices of fossil fuels may lead to economical and instability in the future. These problems can be solved by the use of renewable energy resources. The renewable energy resources are sufficient enough to meet the world energy requirement. Most of the countries have recognized the new energy policy to encourage the investment photovoltaic energy system which is one of the biggest renewable energy resources. In this thesis the basic theory of grid connected photovoltaic systems is explained, giving an introduction to the different aspects of inverter designs. Starting with a look at the standards concerning grid connection of distributed resources, and working its way through how the photovoltaic cells work. Some different inverter topologies suitable for use with photovoltaic are found, and based on these topologies; solutions for the control of inverters have been examined.

The inverter is one of the power electronics systems that commonly used in order to convert the alternating current (AC) to direct current (DC). It can be a single phase or three phase systems. These controls involve methods for utilizing the maximum power from solar panels, methods for synchronizing with the grid and methods for current and voltage control.

Based on power system and power electronic knowledge this thesis presents three-phase voltage source inverter with Space Vector Modulation (SVM) as switching pattern by using MATLAB/Simulink. Space vector PWM (SVPWM) is used because of their easier digital realization and better dc bus utilization. For converter's gating signals generation, the space-vector pulse width modulation (SVPWM) strategy reduces the switching losses by limiting the switching to the two thirds of the pulse duty cycle. Space Vector Modulation became a standard for the switching power converters and important research effort has been dedicated to this topic. The model of a three-phase a voltage source inverter is discussed based on space vector theory. The simulation model is developed using the most commonly used MATLAB/SIMULINK environment.

The reason for choice of MATLAB/SIMULINK as a development tool is because it is the most important and widely used simulation software and is an integral part of taught programmes in most of the universities in electrical/electronic/computer engineering courses.

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ABBREVIATIONS

PV	Photovoltaic
D.C	Direct Current
A.C	Alternating Current
W	Watt
MPPT	Maximum Power Point Tracker
HBDC	Half-Bridge Diode Clamped Three-Level Inverter
SLSC	Full-Bridge Single Leg Switch Clamped Inverter
SLDC	Full-Bridge Single Leg Diode Clamped Inverter (SLDC)
CC	Cascaded
FC	Flying Capacitor
UPS	Uninterruptible Power Supply
CCVSI	Current Controlled Voltage Source Inverter
VCVSI	Voltage Controlled Voltage Source Inverter
ADRC	Auto-Disturbance Rejection Controller
PWM	Pulse-Width Modulation
PCS	Power Conditioning System
CSI	Current Source Inverter
VSI	Voltage Source Inverter
OCC	One Cycle Control
SVPWM	Space Vector Pulse Width Modulation

Chapter- 01

INTRODUCTION

1.1 The Need of Photovoltaic

The energy sources are “the fossil fuels and nuclear fission” need for electric power. Burning oil, coal and natural gas (called “fossil fuels” because they have been formed by the decayed remains of prehistoric plants and animals) pumps nitrogen oxide, sulphur dioxide, and mercury and other toxic metals into our atmosphere, directly causing increasing incidents of lung disease, polluting soils and waters, damaging crops.

Nuclear fission produces radioactive waste, material that will remain deadly for thousands of years. The apparent costs of oil, gas, coal and nuclear fission do not take into account the hidden health, environmental and economic costs to us all. Solar radiation provides a huge amount of energy to the earth. Solar energy is considered to be one of the most useful natural energy sources because it is free, abundant, pollution-free, and most widely distributed and photovoltaic (PV) grid-connected generation system is the trend of solar energy application.

The total amount of energy, which is irradiated from the sun to the earth's surface, equals approximately 10,000 times the annual global energy consumption. The greater available solar resources, such as greater the electricity generates. In order to seek new energy to replace the traditional fossil energy, alternative sources such as wind and solar energy are becoming more and more attractive.

1.2 PHOTOVOLTAICS: THE BASICS

1.2.1 WHAT ARE PHOTOVOLTAIC’S?

Electricity can be produced from sunlight through a process called photovoltaic (PV). "Photo" refers to light and "voltaic" to voltage. Because the source of light is usually the sun, they are called solar cells. Photovoltaic (PV) or solar cells are often refers to, are semiconductor devices that convert sunlight into direct-current (DC) electricity.

A silicon PV cell is a thin wafer consisting of a very thin layer of phosphorous 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 (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 cell is connected to an electrical load. Photovoltaic offer the ability to generate electricity in a clean, quiet and reliable way. Therefore, the photovoltaic process is “producing electricity directly from sunlight.” Photovoltaic are often referred to as PV.

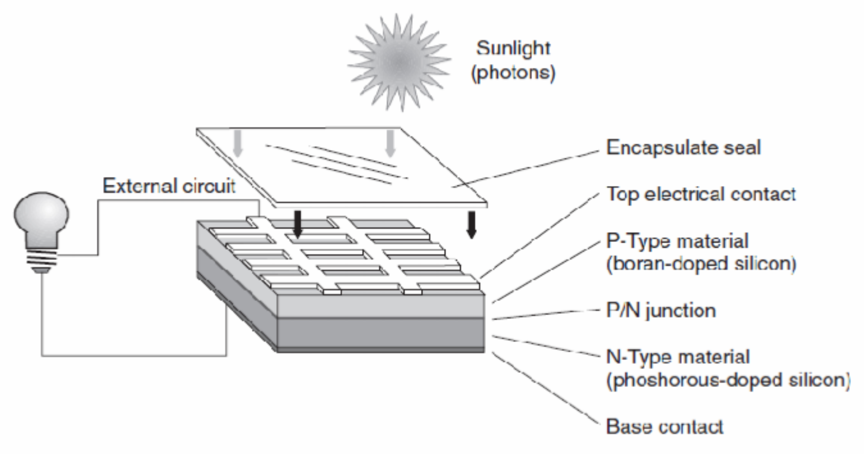


Figure 1.1: Basic solar cell

1.2.2 HOW IT WORKS?

PV cells convert sunlight directly into electricity without creating any air or water pollution. PV cells are made of at least two layers of semiconductor material. One layer has a positive charge, the other negative. When light enters the cell, some of the photons from the light are absorbed by the semiconductor atoms, freeing electrons from the cell’s negative layer to flow through an external circuit and back into the positive layer. This flow of electrons produces electric current. To increase their utility, dozens of individual PV cells are interconnected together in a sealed, weatherproof package called a module. When two modules are wired together in series, their voltage is doubled while the current stays constant. When two modules are wired in parallel, their current is doubled while the voltage stays constant.

To achieve the desired voltage and current, modules are wired in series and parallel into what is called a PV array. To be able to use the generated electricity, more components need to be added to the system.

PV systems for “**stand-alone applications**” (also called off-grid applications) may comprise also a control, storage (e.g. battery), cables and a load (e.g. lights, radio, and television).

PV systems for “**grid-connected applications**” need an inverter to convert the direct current (D.C.), generated by the PV-modules, into alternating current (A.C.).

Stand-alone applications relate mainly to rural areas of developing countries and the majority of grid-connected applications relate to industrialized countries. The electrical power that can be extracted from a photovoltaic cell is proportional to its area and to the intensity of the sunlight that hits the area, and is measured in watt (W).

1.2.3 GRID CONNECTED PV POWER SYSTEMS

When using grid-connected systems solar photovoltaic electricity is fed into the grid. As the electricity generated by a PV module is in the form of direct current (D.C.) the electricity needs to be converted to alternating current (A.C.) for which an inverter is required.

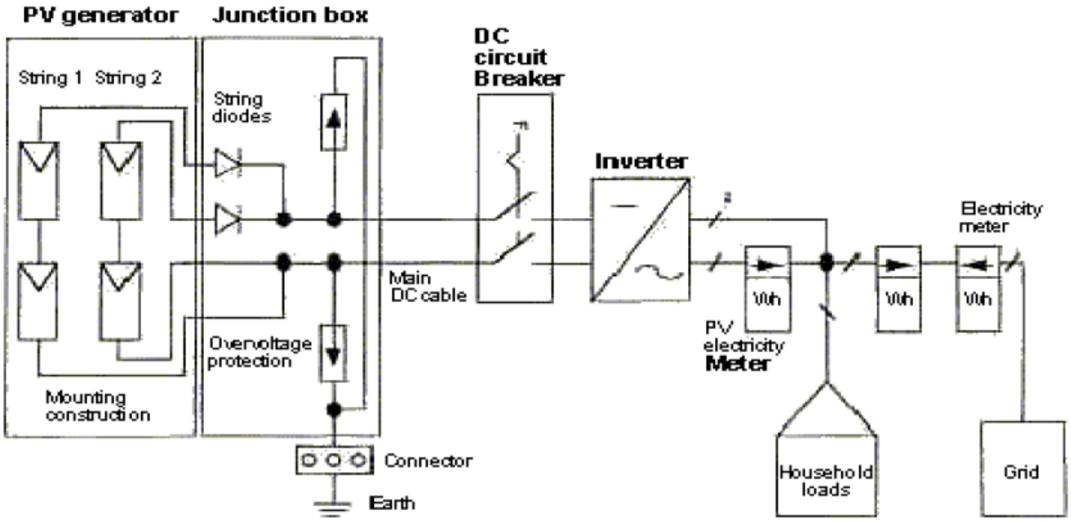


Figure 1.2: Grid-connected PV power systems

Energy surplus will be fed into the grid, while in times of shortage (e.g. at night) energy will be consumed from the grid. The other option is utility scale, central station PV fields, managed by the utilities in the same way as other electric power plants.

All D.C output of the PV field; which is generally of megawatt range, is converted to A.C and then fed into the central utility grid after which it is distributed to the customers. In a grid-connected power system the grid acts like a battery with an unlimited storage capacity.

Therefore the total efficiency of a grid-connected PV system will be better than the efficiency of a stand-alone system: as there is virtually no limit to the storage capacity, the generated electricity can always be stored, whereas in stand-alone applications the batteries of the PV system will be sometimes fully loaded, and therefore the generated electricity needs to be "thrown away".

PV system applications basically fall into two categories:

- Stand-alone applications: systems operating independently of the grid network.
- Grid-connected applications: systems are tied into the grid network.

Stand-alone applications relate mainly to rural areas of developing countries and the majority of grid-connected applications relate to industrialized countries. PV systems for stand-alone applications (also called off-grid applications) may comprise also a control, storage (e.g. battery), cables and a load (e.g. lights, radio, television). PV systems for grid-connected applications need an inverter to convert the direct current (D.C), generated by the PV-module, into alternating current (A.C).

1.2.4 USE OF INVERTER

The electricity generated by a PV module is in the form of direct current (D.C). Transformation of direct current to alternating current (A.C) required by many common appliances and for grid-connection is achieved with an inverter.

The efficiency of inverters is generally greater than 90%. Inverters connected directly to the module (as opposed to through a battery) incorporate a Maximum Power Point Tracker (MPPT), which continuously adjusts the load impedance such that the inverter is always extracting the maximum power from the system.

Inverters fall into two-main categories:

- Line-commutated
- Self-commutated

In line-commutated inverters thyristors as switching elements are used. Line-commutated inverters are not suitable for use in stand-alone systems because AC voltage is required to turn off thyristors.

In self-commutated inverters, these can be operates without AC grid voltage. In these inverters IGBT, MOSFET or GTO (Gate Turn Off) thyristors are used. According to the inverter operation, voltage and current control scheme are distinguished. Because of some advantages in grid-connected inverters in most cases current control scheme is applied.

The Advantages are:

- Higher power factor.
- Better transient current suppression.
- Short circuit current is limited to rated AC current.

Utilities require that inverters connected to the grid must contain suitable control and protection to ensure that systems are installed safely and do not adversely affect the power quality.

1.3 INVERTER TOPOLOGIES

An inverter has to fulfill three functions in order to feed energy from a PV array into the utility grid:

- To shape the current into a sinusoidal waveform;
- To invert the current into an AC current, and
- If the PV array voltage is lower than the grid voltage, the PV array voltage has to be boosted with a further element.

The way these three functions are sequenced within an inverter design determines the choice of semiconductors and passive components and consequently their losses, sizes and prices. It introduces a comparative study for topologies in photovoltaic energy conversion systems.

In special, a study of the methodology is used to compare different topologies for grid connected photovoltaic systems in such a way that can be chosen the option of best efficiency.

Several grid connected photovoltaic system topologies are used in existing installations. It presents a different designs and control strategy of the Inverter for grid connected PV systems, in order to achieve high power density, high efficiency, and high power factor regulation.

1.4 ISSUES REGARDING GRID CONNECTED PV SYSTEM

- Long life time (20 years and longer)
- High efficiency
- Good environmental conditions (availability of solar radiation)
- Power quality
- Electromagnetic compatibility
- Low acoustic noise
- Safety and protection
- Reliability
- Low cost
- Low maintenance

1.5 APPLICATIONS OF PV SYSTEM

- **Refrigeration systems:** particularly to preserve vaccines, blood and other consumables vital to healthcare programs.
- **Lighting:** for homes are community buildings such as schools and health centers to enable education and income generation activities to continue after dark.
- **Battery charging stations:** to recharge batteries, which are used to power appliances ranging from torches and radios to televisions and lights.
- **Solar home systems:** to provide power for domestic lighting and other DC appliances such as TVs, radios, sewing machines, etc.

Chapter-02

LITERATURE REVIEW

2.1 INTRODUCTION

The grid-connected PV system consists of two parts: PV arrays that convert irradiation to electrical energy, and the converter that feeds the energy into the grid. The grid connected PV system requires an inverter which is needed for two reasons. First, the low DC voltage generated by the module must be amplified to the higher AC level in the grid. Second, the power delivered from the modules is very sensitive to the point of operation, and the inverter should therefore incorporate a function for tracking the Maximum Power Point (MPP). Many methods for interfacing PV system with utility grid have been reported in the literature.

In this chapter, different reviews on inverters designs such as Z-source Inverter, Fly back inverter, Boost-buck inverter, Dual Converter, Pulse Width Modulation (PWM) inverter, Transformer-less converter, H-Bridge multilevel inverter, Current Controlled Voltage Source Inverter and topologies such as Centralized Inverter topologies, String Inverter topologies, Multi-string inverter topologies, Multi-level inverter topologies and control strategies in grid connected photovoltaic systems are discussed.

2.2 Earlier Works- An Overview

Peterson K. Hinga [1] and fellows introduced that a novel multi-step PWM Inverter for a solar power generation system. The new type of PWM inverter presented has many features such as the good output waveform, small size of filter, low switching losses, low acoustic noise. The circuit configuration, control method and the characteristics of the system has described in their paper and also investigate the relation between the inverter and the solar cell characteristics.

Martina Calais, Vassilios G. Agelidis [2] provided an overview on different multilevel topologies and investigated their suitability for single-phase grid connected photovoltaic systems. The need of several sources on the DC side of the converter makes multilevel technology attractive for photovoltaic applications. They discussed and compared the Half Bridge Diode Clamped, Full

Bridge Single Leg Clamped, Cascaded (CC), Step, Magnetic Coupled and Flying Capacitor (FC) multilevel converter topologies.

Chem Nayar [3] and fellows described a novel power converter capable of extracting maximum power from solar photovoltaic panels. This proposed dual converter (combination of VCVSI and CCVSI) has able to provide uninterruptible power supply feature, load voltage stabilization, unity power factor operation, maximum power point tracking as well as reactive power support. The overall efficiency has higher than the conventional system with a dc-dc converter between the PV panels and the battery.

J.S.Siva Prasad and B.G.Femandes [4] proposed a new three phase active commutated thyristor current source inverter (CSI) topology for grid connected photovoltaic systems. The basic active commutated thyristor CSI with pulse width modulation (PWM) capability has recently implemented with a resistive load. To suppress the natural frequency of oscillations of LC filter and to ensure stability of the system, a charge controller in synchronous rotating reference frame is described. It allows easy design of PI controller gains.

Anastasios Ch. Kyritsis, Nikolaos P. Papanikolaou [5] and fellows proposed a new design and control strategy of the Fly back Inverter for decentralized grid connected PV systems. It achieves high power density, high efficiency, and high power factor regulation. The design and control strategy has investigated to the achievement of a converter with the smallest possible volume for a given power or to the maximization of the power transfer for given converter parameters. In contrast to the classic converter topologies this proposed scheme has presented a very high efficiency, due to its simplified structure.

Qingrong Zeng, Liuchen Chang [6] introduced that the Space vector pulse-width modulation is widely used in the current control of three-phase voltage-source inverters. In grid-connected distributed generation systems, SVPWM introduce the drawbacks to current controllers, such as the compromised output current due to the grid harmonic disturbance and nonlinearity of the system, the lack of inherent over-current protection etc. It gives high performance even under the influence of the grid harmonics. It also offers an improved response for over-current protection to the system.

Juan Jose Negroni, Francesc Guinjoan [7] and fellows described the analysis, modelling and design of a Buck-based inverter control for grid-connected photovoltaic (PV) systems. On one hand a linear digital voltage controller is designed from a large-signal linear sampled-data model of the system to maximize the steady state input-output energy transfer ratio. On the other hand, a sliding-mode current controller is also designed to assure a unity power factor.

Yi Huang, Miaosen Shen [8] proposed a Z-Source inverter system for a split-phase grid-connected photovoltaic system. Due to the development of solar cell technology, the price of solar modules has dropped dramatically. To lower the cost of the PCSs had been a very urgent issue of grid connected PV systems. By utilizing the Z -source inverter, the number of switching components and the total volume of the system can be minimized. All the advantages of the Z -source inverter and the six-switch split-phase inverter are inherited and integrated together to create a highly reliable PCS system with minimized volume and cost.

Yang Chen, Keyue Smedley and Jack Brouwer [9] determined that the utilisation of solar energy the utility grid infrastructure for power transmission and distribution, grid connected dc-to-ac inverters is needed for solar power generation. Thus a cost-effective MPPT method integrated within the One-Cycle Control (OCC) core has proposed. There is no power calculation in the controller; it yields a simple and cost-effective solution and reduced the circuit complexity, power losses.

Hooman Dehbonei, C.V. Nayar [10] and fellows presented a grid-connected photovoltaic system with direct coupled power quality controller. This system is based on two control loops and used a single stage CCVSI. This system has the advantage to reduce the complexity, cost and number of power conversions and high efficiency. The proposed system also improves the system utilization factor to 100%, which is generally low for PV systems (20%).

Babak Farhangi, Shahrokh Farhangi [11] presented the design procedure of the traditional double stage boost-buck inverter and single stage Z-source converter, as a single phase PV grid connected transformer-less power conditioner. The research goal in PV grid connected systems reduction of the component cost. The omission of the isolation transformer, and the usage of a single-stage Z-source inverter, helps to develop a cost-effective PV-PCU.

Pedro Gomes Barbosa, Henrique Antonio Carvalho Braga and fellows [12] presented a novel current multilevel (CML) inverter topology, named boost CML inverter, and its application on energy processing of single-phase grid-connected photovoltaic (PV) systems. The structure allows a high power factor operation of a PV system. The major appeals of using the CML technique are the balanced current sharing among semiconductor switches and the decrease of the current slope in the circuit devices, with a consequent reduction of conducted and radiated electromagnetic interference (EMI). The CML technique also allows adapting or minimizing current waveforms harmonic content.

Hirotaka Koizumi, Kosuke Kurokawa and fellows [13] developed a novel microcontroller for grid-connected photovoltaic (PV) systems. As a prototype model, a 100-W-class module-integrated converter composed of the proposed controller and a fly-back inverter had been built.

Mi dong, Lisha bai [14] and fellows proposed a new integrative scheme for the boost-buck inverter. It has controlled by two closed-loops. The proposed buck converter DC-AC stage obtains unity power factor and low harmonic distortion at the output. This controller possesses good performance of the anti-interference for internal and external perturbation. It achieves better robustness and adaptability. The boost-buck inverter for PV grid connected systems gathers all the advantages of a string inverter topology and a transformer less converters.

J. B. Wang, Joe Chen, Ronald Li [15] presented a grid connected photovoltaic (PV) system, which consists of PV modules, a boost converter with maximum power point tracking (MPPT) controller and a current controlled full bridge inverter with L-C-L filter. They used a simple PIC16F877 microprocessor to implement the InCond MPPT controller by adjusted the duty ratio of the boost converter. Then a DC bus voltage controller is designed to regulate the DC bus voltage within the specified voltage, and generated the injected current command in proportion to the sunlight irradiation. Finally, a 150W prototype grid connected PV system was built to demonstrate the performance of the proposed control schemes.

G. Brando, A. Dannier, R. Rizzo [16] determined the high development of grid-connected photovoltaic systems that utilize static converter which influence the efficiency of the system. They utilized a proper architecture of H-bridge multilevel converters an optimal solution for the power quality and set up a control optimized to have the energy conversion at maximum efficiency. In the proposed sensor-less control set up to deliver the maximum power to the grid in presence of variations of incident irradiation on the photovoltaic arrays.

Gabriele Grandi, Darko Ostojic, Claudio Rossi [17] presented the design and control issues associated with the development of a novel three-phase grid-connected photovoltaic generation system. The resulting conversion structure performs as a multilevel power active filter, doubling the power capability of a single VSI with given current rating. An original control method is introduced to regulate the dc-link voltages for each VSI.

T. Shanthi and N. Ammasai Gounden [18] purposed a power electronic interface using boost converter and line commutated inverter. The controller extracts maximum power from the solar array and feeds it to the single phase utility grid. This closed loop scheme employed a PI controller.

Ulrich Boeke and Heinz van der Broeck [19] proposed a transformer-less converter concept for grid connected photovoltaic systems with combination of a DC/DC converter front-end with a DC/AC inverter. This converter system has an earth-connected DC input, required from many thin-film photovoltaic modules. This architecture extends power electronic converter topologies for thin-film photovoltaic modules considering their special requirements of higher power conversion efficiencies at lower cost.

Mateus F. Schonardie and Denizar C. Martins [20] presented a three-phase grid connected photovoltaic generation system with unity power factor for any situation of solar radiation. They proposed a model of the PWM inverter and used the control strategy of dq0 transformation in which the whole system is operated. It achieves the maximum power point operation.

Wen-Jung Chiang, Hurng-Liahng Jou and Jinn-Chang Wu [21] proposed a novel maximum power point tracking (MPPT) method for the voltage-mode grid-connected inverter of photovoltaic generation system. The main feature of this method is that no current is sensed for MPPT. Therefore, it has the advantage of simplifying the control circuit in comparison with the conventional perturbation and observation methods where both current and voltage are sensed.

Praveen Jain, Alireza Bakhshai [22] and fellows introduced a new control scheme and converter topology for low to medium power PV applications. This proposed topology provides independent MPPT and power decoupling without the use of bulky electrolytic capacitors. The grid-connected output stage is a current source inverter with a modified modulation strategy to inject a low harmonic current into the grid at unity power factor.

Bing Hu, Liuchen Chang, Yaosuo Xue [23] proposed and developed an innovative single-phase, single-stage, fly-back-based, buck-boost inverter for PV systems in grid-connected applications. They focus mainly on the analysis of the working principles, computer simulation of the operation, and design consideration of the inverter for grid-connected applications.

J. Selvaraj, N.A. Rahim, C. Krismadinata [24] described a digital Proportional-Integral (PI) control method for single-phase grid-connected Photovoltaic (PV) system. The control algorithm is implemented in Digital Signal Processor (DSP) TMS320F2812. A detail analysis of system control and mathematic formation of digital PI control is presented to show that this control method provides robust current regulation and operates at near to unity power factor.

Genping Wang, Ming Li [25] proposed a new constant-frequency hysteresis current control algorithm for PV grid-connected inverter, in which the complex plane is divided into six sectors based on line voltage space vector of electric power grid, and two-phase switches are decoupled respectively in every sector to control corresponding line currents, and the hysteresis band is modified by prediction, so that the output current waveforms can be improved, and the control is more accurate.

B. Raison, D. Picault [26] and fellows presented the several grids connected photovoltaic system topologies. These topologies are used in existing installations. The growing concern for climate change has participated in the growing number of grid-connected PV systems. They discussed the Centralized Inverters, String Inverters and Multi-string Inverters topologies and their comparisons.

Longhua Zhou, Changshu Liu [27] and fellows introduced a novel Photovoltaic Grid-connected Power Conditioner system based on a hybrid multilevel inverter. It attains near sinusoidal outputs of the grid-connected photovoltaic system, improve the power quality, and decrease the energy loss. A Space Vector Pulse-width Modulation is employed in this method which solves the application shortage of hybrid PWM method.

H. Lopez, E. Rodriguez [28] and fellows determined that the Co-generation systems requires the converters able to inject current with low harmonic content, traditionally the inverters are considered. This proposed current source inverter is used instead of voltage source inverter; this type of inverters can accept a low input voltage to inject current to the ac mains.

Hui Zhang, Shaohua Ruan [29] and fellows presented an effective control strategy for reliable photovoltaic grid-connected systems are needed to efficiently use solar energy, an abundant and clean renewable energy source. A space vector pulse width modulation is applied in the current control of three-phase voltage source inverters. The control strategy combines a constant voltage tracking method for the variable photovoltaic power with SVPWM based proportional-integral (PI) current controller in a single stage three-phase PV grid-connected system. It is very simple and robust to implement.

S. J. Chiang, M. J. Lee [30] and fellows proposed a PV inverter system formed by a DC-DC converter and a full-bridge DC-AC converter. The combination of boost and fly-back topologies used in the DC-DC converter. The low-frequency switching techniques are used to control the full-bridge DC-AC converter. The overall efficiency is high due to the low losses of both stages.

2.3 CONCLUSION

From the various earlier works that in grid connected PV system various types of inverters topologies, control strategies and different types of inverter designs are used. Their applications, performances and their experimental results are also discussed as earlier work review. Now, a novel SVPWM inverter design in grid connected PV system is tried. For which the analysis and simulation results are done in the next chapter. SVPWM provides excellent output performance, optimized efficiency, and high reliability compared to similar inverters with conventional Pulse Width Modulation.

2.4 SCOPE OF THE THESIS

The formulation of this thesis consisted of several main stages. These are represented in the figure 2.1. Initially, a review work of theoretical groundwork on SVPWM inverter was carried out. As SVPWM inverter in PV system is now hot research, many books do not mention this and much of the effort was spent reading and extracting information from relevant journal articles. Following that, a literature review of the PV Inverter topologies has been done. The literature review was beneficial in understanding the operation of SVPWM inverter. After all of the components in MATLAB/SIMULINK had been selected, a SIMULINK model of the SVPWM inverter was developed so as to enable the designer to have a better visualization of the whole system structure and the components to be used. Then, the SVPWM inverter design model was implemented into MATLAB/SIMULATION and results were obtained. The simulation results for SVPWM inverter were analyzed.

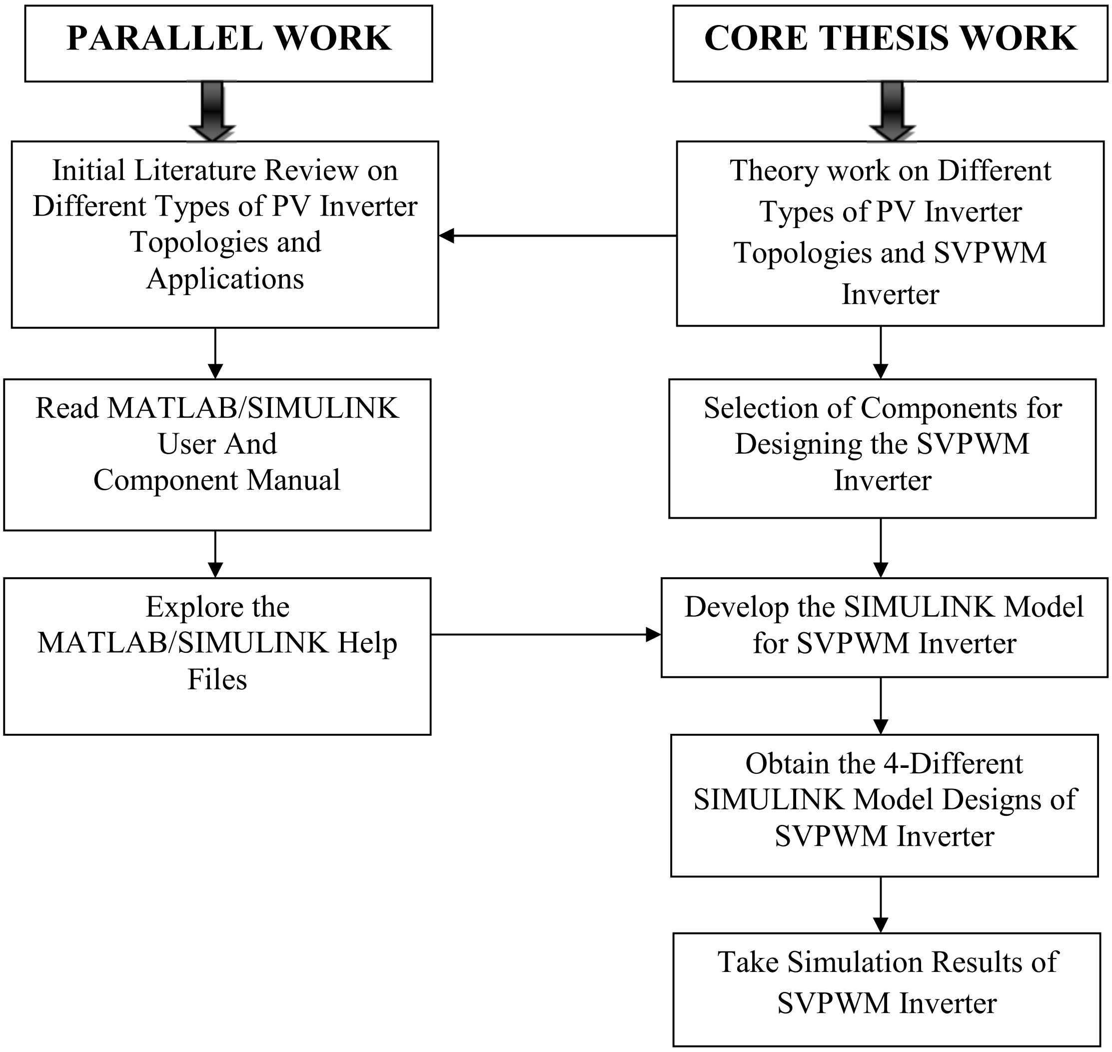


Figure 2.1: Main Stages in Thesis

2.4 OBJECTIVE OF THE THESIS

The objective of this thesis is to develop a novel SVPWM inverter for a grid connected PV system. The design has been tried out with and without transformers. Even a 3 phase RLC load is connected along with the circuit. A series and a parallel RLC load are connected to the inverter system to have a relative comparison. Simulink models are developed using MATLAB software and their waveforms are discussed. The proposed models seem satisfactory from the results obtained.

2.5 ORGANIGATION OF THE THESIS

The thesis has been organized into five chapters. Contents of each chapter are briefly described as under:

Chapter 1 contains the introduction of Photovoltaic (PV) system, use of inverter and PV inverter applications.

Chapter 2 deals with the literature review of different types of PV inverters.

Chapter 3 shows that for conversion of dc-ac in grid connected PV system, there are several types of topologies and inverter designs are used in existing installations. Their advantages and drawbacks are also highlighted.

Chapter 4 shows the performance of SVPWM Inverter. It also includes the simulation result of four different SVPWM inverter Simulink model.

Chapter 5 highlights the conclusions of the thesis and provides the future scope of the work.

Chapter: 03

INVERTER TOPOLOGIES

3.1 INTRODUCTION

Grid-connected inverters are necessary for dc–ac conversion. To avoid the distortions to the power grid, the generated currents from these inverters are required to have low harmonics and high power factor. When the output currents are in phase with the grid voltages, the maximum real output power is achieved. For conversion of dc-ac in grid connected PV system, there are several types of topologies and inverter designs are used in existing installations. There are still some subjects as yet unproven. Reliability, life span, and maintenance needs should be certified through long-term operation of a PV system. Further reductions of cost, size, and weight are required for the PV systems. The topologies of PV module and converter arrangements are described below; and their advantages and drawbacks are also highlighted in this chapter.

3.2 DIFFERENT INVERTER TOPOLOGIES

In this chapter the different types of grid connected PV inverter topologies are discussed. These topologies have their advantages and disadvantages are as follow:

3.2.1 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. 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. The most common PV system layout is the centralized inverter (or plant-oriented) topology. The simplicity of this module arrangement, which consists of series connected PV modules (also called PV strings) all connected in parallel in order to fit voltage and power constraints, as shown in Figure 3.2.1 has led this structure to be widely used in large grid connected installations[26].

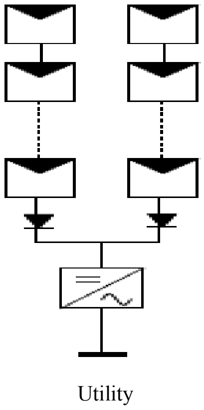


Figure 3.2.1: Centralized Inverter

Advantages

- Low specific converter cost
- Simple maintenance
- Robust
- Highly efficient

Disadvantages

- Power losses due to a centralized MPP Tracking (MPPT)
- The necessity of high voltage DC cables between the modules and the inverter.
- Power factor between 0.6 and 0.7
- Losses and security risks in high voltage DC cables
- Low upgradeability
- Very low continuity of service
- Mismatch between the modules and at last the string diodes

3.2.2 STRING INVERTERS

In more recent installations, string inverters (also called module-oriented inverters) have been preferred. String-inverters use a single string of modules, to obtain a high input voltage to the inverter. This arrangement differs from the centralized topology by replacing the PV array with a single string, as shown in Figure 3.2.2 (a). String inverter prevents mismatch losses between strings and each string operate at its maximum power point. Furthermore, string diodes are removed which reduces energy losses. The extra inverters not only add power conversion losses but also elevate the cost of the PV system. That’s why large plants usually favor centralized configurations. In terms of continuity of service, all string inverters are down simultaneously, which ensures at least a minimal photovoltaic production on the grid. String inverters are also future proof, in the sense that the capacity of a module oriented installation can be upgraded easily, if the grid connection allows additional capacity flow. This topology has aims to improve power conversion efficiency during low solar irradiance. By using dc switches which cross-connect strings together, as shown in Fig.3.2.2 (b), the strings may be combined (as in the centralized topology) in order to accept a larger solar irradiance PV production range and enhance conversion efficiency by using only one inverter [26]. The team concept may increase the overall efficiency by 4%.

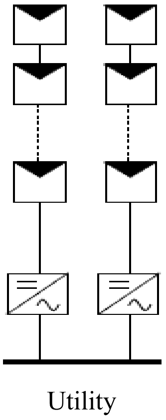


Figure 3.2.2 (a)

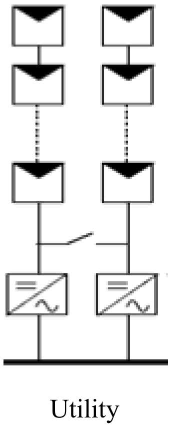


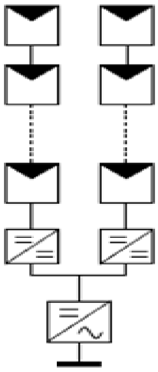
Figure 3.2.2 (b)

Advantage

- The capability of staying connected to the grid with low irradiance.
- It removes the losses due to mismatch between modules and inverter.
- Used in a higher power range, this decreases the price per watt.
- System efficiency is 1-3% higher than in systems with central inverters.

3.2.3 MULTI-STRING INVERTERS

The multi-string inverter concept, shown on Figure 3.2.3 combines the two previous topologies by introducing a dc-dc converter with MPPT control strategies for each string of the PV array. The dc-dc string converters are also used to elevate PV string voltage to a high voltage dc bus while using a MPPT strategy. The introduction of a dc bus reduces inverter functionalities, for example the MPPT is transferred to the dc-dc converters and also eases heterogeneous PV module integration. Indeed, modules used from one string to another, may differ in age, size, technology, or even nominal power values. This topology is also upgradeable to a certain extent, where at most a few strings with dc-dc converters can be added to the bus without exceeding inverter specifications [26].



Utility

Figure 3.2.3: Multi-String Inverter

Furthermore, due to the share of power conversion tasks between chopper and inverter: voltage elevation, grid current oscillation, measure and surveillance of electrical variables, price cuts can be made on converter configurations. However, continuity of service risks still remain with respect to the unique inverter connected to the grid.

3.2.4 MULTILEVEL VOLTAGE SOURCE INVERTERS

Multilevel voltage source inverters offer several advantages compared to their conventional counterparts. By synthesizing the AC output terminal voltage from several levels of voltages, staircase waveforms can be produced, which approach the sinusoidal waveform with low harmonic distortion, thus reducing filter requirements. The need of several sources on the DC side of the converter makes multilevel technology attractive for photovoltaic applications. Multilevel converter technology is based on the synthesis of the AC voltage from several different voltage levels on the DC bus. As the number of voltage levels on the DC side increases, the synthesized output waveform adds more steps, producing a staircase wave which approaches the sinusoidal wave with minimum harmonic distortion. Multilevel converter topologies are especially suitable for PV applications since due to the modular structure of PV arrays different DC voltage levels can easily be provided.

3.2.4.1 HALF-BRIDGE DIODE CLAMPED

Fig. 3.2.4.1(a) shows a half-bridge diode clamped three-level inverter (HBDC) as part of a single-phase transformer-less grid connected PV system. With simultaneously switching on the switches S1 and S2 a positive voltage can be created at the inverter output terminal. A zero output voltage is created by switching on *S2* and S3 and a negative voltage is created by switching on S3 and S4 respectively. In order to allow power transfer into the grid the DC bus voltages V_{PVAI} and V_{PVA2} have to be always higher than the grid voltage amplitude V_{grid}. Since currently available PV modules have operating voltages around 17 V a large number of modules is required resulting in a minimum system size of approximately 3 kW. An advantage of this system is that the midpoint of the PV array is grounded which eliminates capacitive earth currents and their negative influence on the electromagnetic compatibility of the circuit [2].

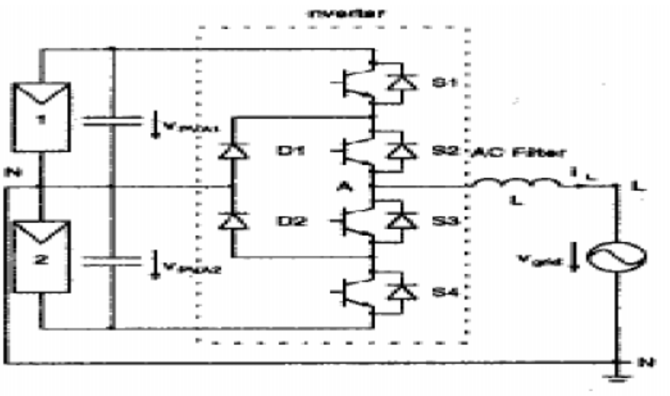


Figure 3.2.4.1(a): Half-bridge diode clamped three-level inverter (HBDC)

Drawbacks of this topology, however, are the high number of semiconductor devices required and since the loading of the outer PV sub arrays (1 and 4) is different to that of the middle PV sub arrays (2 and 3) careful sizing of each PV sub array is necessary to ensure maximum power transfer from each sub array.

3.2.4.2 FULL BRIDGE SINGLE LEG CLAMPED

A full-bridge single leg switch clamped inverter (SLSC) is described and suggested for residential PV systems. The topology (see Fig. 2.1.2(a)) comprises of a conventional full-bridge (switches S_{a1}, S_{a2}, S_{bl} and S_{b2}) where a bi-directional switch (realized with S_{a3}, S_{a4}, D_{al} and D_{a2}) is added which controls current flow to and from the midpoint of the DC bus. When applied in a transformer-less PV system the minimum system size with this topology is approximately 1.5 kW [2].

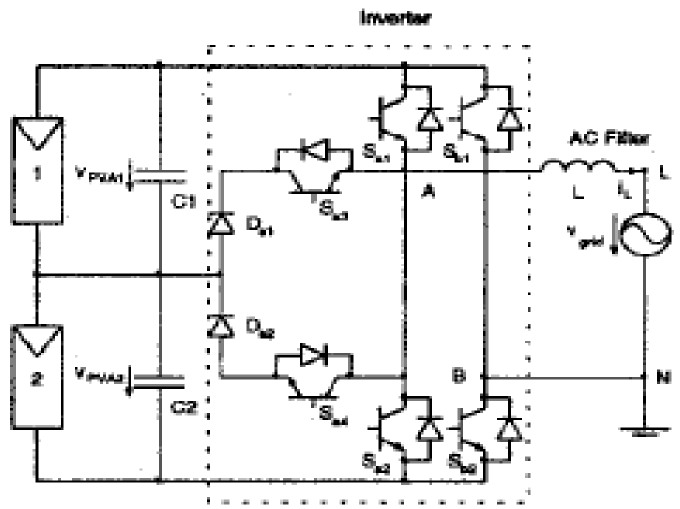


Figure 2.1.2(a): Full-bridge single leg switch clamped inverter (SLSC)

A transformer-less PV system with similar characteristics can be realized with a full-bridge single leg diode clamped inverter (SLDC) as shown in Fig. 3.1.2(b). With the single leg diode clamped configuration the devices D_{a1}, D_{a2}, S_{al}, S_{a2}, S_{a3} and S_{a4} all can be rated for half the blocking voltage of switches S_{bl} and S_{b2}, whereas with the single leg switch clamped configuration this only applies to the devices D_{al}, D_{a2}, S_{a3} and S_{a4} , not S_{al} and S_{a2}. In both systems both PV sub arrays are symmetrically loaded.

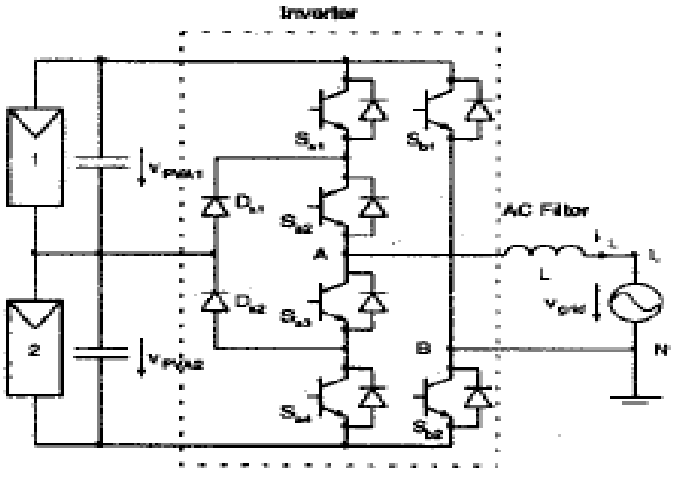


Figure 2.1.2(b): Full-bridge single leg diode clamped inverter (SLDC)

3.2.4.3 CASCADED INVERTERS

Fig. 3.2.4.3 shows a transformer-less grid connected PV system where a cascaded inverter is used for DC to AC power conversion. The topology comprises of two full-bridges with their AC outputs connected in series. Each bridge can create three different voltage levels at its AC output allowing for an overall five-level AC output voltage [2]. The advantage of this topology is the modular character. In the concept is suggested for transformer-less PV systems using more than two full-bridges connected in series on the AC side with small DC bus voltages of e.g. 40 V each.

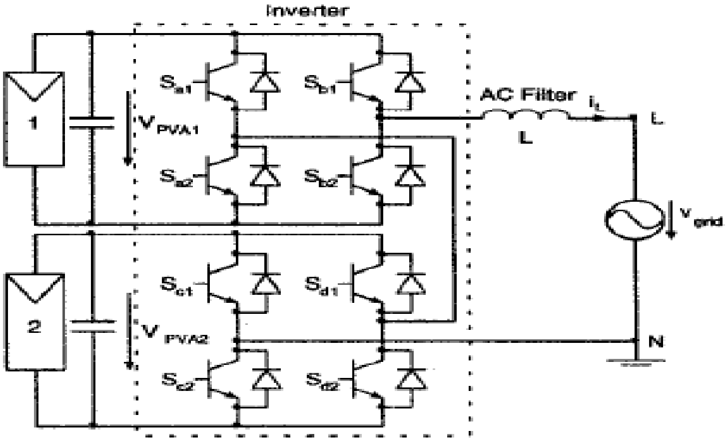


Figure 3.2.4.3: Cascade Inverter

3.2.4.4 MAGNETIC COUPLED INVERTERS

Fig. 2.1.4 shows a single-phase PV system with a magnetic coupled inverter. The inverter consists of three full-bridges each with their midpoints connected to a primary winding of a transformer. The secondary windings of the transformers are connected in series. Due to different turns ratios of each of the transformers and the ability of each full-bridge to create three different voltages across the primary winding ($+V_{PVA}$,$-V_{PVA}$ and 0) the voltage at the AC terminals can be comprised of 27 levels [2].

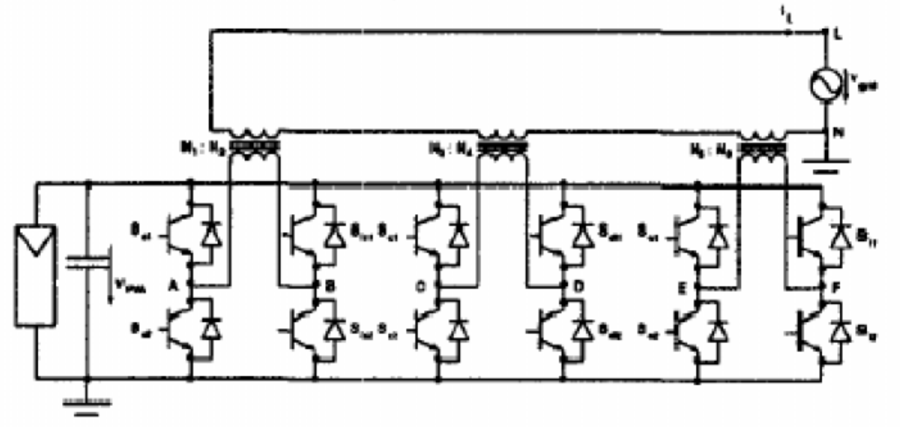


Figure 2.1.4: Magnetic Coupled Inverter

The advantage of this circuit is the relatively accurate replica of a sine wave accomplished with low switching frequencies. A major drawback of the circuit, however, is the need for three transformers.

3.2.4.5 FLYING CAPACITOR (FC)

Fig.3.2.4.5 a half-bridge three-level flying capacitor inverter is suggested for a transformer-less grid connected PV system. This topology is similar to the diode clamped topology. Important for the operation of this converter is a stable voltage ratio of $V_{PVAl}/V_{C2} = V_{PVA2}/V_{C2} = 1$. Therefore control methods are required which ensure that the average current flowing in the capacitor C2 is zero [2].

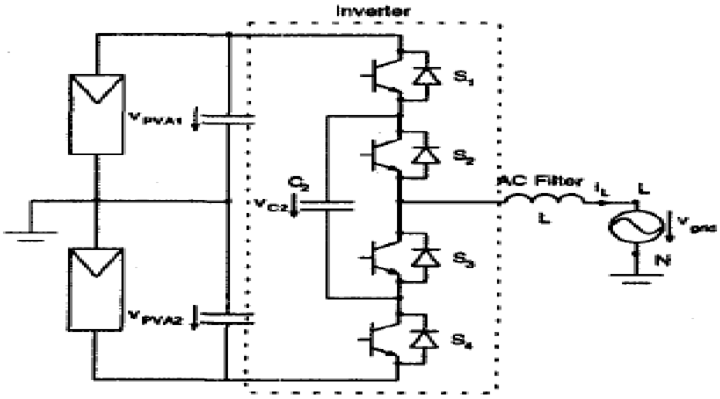


Figure 3.2.4.5: Flying Capacitor Inverter

This complicates the control of the inverter and excludes solution with varying duty-cycles (e.g. hysteresis control).

3.2.5 DUAL CONVERTER

A power converter capable of extracting maximum power from solar photovoltaic panels and employs a combination of a voltage controlled voltage source inverter and a current controlled voltage source inverter, connected in series on the DC side and in parallel on the AC side. Recently, the application of photovoltaic assisted uninterruptible power supply (UPS) systems for poor quality utility power grids has been reported, where a conventional bi-directional inverter is used in an ‘‘in-line’’ configuration. A dc-dc converter charge controller is used to operate the PV generator at a DC voltage corresponding to the maximum power at varying solar insulation and ambient temperatures. The charge controller has to be rated for the full PV capacity regardless of whether the energy is intended to flow entirely into the battery or out to the AC grid system. The charge controller is not utilized or underutilized during the night time or when the solar power is unavailable. The system can extract maximum power from the PV panels and provide reactive power support during the night.

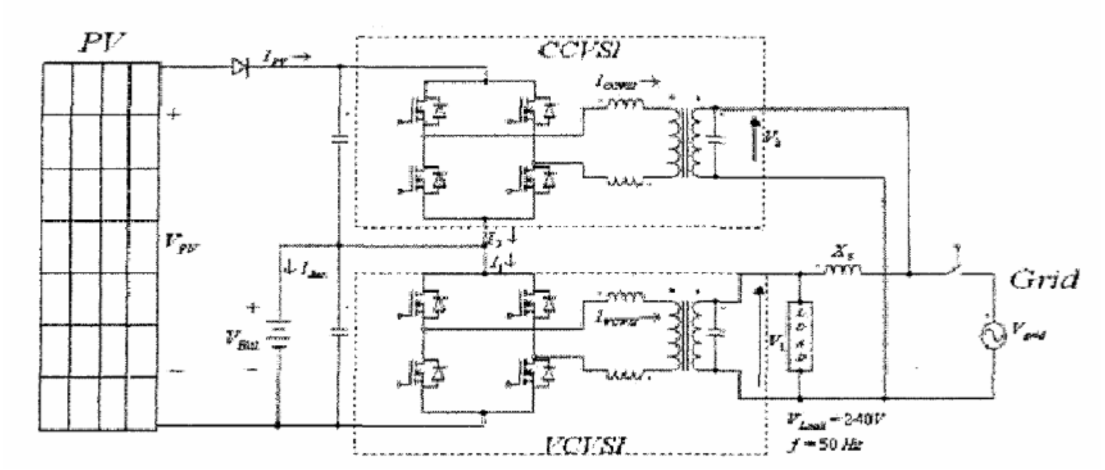


Figure 3.2.5: Dual Converter

CCVSI: Current Controlled Voltage Source Inverter.
VCVSI: Voltage Controlled Voltage Source Inverter.

This converter consists of a voltage controlled voltage source inverter (VCVSI) and a current controlled voltage source inverter (CCVSI), connected in series on the DC side and in parallel on the AC side, as shown in Fig.3.2.5 The CCVSI is connected in series with a combination of the battery and VCVSI on the dc side in order to regulate the difference in voltage between the battery and the PV and hence provide the MPPT operation. The CCVSI is connected directly across the grid and is able to supply a controlled current to the grid. In the absence of PV input, it can provide rated reactive power support or active filtering of the line current to minimize the harmonic distortion. The VCVSI is connected to the battery, providing bi-directional power (both rectification and inversion) flow capability between the battery and the AC side. The VCVSI is connected through the decoupling inductor (X_s) and produces a constant output voltage across the load. In extended periods of grid failure, a backup generator can be used to provide the ac supply. Thus the dual converter system provides a highly reliable source of AC power, capable of operating in both stand-alone and Grid/backup generator-connected modes [3].

3.2.5.1 Performance Enhancement of Dual Converter:

- **MPPT efficiency improvement:**

As the CCVSI and VCVSI are in series on the DC side, the total voltage of PV is shared between them. The PV power is split between the two inverters proportional to the respective dc voltages of the two VSI's. Since the battery is directly connected to the dc side of the VCVSI, that portion of the PV power can be delivered to the battery with no conversion losses. The power delivered to the CCVSI must be delivered to the ac side, and can then be routed back through the VCVSI to the battery if desired (e.g. operating stand-alone, with no ac loads).

- **Power factor correction to unity:**

In the dual converter topology, the CCVSI can provide the reactive power required for operation of the system at unity power factor. However size of the CCVSI should he defined based on the amount of required reactive power support while supplying the required active power. Therefore the size of the CCVSI can be defined based on the demand.

3.2.5.2 The system has the following additional features:

- The PV panels operate at a higher DC voltage, resulting in greater overall efficiency and reduce wiring costs.
- A simple ac circuit of the dual converter.
- Load voltage stabilisation.
- Unity Power factor.
- Harmonic minimisation.
- Reduce overall converter power rating and cost.
- Operation in stand-alone and grid-connected modes.

3.2.5.3 Advantages

- Uninterruptible power supply and load voltage stabilization.
- Unity power factor operation and Maximum power point tracking.
- Reactive power support.
- The overall efficiency is higher.

3.2.6 BOOST-BUCK INVERTER

Electricity production from photovoltaic (PV) power has become less costly and more efficient in recent years. Moreover, a string inverter topology allows further cost savings because of the more efficient energy extraction than the widely used centralized topology. The boost-buck inverter for PV grid connected systems gathers all the advantages of a string inverter topology and a transformer-less converter.

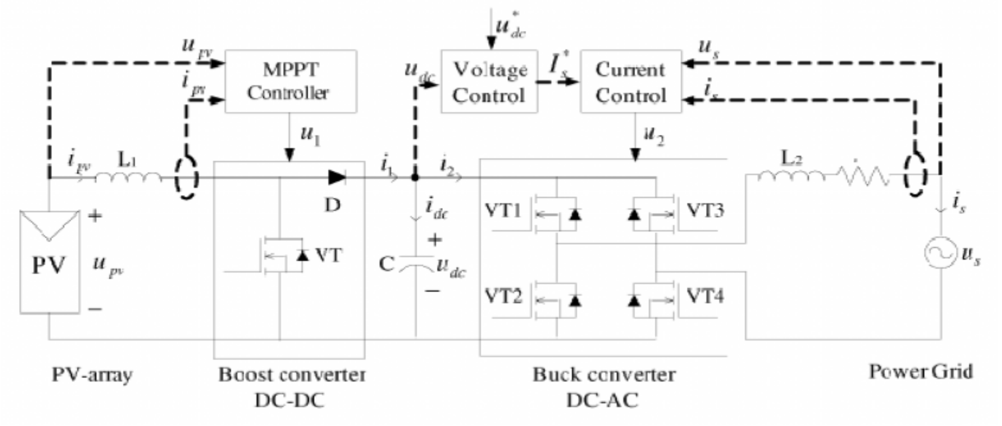


Figure 3.2.6: Boost-buck Inverter

Fig. 3.2.6 shows the Boost-Buck inverter structure, used to connect the photovoltaic array and the power grid, and the control scheme applied to accomplish effectively transferring the energy, generated by photovoltaic, into the utility grid. It is controlled by two closed-loops. First, a new linear cycle discrete control method is proposed in voltage control, which realizes linear control for DC-bus voltage. Then second, for grid-connected PV system's output current control, presented is a nonlinear controller, so called Auto-Disturbance Rejection Controller (ADRC). Combining these two control algorithms, the buck converter DC-AC stage obtains unity power factor and low harmonic distortion at the output. Therefore, this integrative control scheme brings new methodology to ensure robustness and conduct disturbance rejection. The boost converter is governed under control signal Ul, generated by a controller, dealing exclusively with the photovoltaic array's Maximum Power Point Tracking (MPPT). Output signal U2 controls the buck inverter for unity power factor. Cycle discrete control is advanced in DC-bus voltage control. ADRC is employed in output current control. According to a new integrative control scheme for boost-buck inverter in grid connected photovoltaic systems, DC-bus model of the inverter, a linear cycle discrete control method for DC-bus voltage is introduced. Meanwhile, ADRC controller is employed for PV system's output current control. This controller possesses good performance of the anti-interference for internal and external perturbation [14].

3.2.6.1 Control Scheme

- MPPT Control
- Cycle Discrete Control for DC-bus Voltage
- ADRC Control for Output Current

3.2.6.2 Features of the systems

- Better robustness and good performance.
- Low harmonic distortion and good adaptability to noise.
- Unity power factor.

3.2.7 MULTI-STEP PWM INVERTER

A multi-step PWM Inverter for a solar power generation system is constructed by adding a bi-directional switch to the conventional bridge type inverter circuit using the two isolated DC power supply for which the solar cell is suitable. To convert the dc power from the photovoltaic cells to a single phase ac power by using advanced pulse width modulated inverter. In photovoltaic power generation system, it is required to use a simple single phase and high quality inverter for residential. The multistep PWM inverter has special features such that it can be connected conveniently to separate solar cell modules that contribute to an easy implementation of the photovoltaic power generation system.

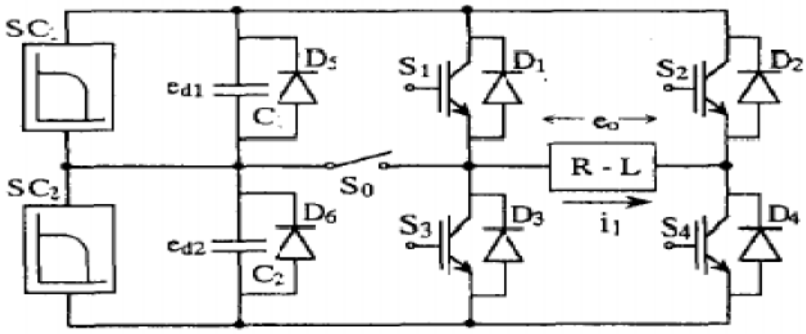


Figure 3.2.7: Multi-Step PWM Inverter Circuit configuration

The cost of the solar cell has reduced due to technological advancement in production; the system cost is still high because of the expensive inverter system with filter circuit. So, many types of inverter system for photovoltaic power generation system have been investigated**.** For the application to the residential solar power generation system, the single phase inverter is usually used. For the general use of the inverter, the small size and low cost of the inverter system are very important. Especially, the filter circuit is bulky and expensive generally. The two level converters can satisfy the specification using very high switching technique. But it has unfortunate possibilities such as the increase of the switching losses, the acoustic noise and the interference to the other equipment and so on.

A multi-step PWM inverter is required to reduce filter size. When the stepwise waveform obtain, the simple construction and high efficiency are important points. Although the NPC inverter (Neutral Point Clamped Inverter) is useful to obtain the stepwise waveform, the circuit construction becomes somewhat complicate and the forward voltage drop is high for the case of the single phase system. The inverter can be constructed by adding a bidirectional switching circuit to the conventional two-level inverter. This system requires two isolated or controlled DC power supply because the inverter cannot control the neutral point voltage**.** In a residential photovoltaic system of a few kilowatts in size, the array is mounted on top of the roof taking into consideration the most suitable angle for maximum utilization of the light intensity and temperature. The amount of dc power, which varies with solar light intensity and temperature, is converted to a single-phase 50 Hz ac using an improved type of a pulse width modulation inverter [1].

This inverter meets most of the specifications required in the residential system such as small size and light load applications, high reliability, high efficiency and low cost performance. The inverter under consideration is capable of minimizing the level of the harmonic content of the load current waveform. It should not be susceptible to the load variations and therefore its overall performance must be superior over the conventional type of PWM inverter.

3.2.7.1 Multi-Step PWM inverter has special features

- Stepwise PWM waveform.
- Small size of the output filter.
- Easy construction with separate solar cell module.
- Low switching loss.
- Low acoustic noise.
- High efficiency (approximately 95% over a wide range of load variations).

3.2.8 Z-SOURCE INVERTER

Z-Source inverter system is for a split-phase grid-connected photovoltaic system. Due to environmental concerns, more effort is now being put into clean distributed power like geothermal, wind power, fuel cells, and photovoltaic (PV) that directly uses the energy from the sun to generate electricity. As the energy from the sun is free, the major cost of photovoltaic generation is the installation cost, which is mainly composed of the costs of solar modules and the interface converter system, also called the power conditioning system (PCS). PCS is required to convert the dc output from PV to grid synchronized 50-60-Hz ac.

By utilizing the Z -Source inverter, the number of switching components and the total volume of the system can be minimized. Thus, the cost of the PCS is minimized [8].

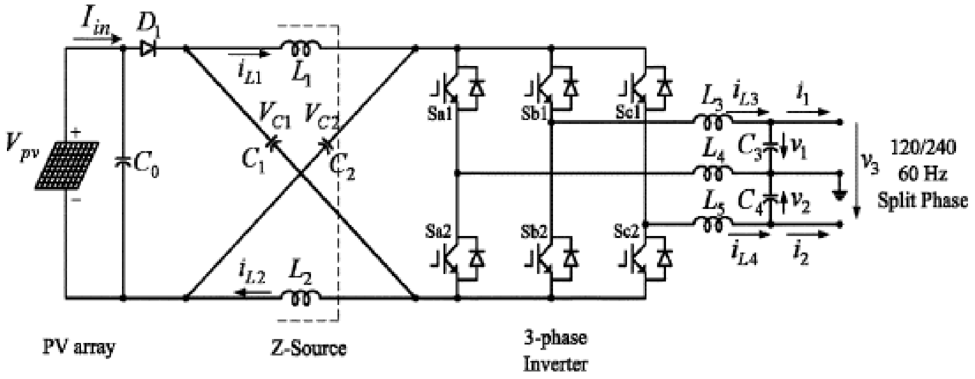


Figure 3.2.8: Z-Source Inverter

A Z-Source inverter is utilized to realize inversion and boost function in one single stage. Unlike the traditional voltage source or current source inverters, the Z-Source inverter employs a unique impedance network with split inductors L_1, L2 and capacitors C_1, C_2 connected in X shape. With the impedance network, the Z-Source inverter can advantageously use the shoot through states to boost voltage. PCS for PV system comes more reliable. The inductors and capacitors in the Z-Source are both energy storage devices, so their value can be optimally designed to ensure small size and low cost. In this system, there is no bulky transformer or a dc–dc converter to boost the voltage in the circuit. The size and cost are minimized. Because no dead time is needed, the control accuracy and THD value can also be improved. Furthermore, the split-phase Z–Source inverter naturally inherits all the advantages of the split-phase six-switch inverter. Therefore, by utilizing the Z-Source inverter, the volume, the cost as well as the number of active switching devices are minimized. Because of the single stage operation, the efficiency of the system can be greatly improved. Z-source inverter suffers higher voltage stress at the same input and output condition.

3.2.8.1 Features of Z-Source inverter are as follows:

- One stage to realize inversion.
- Boost and Maximum Power tracking.
- Has the minimized number of switching devices.
- Needs no dead time and can have shoot through state in the inverter.
- Inherits all the advantages of the six switch inverter system.

3.2.9 BOOST TYPE INVERTER

For many of these applications, the input dc voltage is usually below peak voltage of the output and may vary in a wide range. Thus single-stage buck-type inverters may not be adequate, since they have very limited input voltage range and require the input dc voltage to be higher than the peak of the output voltage. For this reason two power-stage topologies, cascaded topologies and multilevel topologies are reported for applications where the input voltage is lower than the peak of the output voltage. Typically, one dc–dc power stage is required to boost the dc voltage in addition to an inverter for dc–ac conversion, which yields increased circuitry complexity. To avoid introducing additional distortions to the power grid, the generated currents from these inverters are required to have low harmonics and high power factor. When the output currents are in phase with the grid voltages, the maximum real output power is achieved.

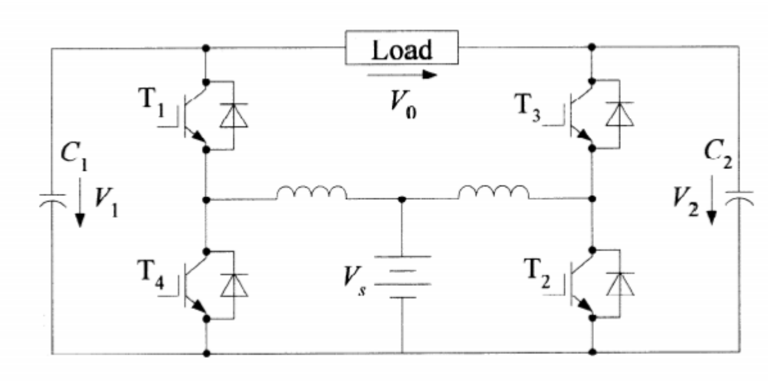


Figure 3.2.9: Boost Type Inverter

For boosting PV output voltage in order to accommodate the buck-type grid-connected inverter, a two-stage topology that boosts the PV voltage by a dc–dc converter in the first stage and then inverts it into ac voltages by the second stage. In a cascaded structure is used in which the individual PV voltage is stepped up to a higher module output voltage and such module output voltages are series connected to build up an array output voltage as the front-end of a buck-type grid-connected inverter. In a multi-level topology is employed to increase the input voltage of the buck-type inverter. In power stages or extra power switches are used for increasing the dc side voltage, which increases circuitry complexity and may reduce system overall efficiency.

An alternative way to achieve dc-to-ac inversion without directly boosting input dc voltage is to use the power stage topology of a current source inverter (CSI). The input side inductor in a CSI topology is “shorted” to the input dc source to build up magnetic energy in certain sections of a switching period and then the energy is released to the ac side during the rest of the switching period, just as in a basic boost converter. With CSI, the input dc voltage is lower than the output ac peak voltage while there is only one power stage in the system. The one-cycle control (OCC) method and the conventional pulse width modulation (PWM) method are proposed based on the CSI topology for a three-phase boost-type grid-connected inverter. The inverter features a single power stage that converts dc power to grid-connected ac power by injecting three in phase sinusoidal currents into grids, which may reduce power losses and circuit complexity. The input dc voltage is lower than the peak grid voltage and can vary in a wide range, which greatly suits the power conversion from photovoltaic or fuel cells to grid lines. The dc inductance may be kept low because the average dc current is maintained constant in a switching cycle. The property of single power stage is preserved and the input dc voltage of the inverter is lower than the output peak grid voltage, which perfectly suits the property of wide output voltage range in PV or fuel cells. The dc side inductance can be kept small in a balanced three-phase system, so the size, weight, and power dissipation of the dc inductor are reduced and system dynamic response is improved.

3.2.9.1 OCC method features:

- Simple control circuit.
- Fast dynamic response.
- Good stability.

3.2.10 SPACE VECTOR PWM INVERTER (SVPWM)

Space Vector PWM (SVPWM) is a more sophisticated technique for generating a fundamental sine wave that provides a higher voltage to the load and lower total harmonic distortion. However, the traditional Direct Current/Alternating Current (DC/AC) technology has the disadvantages such as low utilization of DC voltage, complex operation control and high harmonic content, which cannot meet the requirements of inverter. The SVPWM can be effective to solve these problems and obtain the higher inverter’s utilization of DC voltage and lower harmonic contents.

3.2.10.1 Principle of SVPWM:

Space Vector PWM (SVPWM) refers to a special switching sequence of the upper three power transistors of a three-phase power inverter. It has been shown to generate less harmonic distortion in the output voltages applied to the phases of an AC Load and to provide more efficient use of supply voltage compared with sinusoidal modulation technique.

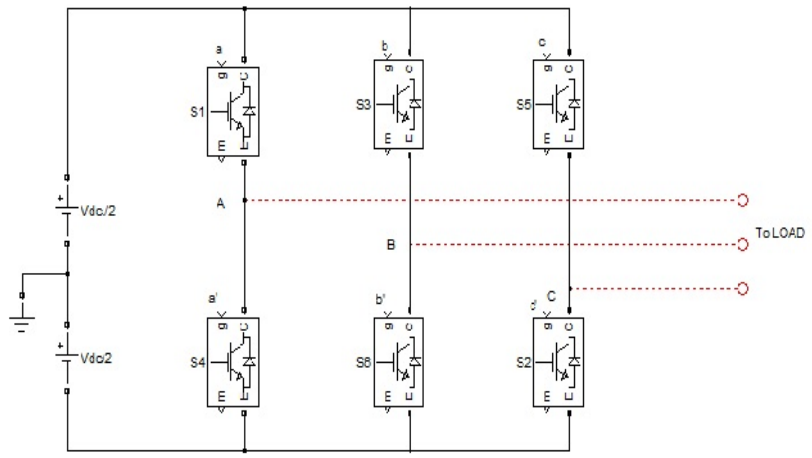


Figure 3.7: Three-phase voltage source PWM inverter

The circuit model of a typical three-phase voltage source PWM inverter is shown in Fig. 3.7. S1 to S6 are the six power switches that shape the output, which are controlled by the switching variables a, a′, b, b′, c and c′. When an upper transistor is switched on, i.e., when a, b or c is 1, the corresponding lower transistor is switched off, i.e., the corresponding a′, b′ or c′ is 0. Therefore, the on and off states of the upper transistors S1, S3 and S5 can be used to determine the output voltage.

- Each power switch can be on and off
    - On = 1
    - Off = 0

$S_1 = 1$ ………….. (3.7.1)

$S_4 = 1 - S_1$ ………….. (3.7.2)

$S_6 = 1 - S_3$ …………... (3.7.3)

$S_2 = 1 - S_5$ …………... (3.7.4)

$V_0 = V_{00} + V_{on}$ …………. (3.7.5)

$V_1 = V_{10} + V_{on}$ …………. (3.7.6)

$V_2 = V_{20} + V_{on}$ ..………... (3.7.7)

When $S_1 = conducts = 1$

$V_{00} = \frac{V_{dc}}{2} S_1$ …………. (3.7.8)

$S_4 = 0$ ………… (3.7.9)

When $S_4 = conducts = 1$

$V_{00} = -\frac{V_{dc}}{2} S_4$ ……….. (3.7.10)

$S_1 = 0$ ………. (3.7.11)

$V_{00} = \frac{V_{dc}}{2} S_1 - \frac{V_{dc}}{2} S_4$ ………. (3.7.12)

$S_4 = 1 - S_1$ ………. (3.7.13)

$V_{00} = \frac{V_{dc}}{2} S_1 - \frac{V_{dc}}{2}(1 - S_1) = (2S_1 - 1)\frac{V_{dc}}{2}$ ………. (3.7.14)

$V_0 = (2S_1 - 1)\frac{V_{dc}}{2} + V_{on}$ ………. (3.7.15)

Similarly,

$V_1 = (2S_3 - 1)\frac{V_{dc}}{2} + V_{on}$ ………. (3.7.16)

$V_2 = (2S_5 - 1)\frac{V_{dc}}{2} + V_{on}$ ………. (3.7.17)

$f_{abc} = T.f_{012}$ ……….. (3.7.18)

$$T = \begin{vmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{vmatrix}$$ ………. (3.7.19)

$$a = -\frac{1}{2} + j\frac{\sqrt{3}}{2} = 1\angle 120^0$$

$$a^2 = -\frac{1}{2} - j\frac{\sqrt{3}}{2} = 1\angle 240^0$$

$f_{012} = T^{-1}.f_{abc}$ ……….. (3.7.20)

$$T^{-1} = \frac{1}{3}\begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix}$$ ………. (3.7.21)

$P_{3\emptyset} = [V_{abc}]^t \, [I_{abc}]^*$

$= [[T]V_{012}]^t \, [[T]I_{012}]^*$

$= [V_{012}]^t \, [T]^t \, [T]^* \, [I_{012}]^*$ ………. (3.7.22)

$$[T]^t[T]^* = 3\begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \qquad \ldots\ldots\ldots\ldots (3.7.23)$$

$$P_{3\emptyset} = 3\,V_{012}I_{012}^* = [V_{abc}]^t[I_{abc}]^* \qquad \ldots\ldots\ldots\ldots (3.7.24)$$

$$V_{ref} = (V_1 + aV_2 + a^2V_3) \qquad \ldots\ldots\ldots\ldots (3.7.25)$$

Write it in terms of peak line-to-line voltage:

$$V_{ref} = \sqrt{\frac{3}{2}}\left(\widetilde{V_1} + a\widetilde{V_2} + a^2\widetilde{V_3}\right) \qquad \ldots\ldots\ldots\ldots (3.7.26)$$

Where $\widetilde{V_1} = \sqrt{3}V_1$ = peak line to line voltage.

State	**Voltage Vector**	**S_1**	**S_3**	**S_5**	**S_4**	**S_6**	**S_2**	**V_{ref}**
1	V_0	0	0	0	1	1	1	0
2	V_1	1	0	0	0	1	1	$\sqrt{\frac{2}{3}}V_{dc}$
3	V_2	1	1	0	0	0	1	$\frac{V_{dc}}{\sqrt{6}} + j\frac{V_{dc}}{\sqrt{2}}$
4	V_3	0	1	0	1	0	1	$-\frac{V_{dc}}{\sqrt{6}} + j\frac{V_{dc}}{\sqrt{2}}$
5	V_4	0	0	1	1	1	0	$-\sqrt{\frac{2}{3}}V_{dc}$
6	V_5	0	0	1	1	1	0	$-\frac{V_{dc}}{\sqrt{6}} - j\frac{V_{dc}}{\sqrt{2}}$
7	V_6	1	0	1	0	1	0	$\frac{V_{dc}}{\sqrt{6}} - j\frac{V_{dc}}{\sqrt{2}}$
8	V_7	1	1	1	0	0	0	0

Table 3.1: Switching Vector, Switching Sequence and Voltage Reference

To implement the space vector PWM, the voltage equations in the V_{abc} reference frame can be transformed into the stationary $V\alpha\beta$ reference frame that consists of the horizontal (α) and vertical (β) axes as depicted in Fig. 3.7.1.

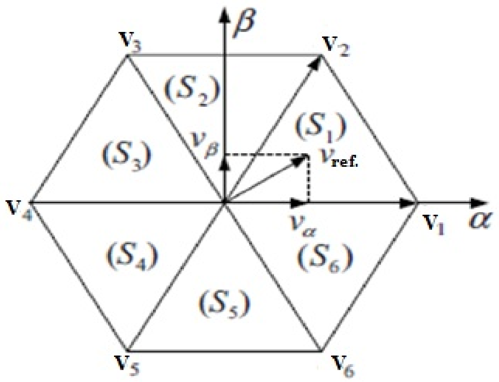
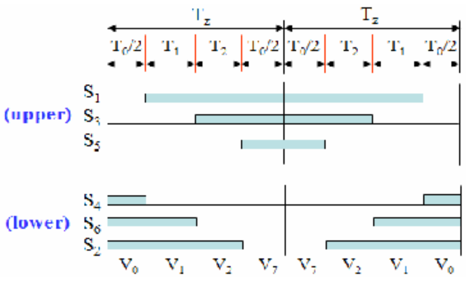


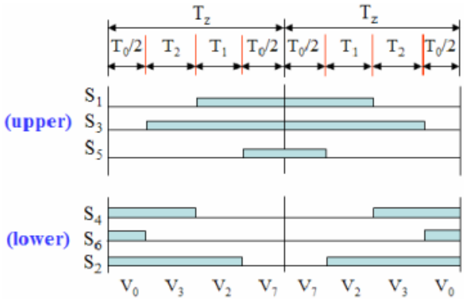
Figure 3.7.1: Basic Spacing Vectors and Sectors

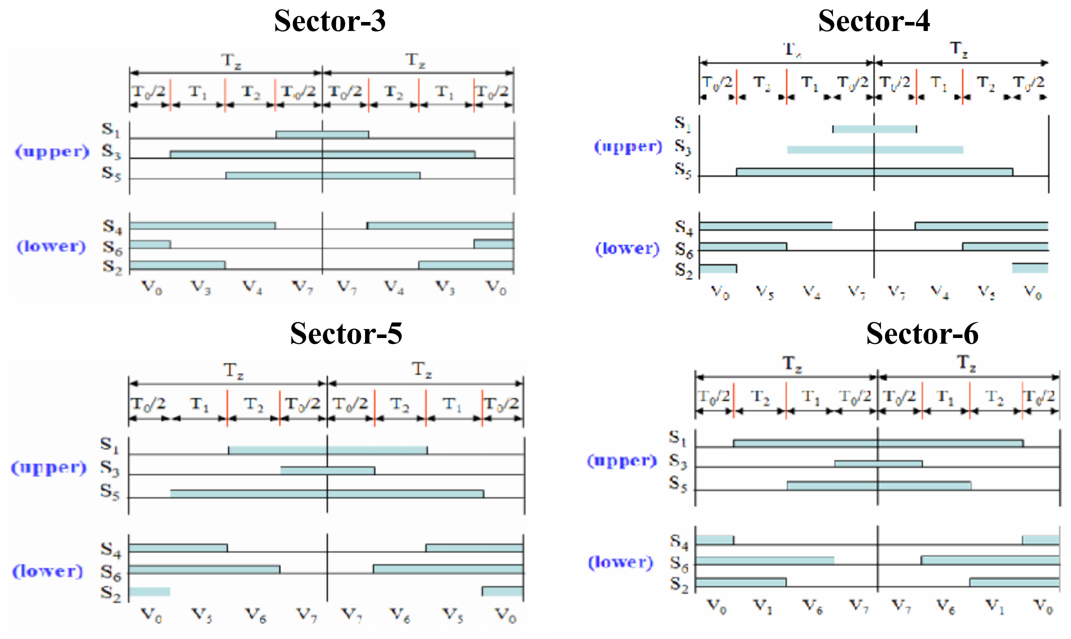
As described in Fig. 3.7.1, this transformation is equivalent to an orthogonal projection of [a, b, c]^t onto the two-dimensional perpendicular to the vector [1, 1, 1]^t (the equivalent α-β plane) in a three-dimensional coordinate system. As a result, six non-zero vectors and two zero vectors are possible. Six non-zero vectors (V1-V6) shape the axes of a hexagonal as depicted in Fig. 3.7.1, and feed electric power to the load. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V0 and V7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V0, V1, V2, V3, V4, V5, V6, and V7. The same transformation can be applied to the desired output voltage to get the desired reference voltage vector V_{ref} in the α-β plane. The objective of space vector PWM technique is to approximate the reference voltage vector V_{ref} using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period, T to be the same as that of V_{ref} in the same period.

Sector-1



Sector-2




Sector-3

Sector-4

Sector-5

Sector-6

Figure 3.7.2: SVPWM Switching Patterns at each Sector

Sector	Upper Switches (S_1, S_3, S_5)	Lower Switches (S_4, S_6, S_2)
1	$S_1 = T_1+T_2+T_0/2$ $S_3 = T_2+T_0/2$ $S_5 = T_0/2$	$S_4 = T_0/2$ $S_6 = T_1+T_0/2$ $S_2 = T_1+T_2+T_0/2$
2	$S_1 = T_1+T_0/2$ $S_3 = T_1+T_2+T_0/2$ $S_5 = T_0/2$	$S_4 = T_2+T_0/2$ $S_6 = T_0/2$ $S_2 = T_1+T_2+T_0/2$
3	$S_1 = T_0/2$ $S_3 = T_1+T_2+T_0/2$ $S_5 = T_2+T_0/2$	$S_4 = T_1+T_2+T_0/2$ $S_6 = T_0/2$ $S_2 = T_1+T_0/2$
4	$S_1 = T_0/2$ $S_3 = T_1+T_0/2$ $S_5 = T_1+T_2+T_0/2$	$S_4 = T_1+T_2+T_0/2$ $S_6 = T_2+T_0/2$ $S_2 = T_0/2$
5	$S_1 = T_2+T_0/2$ $S_3 = T_0/2$ $S_5 = T_1+T_2+T_0/2$	$S_4 = T_1+T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_2 = T_0/2$
6	$S_1 = T_1+T_2+T_0/2$ $S_3 = T_0/2$ $S_5 = T_1+T_0/2$	$S_4 = T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_2 = T_2+T_0/2$

Table 3.2: Switching Time at Each Sector

Chapter – 04

SVPWM INVERTER

4.1 INTRODUCTION

A number of Pulse Width Modulation (PWM) schemes are used to obtain variable voltage and frequency supply from an inverter. The most widely used PWM schemes for a three-phase VSI are carrier-based sinusoidal PWM and space vector PWM (SVPWM). There is an increasing trend of using space vector PWM (SVPWM) because of their easier digital realisation and better dc bus utilisation. However, a proper simulation model is still not available in the literature. Thus, this chapter focuses on step by step development of MATLAB/SIMULINK model of SVPWM followed by their experimental implementation. Now, a simple and flexible simulation model of SVPWM is developed using MATLAB/SIMULINK. The novelty of the chapter relies on the proposal of the flexible and general Matlab/Simulink model of SVPWM. Experimental and simulation results are provided to validate the proposed model.

4.2 Generalised Matlab/Simulink model of SVPWM (Without Transformer):

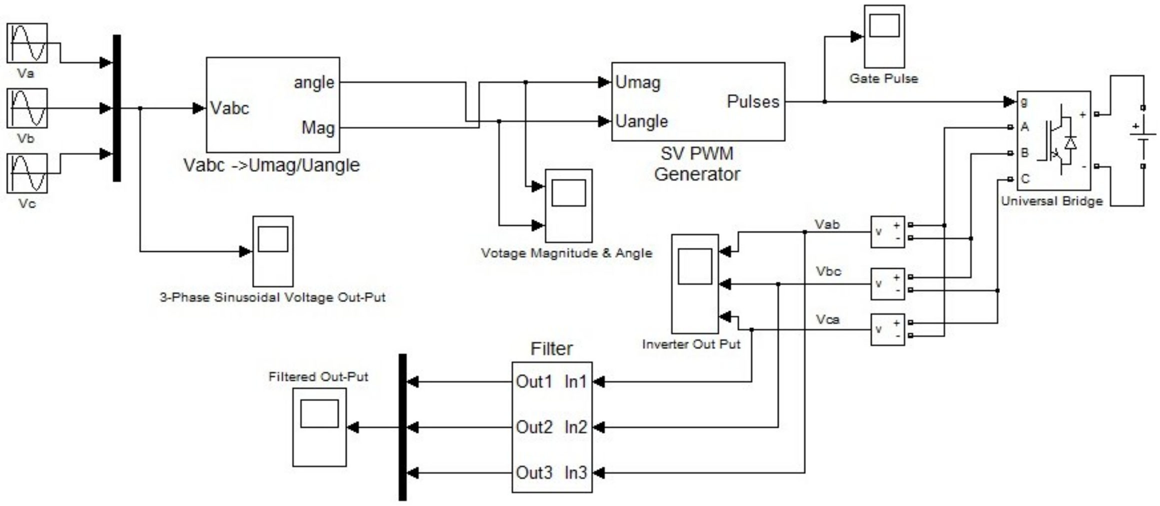


Figure 4.1: SVPWM Inverter without 3-Phase Transformer

This is the step by step development of a Matlab/Simulink based simulation model for implementing SVPWM. Thus the presented simulation mode is general in nature and can be configured very easily to simulate SVPWM in linear modulation range. The simulation model without 3-Phase Transformer is shown in Figure 4.1. Each blocks of Figure 4.1 is described in the following sub-section.

4.2.1 Reference voltage generation block

This block is used to simulate balanced three-phase input reference. Three-phase input sinusoidal voltage is generated using the function block of the Sine Wave block as shown in Figure 4.1, to generate a set of three-phase sinusoidal voltage (V_a, V_b, V_c) as shown in fig. 4.2. It is used for generate the SVPWM pulses.

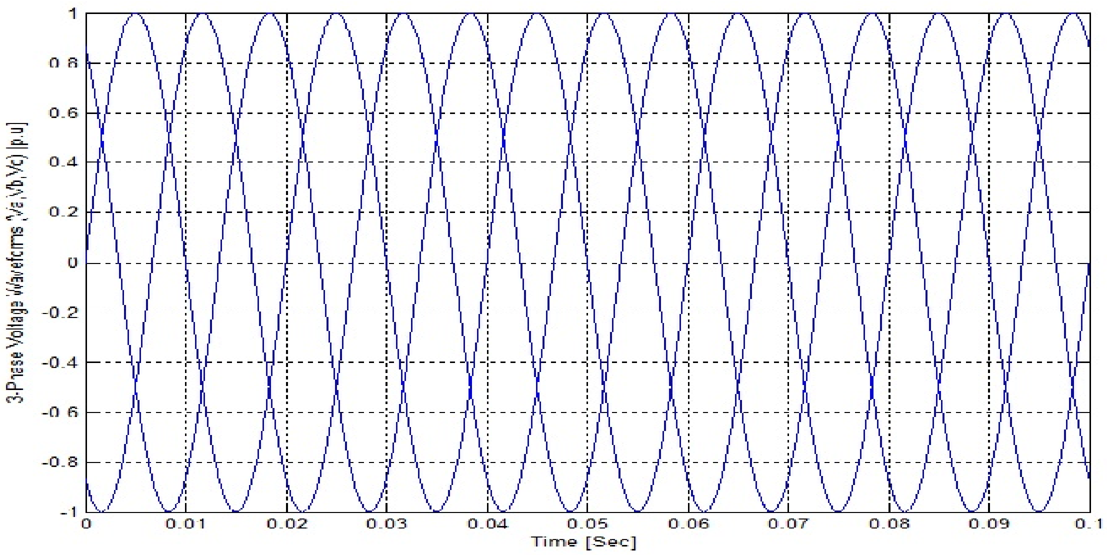


Figure 4.2.1: Reference 3-Phase Voltage waveforms

4.2.2 Voltage transformation block:

The 3-Phase voltage is converted into two-phase voltage equivalent using Clark's transformation equations as follow:

$$V\alpha\beta = \sqrt{\frac{2}{3}}\begin{vmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{vmatrix} Vabc \qquad \text{----------------------} \qquad (4.1)$$

The output of this block is the magnitude of the reference as the first output and the corresponding angle of the reference as the second output. The waveform of magnitude is simply a constant line as its value remains fixed. The waveform of angle is shown in Figure 4.2.2 (a) and the magnitude waveform shown in fig. 4.2.2 (b)

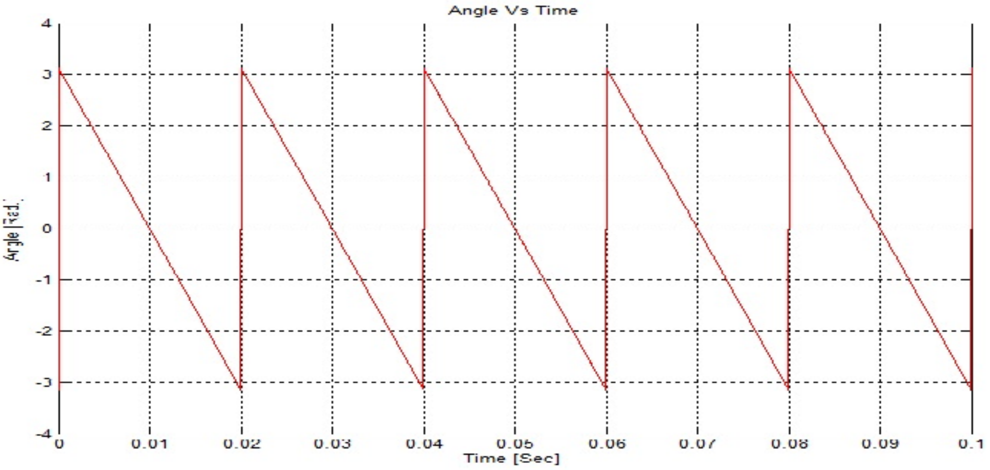


Figure 4.2.2 (a): Voltage Angle

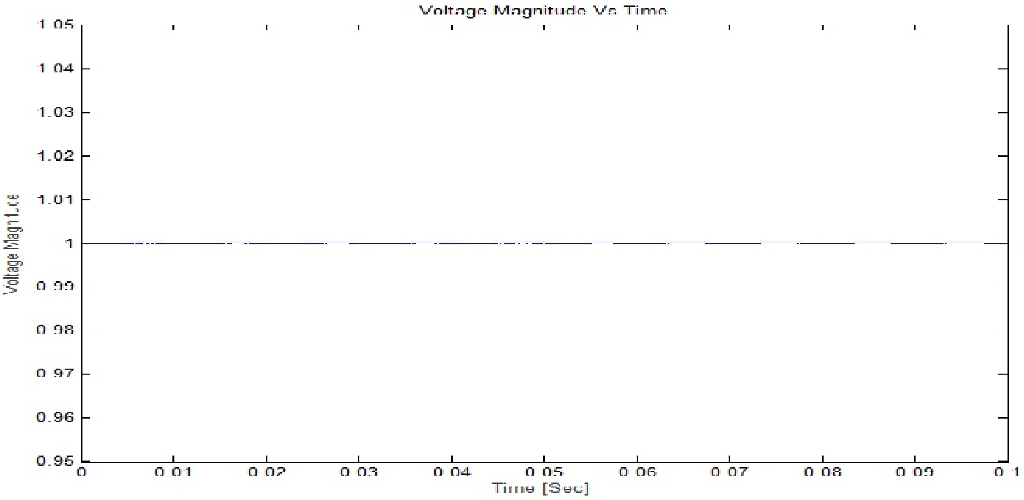


Figure 4.2.2 (b): Voltage Magnitude

4.2.3 Discrete SV PWM Generator

The block utilizes the Space Vector Pulse Width Modulation (SVPWM) technique to generate the firing pulses to the sixth switches of the converter. Two pattern switching can be selected. The modulation index (m) must be range from 0 to 1 and the line-line r.m.s voltage is generated by Voltage Source Converter (VSC) contolled by this block will be:

$$V_{out} = \text{m} \times \frac{V_{dc}}{\sqrt{2}} \qquad \text{-----------------} \ (4.2)$$

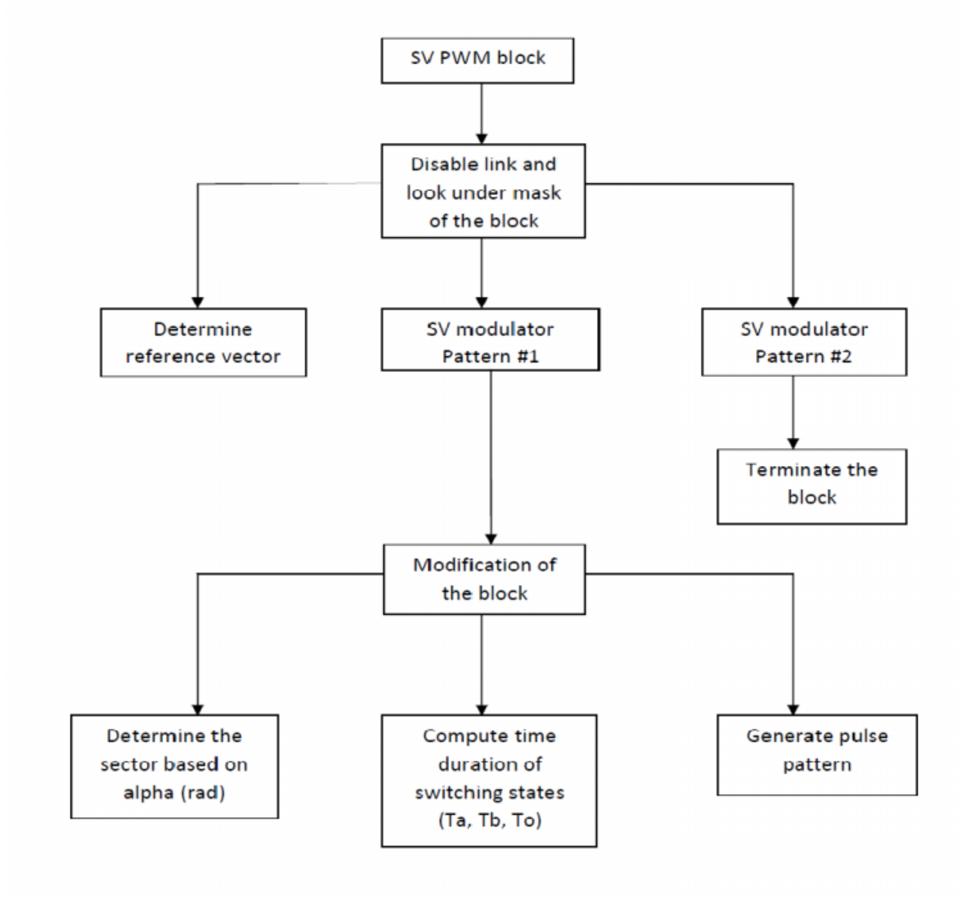


Figure 4.2.3 (a): Internal block diagram of SVPWM block

Fig. 4.2.3(a) shows the internal block diagram of the SVPWM block. It consist determine the reference vector block, the objective of the SVPWM technique is to approximate the reference voltage vector (U*) instantaneously by combination of the switching states corresponding to the basic space vectors.

Two symmetrical switching patterns have been implemented:

- **Pattern-1:** With this pattern, identified as each PWM channel switches twice per every PWM period. The gate pulse is generated by SVPWM generator under the pattern-1 is shown in fig.4.2.3 (b).
- **Pattern-2:** With this pattern, identified as there is always one PWM channel staying constant for the entire PWM period. So the number of switching times for this pattern is less than pattern #1. As a result, switching losses will be reduced with Pattern #2. The gate pulse is generated by SVPWM generator under the pattern-2 is shown in fig.4.2.3 (c).

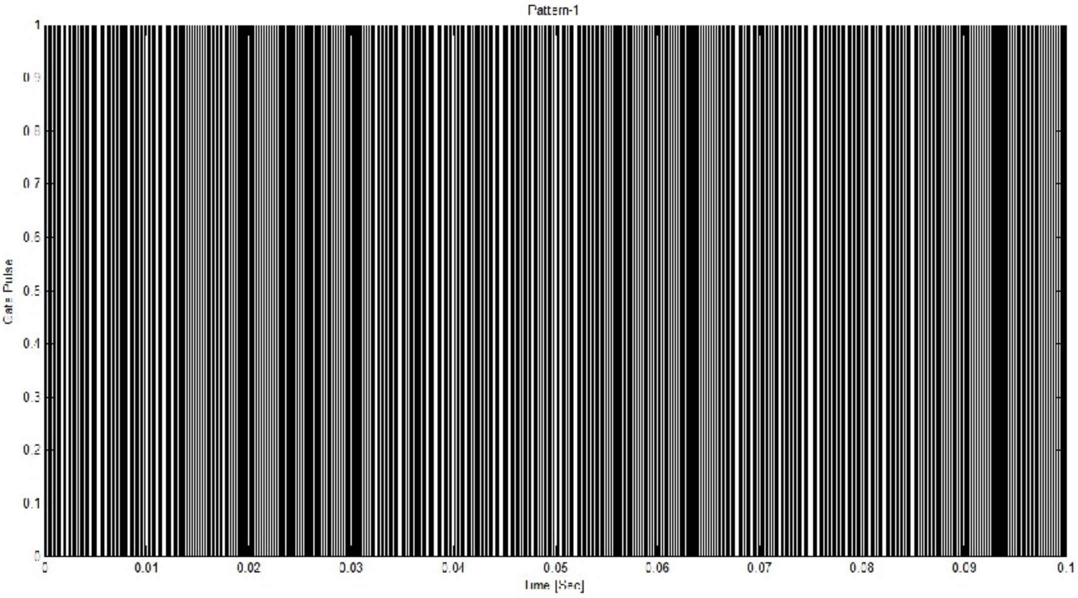


Figure 4.2.3 (b): Pattern-1 Gate-Pulse waveform

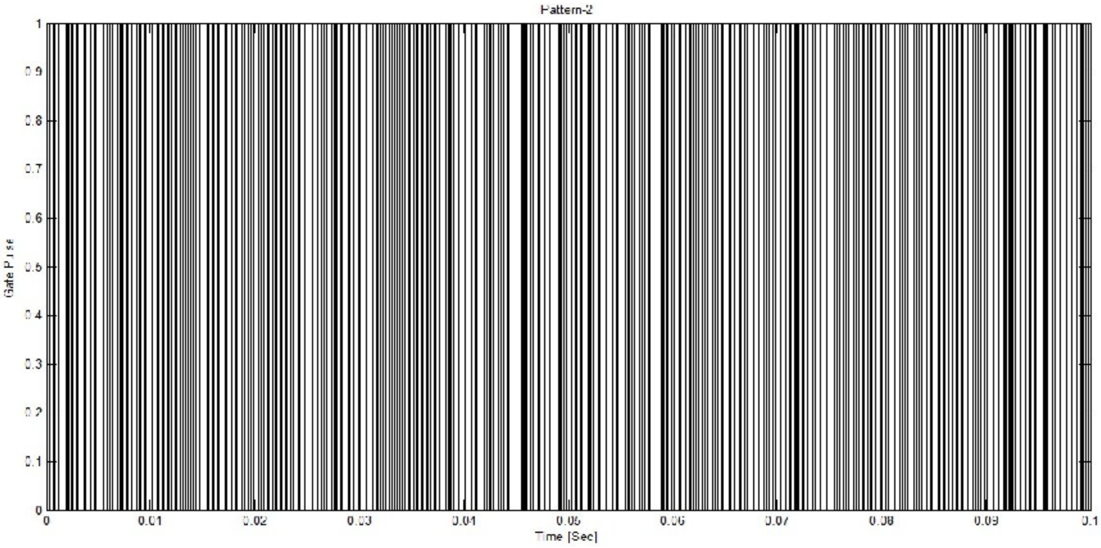


Figure 4.2.3 (c): Pattern-2 Gate-Pulse waveform

4.2.4 Three-Phase Inverter Block (Universal Bridge):

This block is built to simulate a 3-Phase Voltage Source Inverter (VSI) assuming constant dc link voltage. The inputs to the inverter block are the switching signals and the outputs are the SVPWM voltages. The inverter model is built using 'function' blocks. The outputs of SVPWM inverter voltages of both patterns such as Pattern-1 and Pattern-2 are shown in following figures.

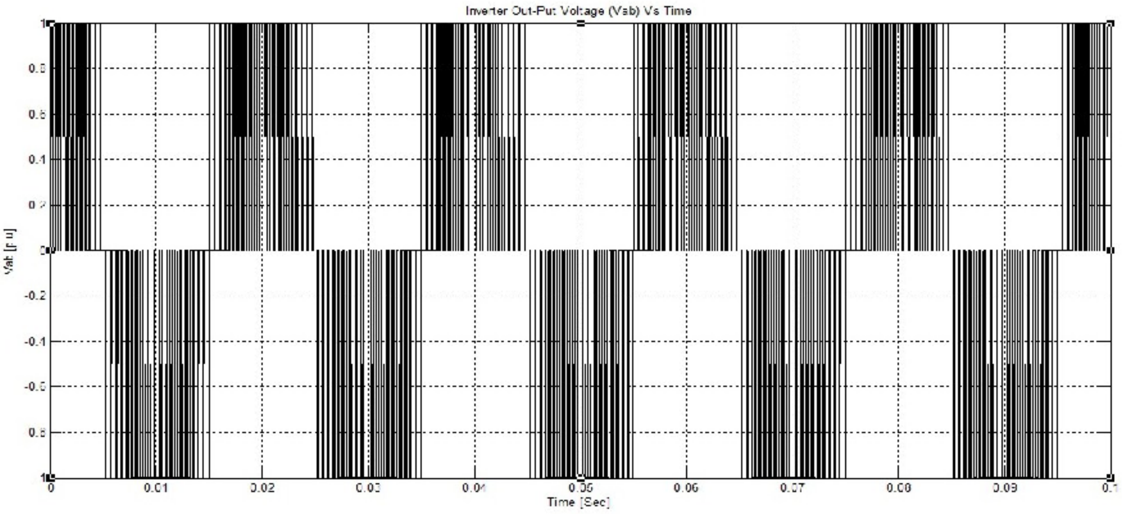


Figure 4.2.4 (a): Pattern-1 SVPWM inverter Voltage waveform (V_{ab})

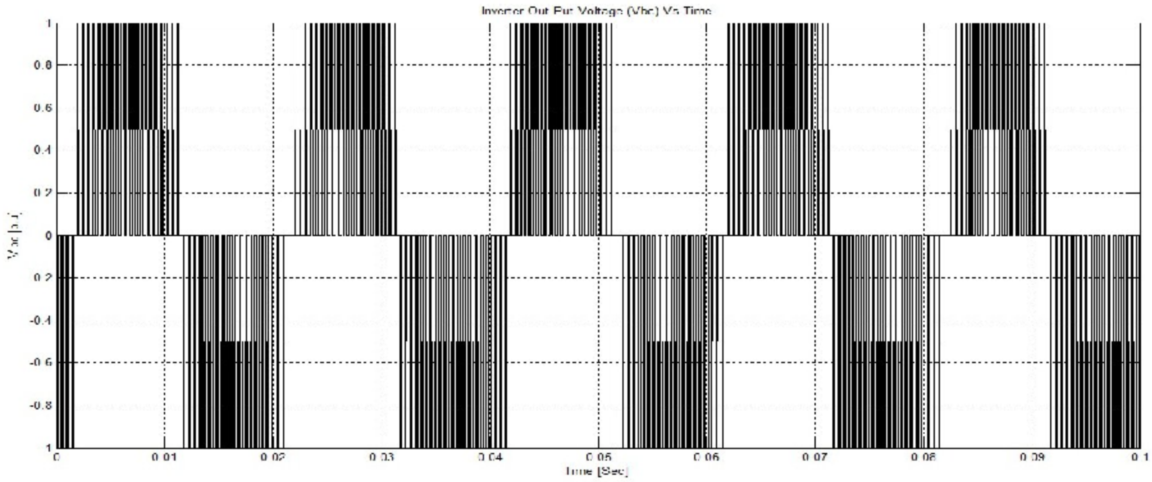


Figure 4.2.4 (b): Pattern-1 SVPWM inverter Voltage waveform (V_{bc})

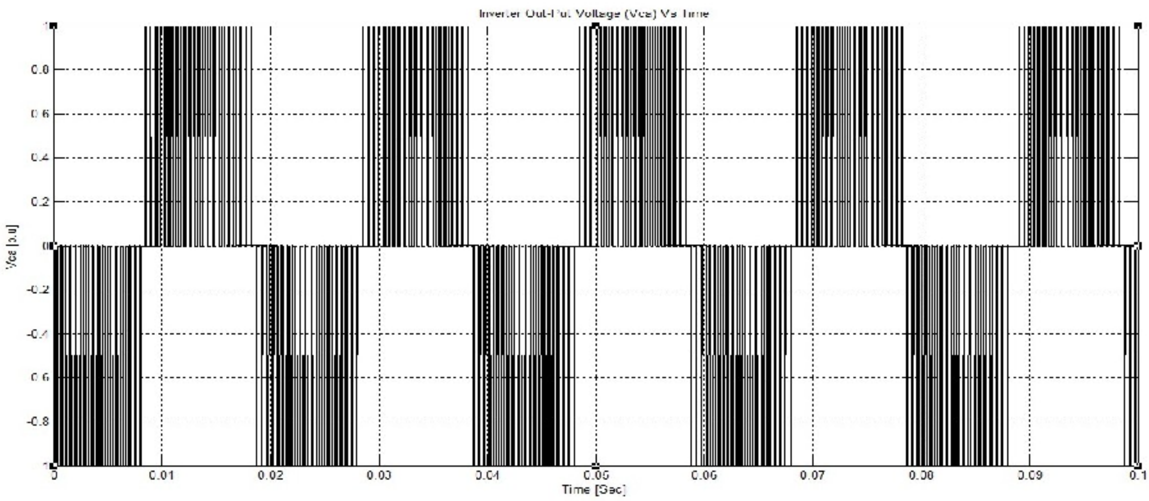


Figure 4.2.4 (c): Pattern-1 SVPWM inverter Voltage waveform (V_{ca})

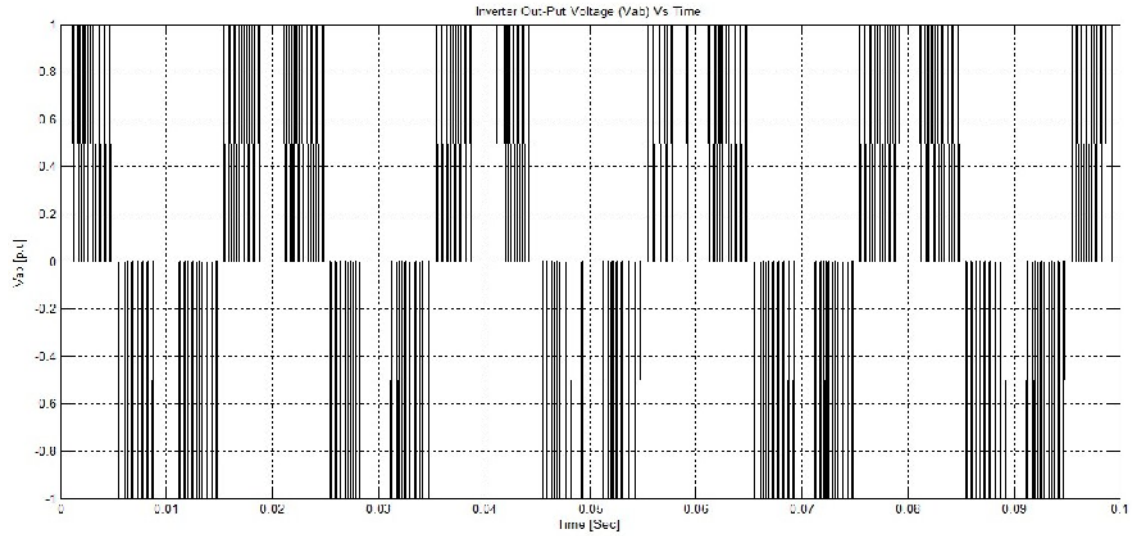


Figure 4.2.4 (d): Pattern-2 SVPWM inverter Voltage waveform (V_{ab})

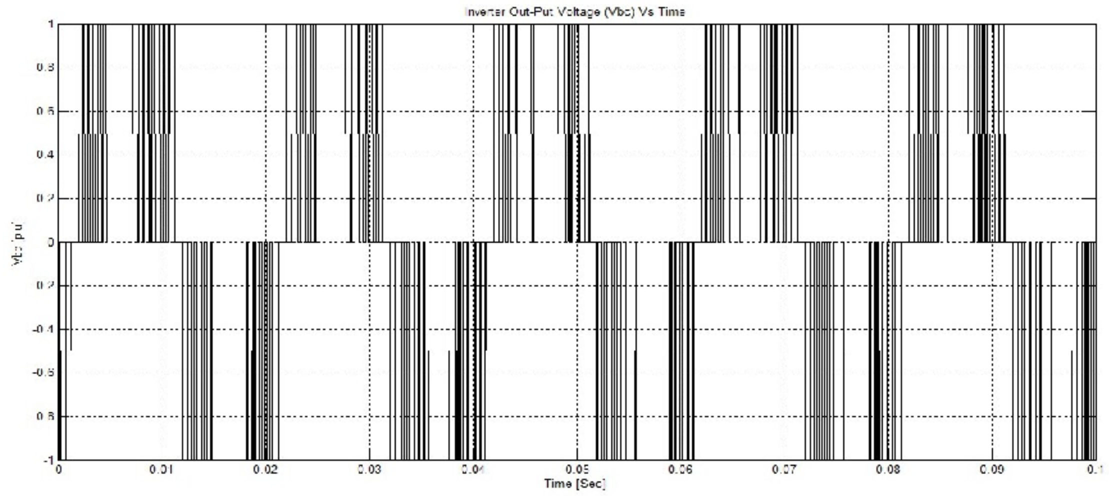


Figure 4.2.4 (e) Pattern-2 SVPWM inverter Voltage waveform (V_{bc})

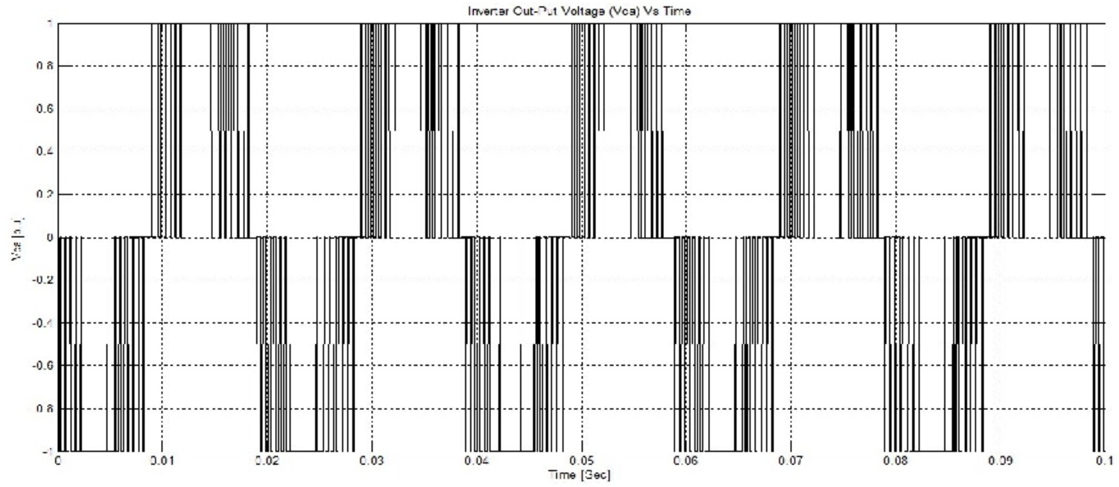


Figure 4.2.4 (f) Pattern-2 SVPWM inverter Voltage waveform (V_{ca})

4.2.5 Filter Blocks

To visualise the actual output of the inverter block, filtering of the SVPWM ripple is required. The PWM voltage signal is filtered here using first order filter. This is implemented using ‘Transfer function’ block. The time constant of the first-order filter is chosen as 0.1ms and 0.8ms. This value is chosen to ensure the cut-off frequency of the low-pass equal to 1250 Hz. So the designed filter will effectively remove the ripple of higher than 1.25 kHz. The value of the filter time constant can be changed if the desired cut-off frequency is different. The filtered voltage outputs of Pattern-1 and Pattern-2 at two different time constants are shown in following figures.

- **Pattern-1 filtered voltage outputs at time constant 0.1ms:**

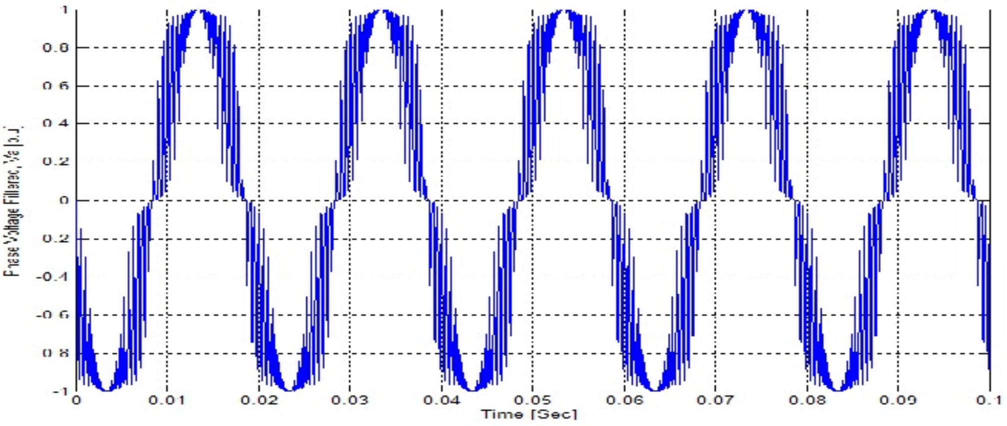


Figure 4.2.5 (a): Filtered voltage waveform (V_a)

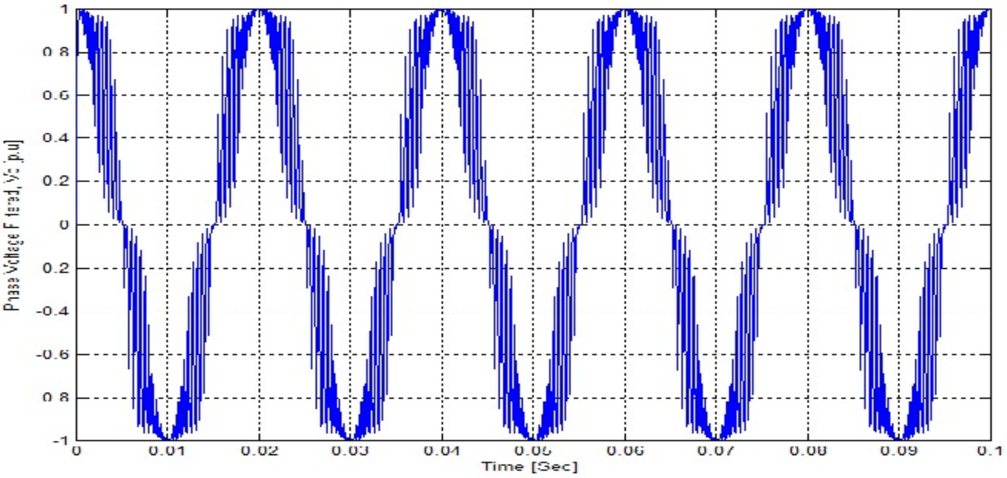


Figure 4.2.5 (b): Filtered voltage waveform (V_b)

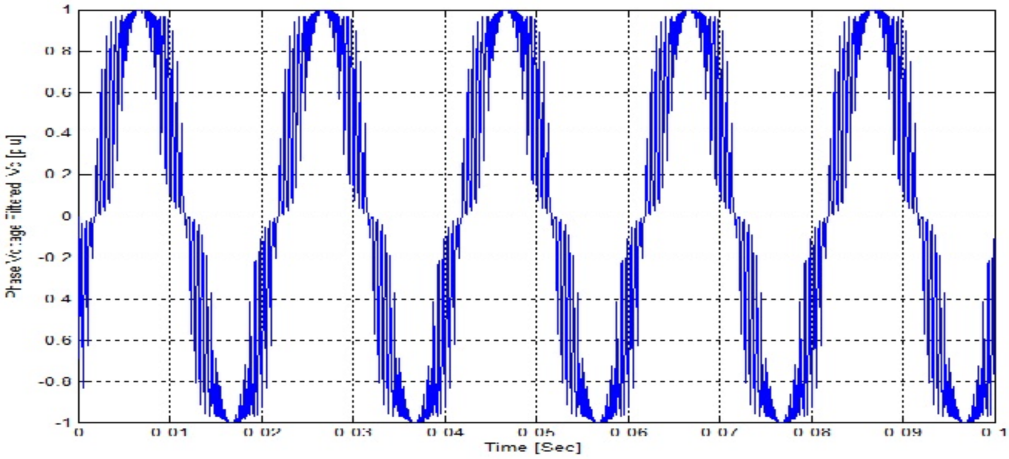


Figure 4.2.5 (c): Filtered voltage waveform (V_c)

- **Pattern-1 filtered voltage outputs at time constant0.8ms:**

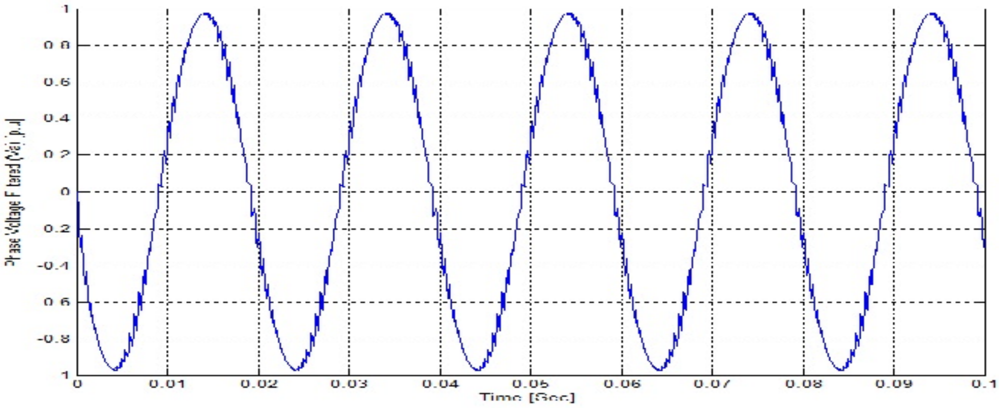


Figure 4.2.5 (d): Filtered voltage waveform (V_a)

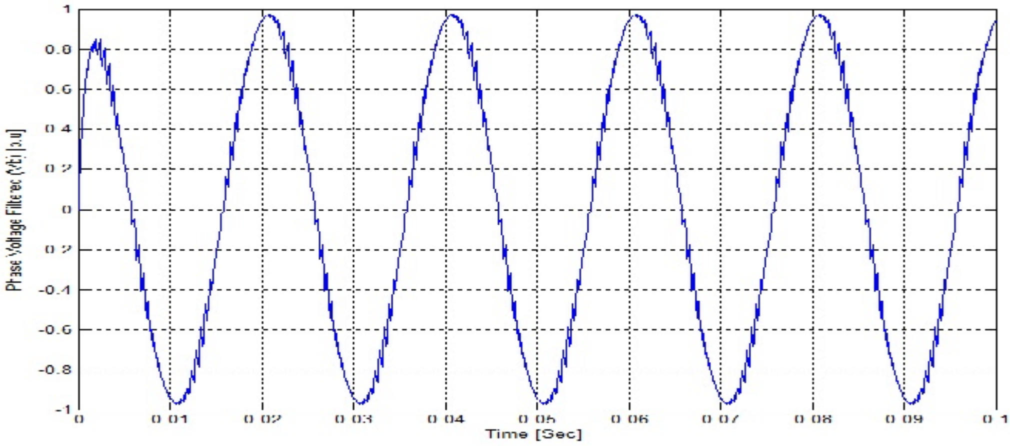


Figure 4.2.5 (e): Filtered voltage waveform (V_b)

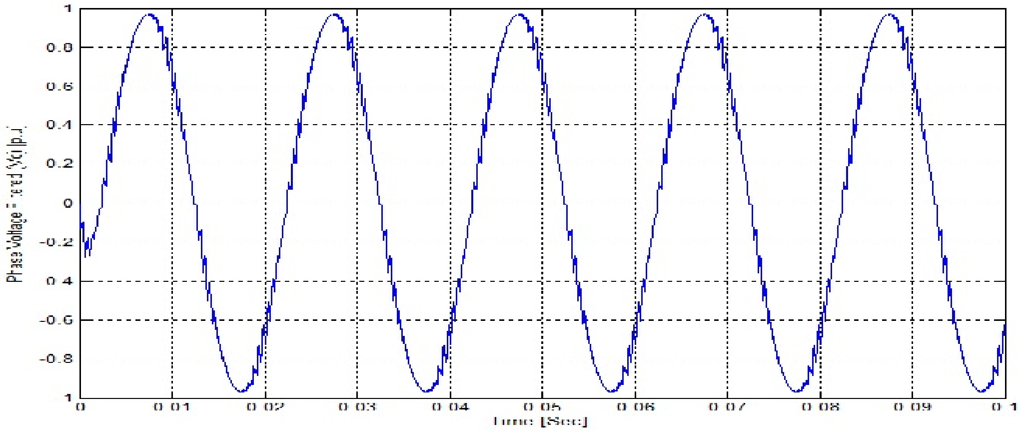


Figure 4.2.5 (f): Filtered voltage waveform (V_c)

- **Pattern-2 filtered voltage outputs at time constant 0.1ms**

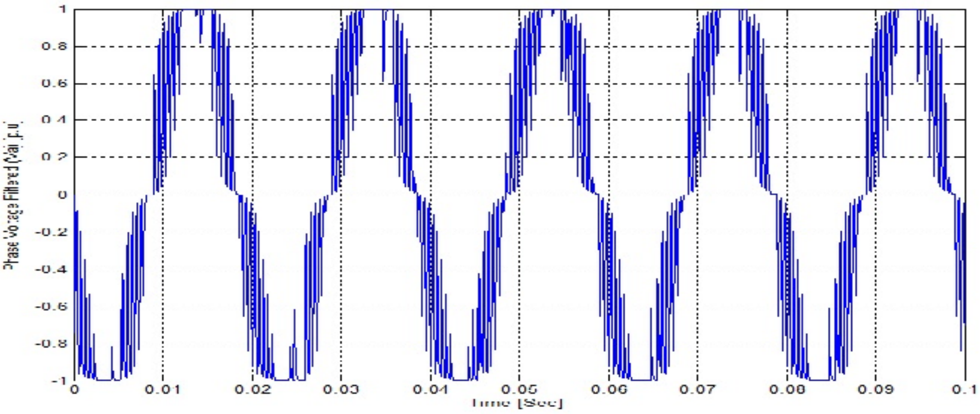


Figure 4.2.5 (g): Filtered voltage waveform (V_a)

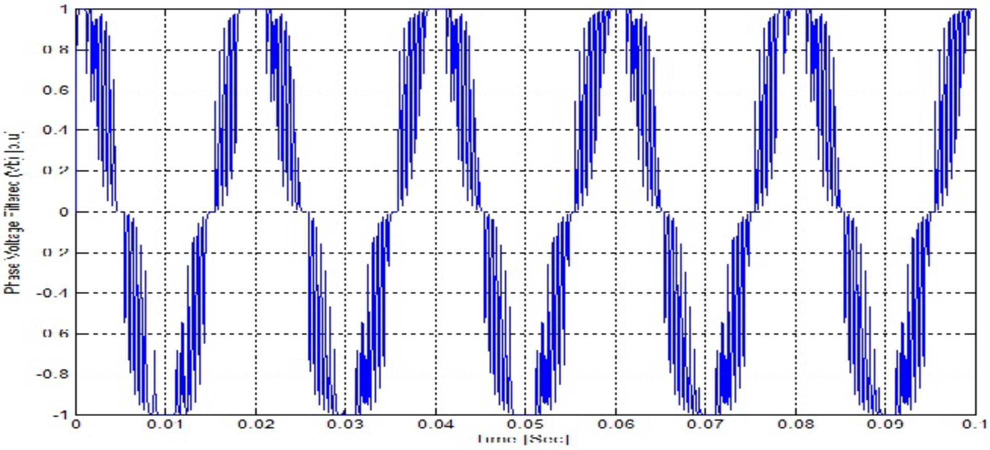


Figure 4.2.5 (h): Filtered voltage waveform (V_b)

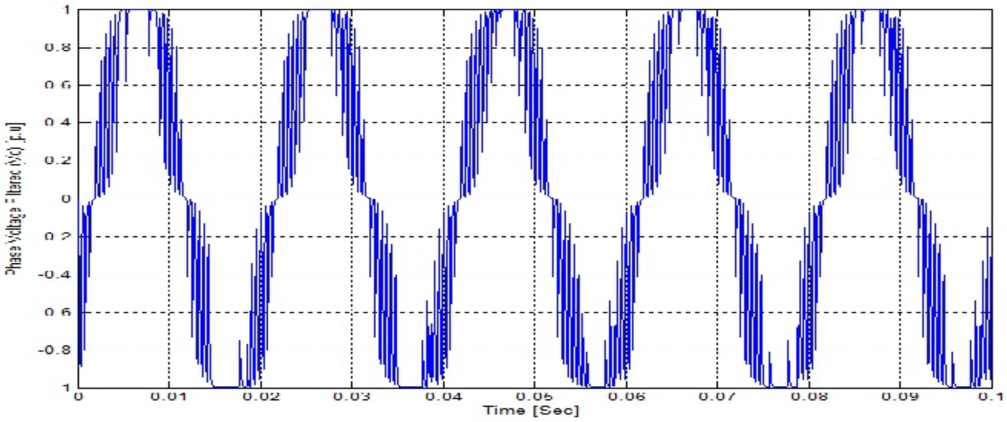


Figure 4.2.5 (i): Filtered voltage waveform (V_c)

- **Pattern-2 filtered voltage outputs at time constant 0.8ms**

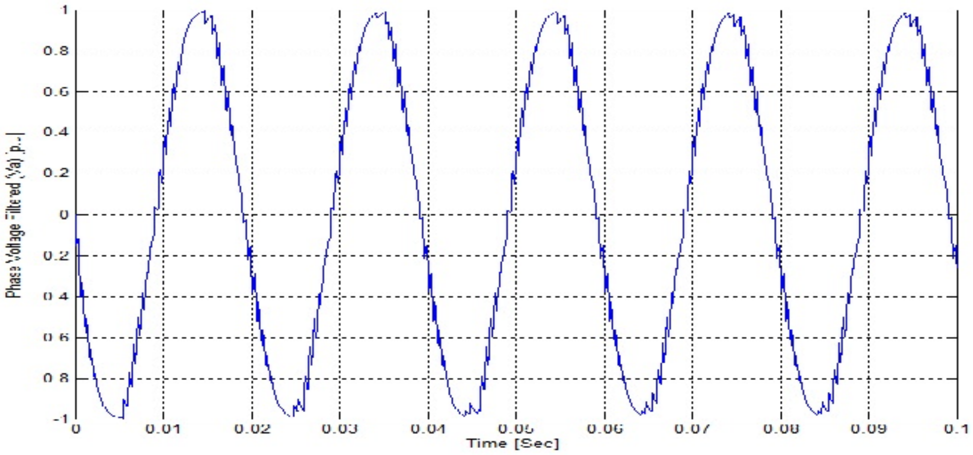


Figure 4.2.5 (j): Filtered voltage waveform (V_a)

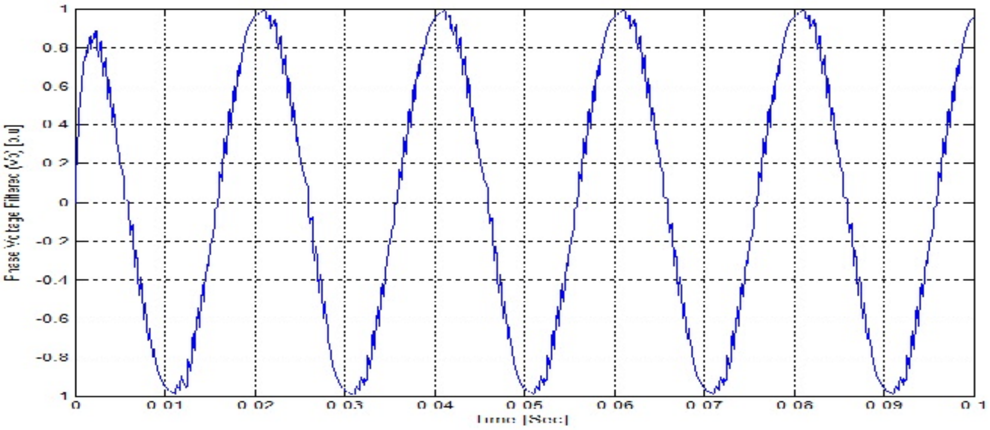


Figure 4.2.5 (k): Filtered voltage waveform (V_b)

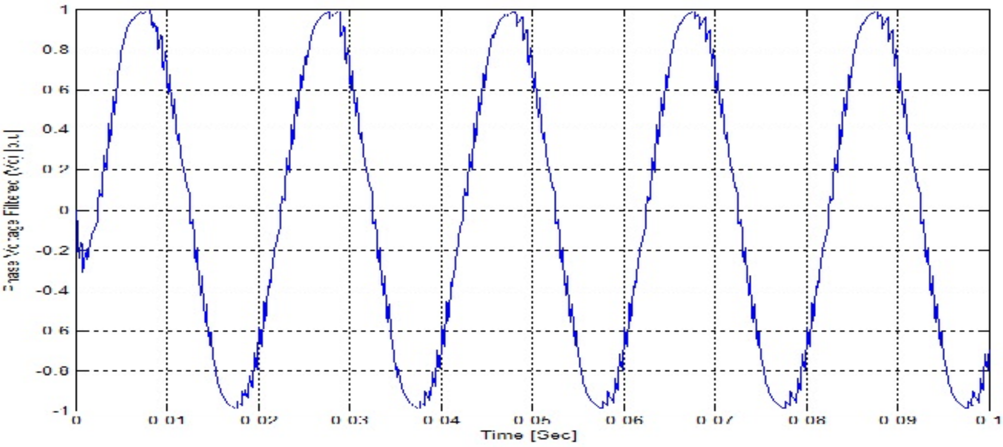


Figure 4.2.5 (l): Filtered voltage waveform (V_c)

4.3 Generalised Matlab/Simulink model of SVPWM (With 3-Phase Transformer):

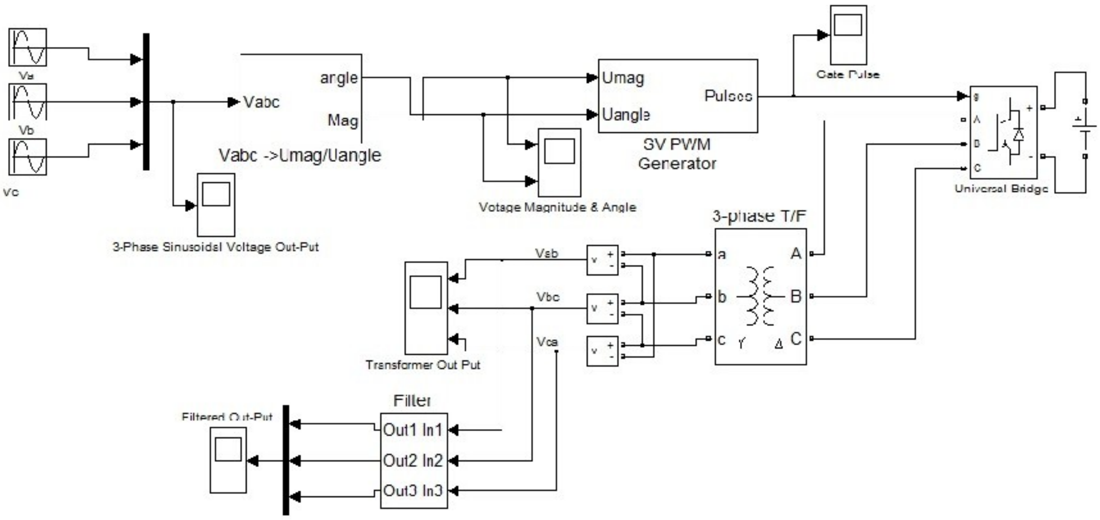


Figure 4.3: SVPWM inverter with 3-phase transformer

Three phase transformers are used throughout industry to change values of three phase voltage and current. Since 3-phase power is the most common way in which power is produced, transmitted and used. In this section the different types of three phase transformers connections.

There are only 4 possible transformer combinations:

- **Delta to Delta** - used in industrial applications.
- **Delta to Wye** - used in most common; commercial and industrial.

- **Wye to Delta** - used high voltage transmissions.
- **Wye to Wye** - used rare, don't use causes harmonics and balancing problems.

Three-phase transformers are connected in “Delta or Wye” configurations. A Wye-Delta transformer has its primary winding connected in a Wye and its secondary winding connected in a Delta. A Delta-Wye transformer has its primary winding connected in Delta and its secondary winding connected in a Wye. Here in this Simulink model Delta-Wye configuration is used. The outputs of SVPWM inverter with 3-phase transformer in both pattern such as Pattern-1 and Pattern-2 are shown in following figures.

- **Pattern-1 outputs SVPWM inverter with 3-phase Transformer:**

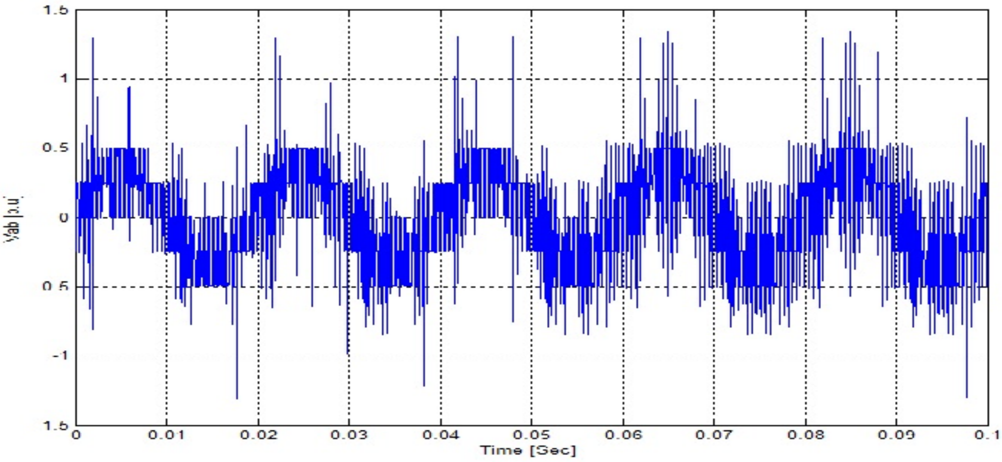


Figure 4.3.1: Voltage waveform (V_{ab})

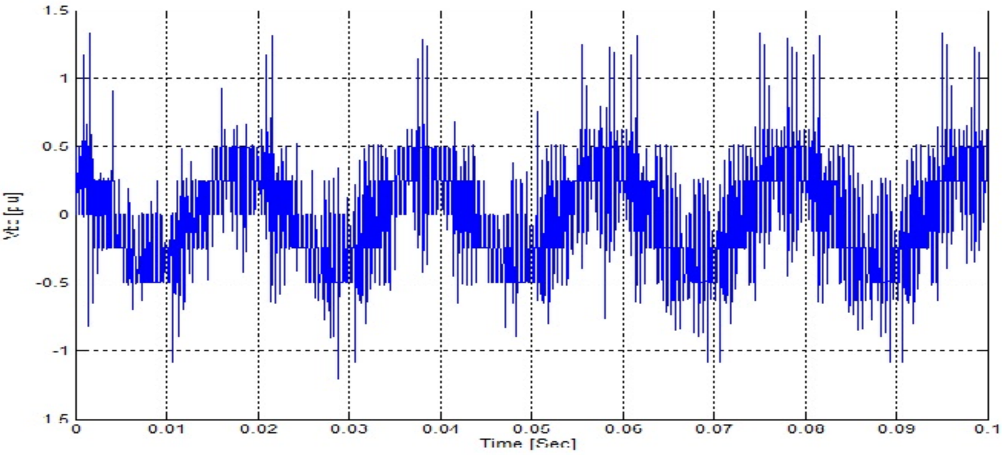


Figure 4.3.2: Voltage waveform (V_{bc})

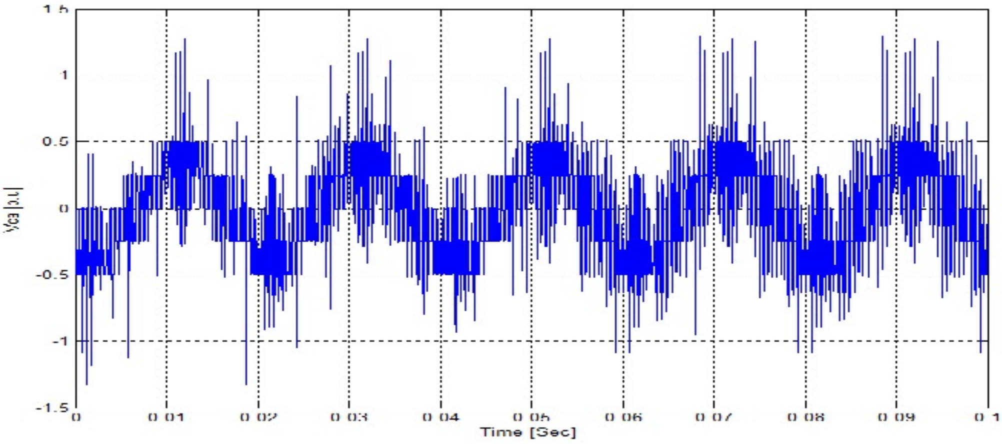


Figure 4.3.3: Voltage waveform (V_{ca})

- **Pattern-1 3-phase filtered voltage (Va,Vb,Vc) output:**

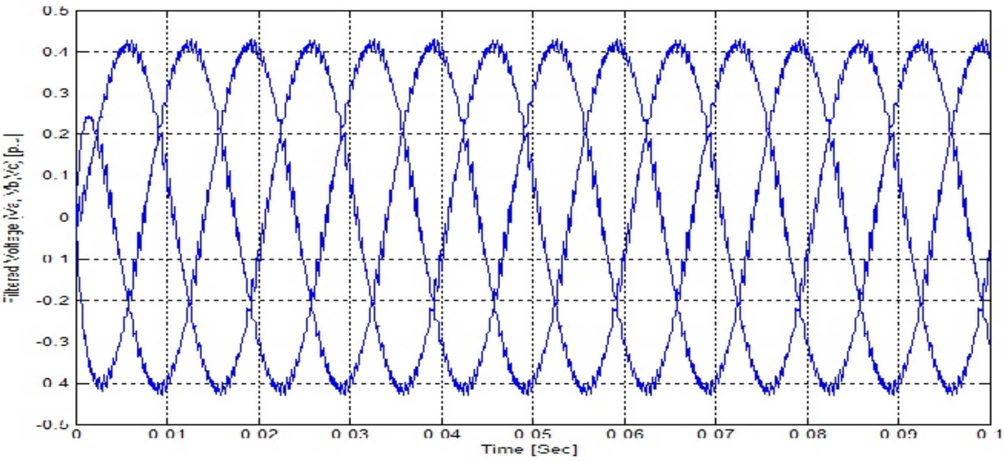


Figure 4.3.4: 3-phase filtered voltage (V_a,V_b,V_c)

- **Pattern-2 Outputs of SVPWM inverter with 3-phase Transformer:**

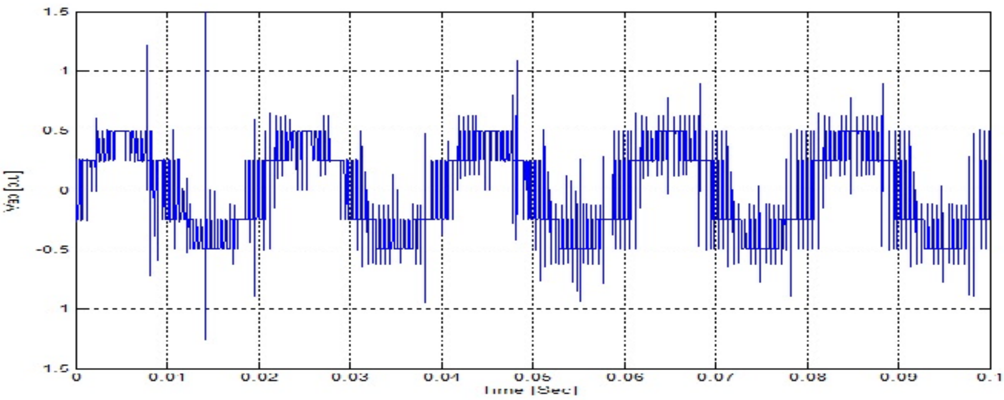


Figure 4.3.5: Voltage waveform (V_{ab})

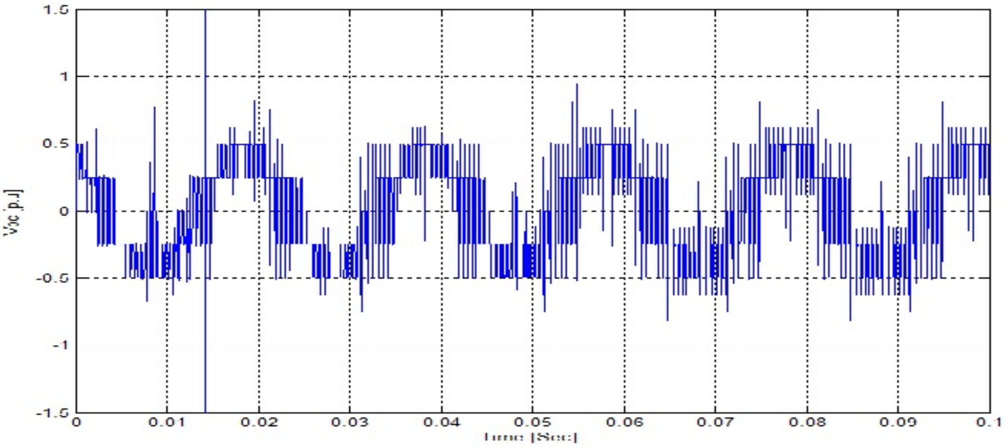


Figure 4.3.6: Voltage waveform (V_{bc})

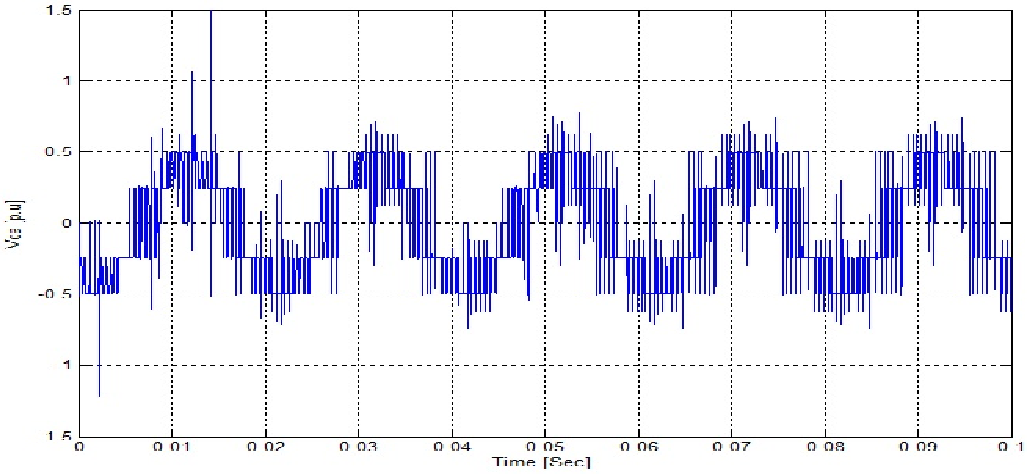


Figure 4.3.7: Voltage waveform (V_{ca})

- **Pattern-2; 3-phase filtered voltage (V_a,V_b,V_c) output:**

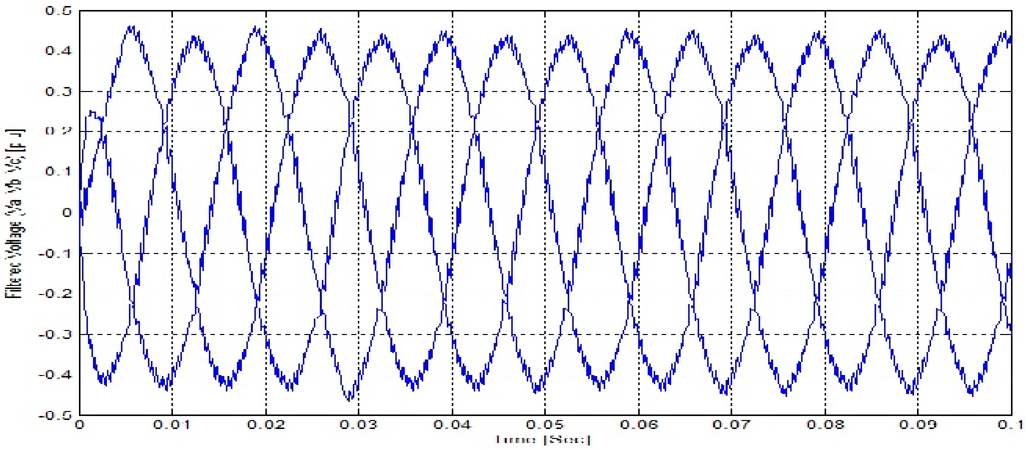


Figure 4.3.8: 3-phase filtered voltage (V_a,V_b,V_c)

4.4 Generalised Matlab/Simulink model of SVPWM (With 3-phase Transformer and 3-phase Series RLC Load):

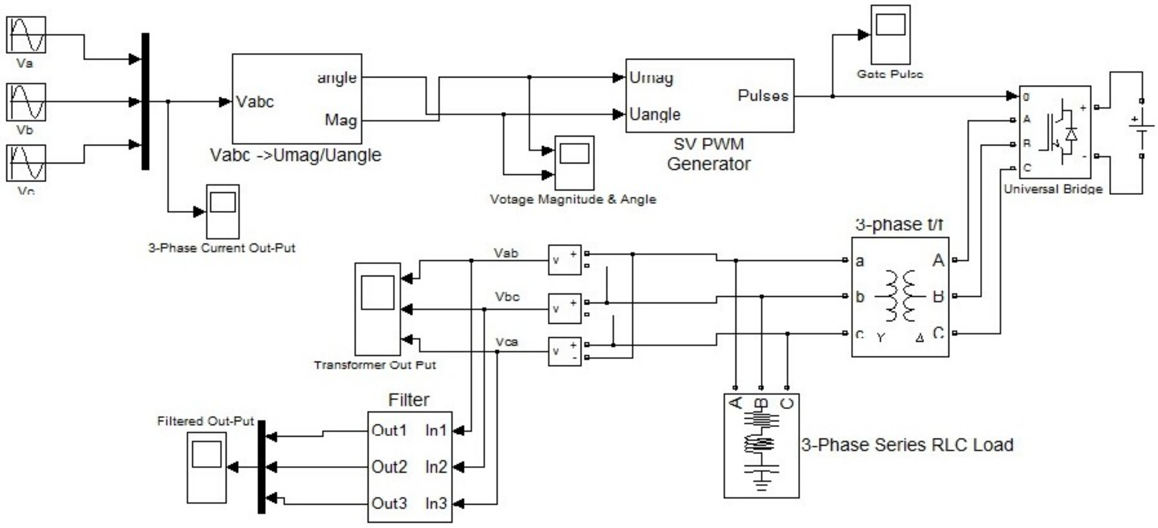


Figure 4.4: SVPWM inverter with 3-phase Transformer and Series RLC Load

In this Simulink model 3-phase transformer with Delta-Wye configuration and Series RLC Load is used. The Series RLC load block implements a linear load as a series combination of R L C elements. At the specified frequency, the load exhibits constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage. The outputs waveform of pattern-1 and pattern-2 are shown in following figures:

- **Pattern-1 outputs with 3-phase Transformer and 3-phase RLC load:**

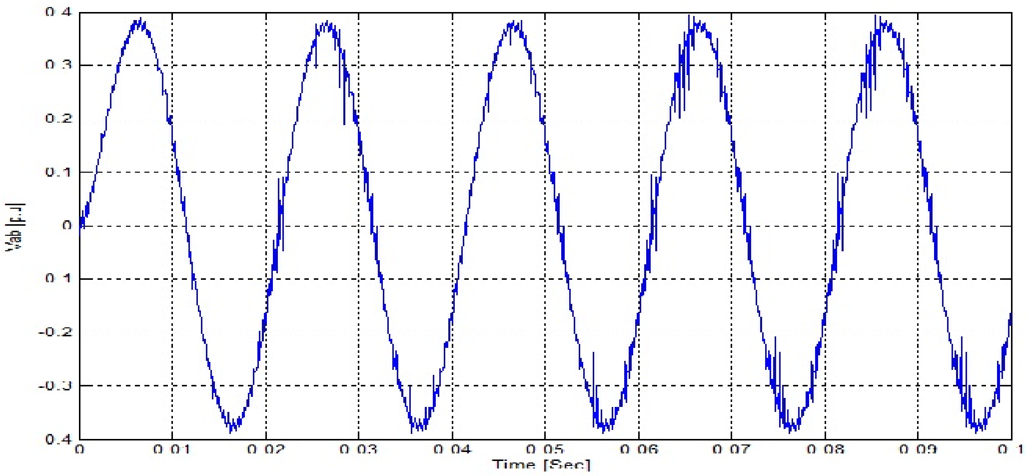


Figure 4.4.1: Voltage waveform (V_{ab})

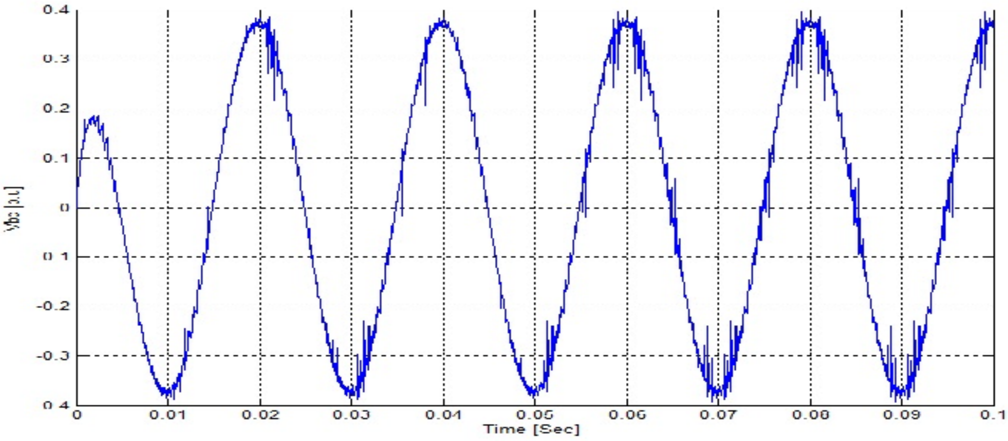


Figure 4.4.2: Voltage waveform (V_{bc})

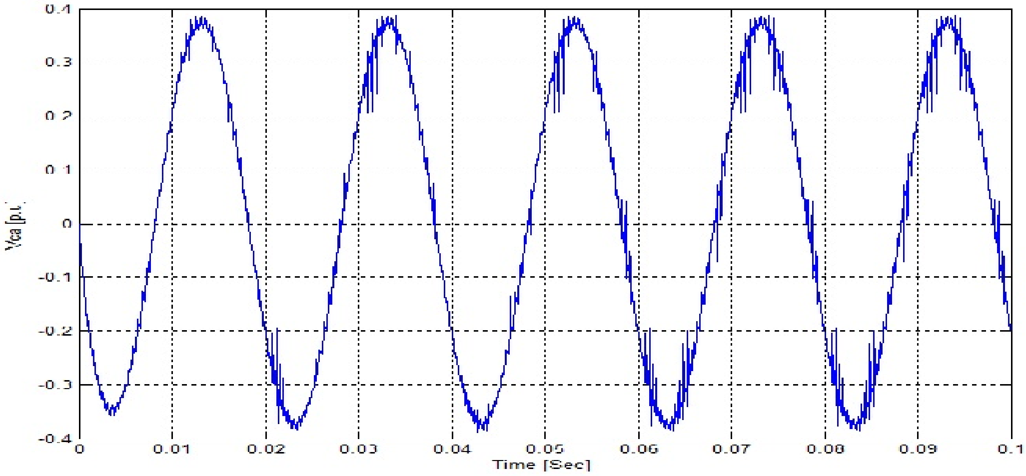


Figure 4.4.3: Voltage waveform (V_{ca})

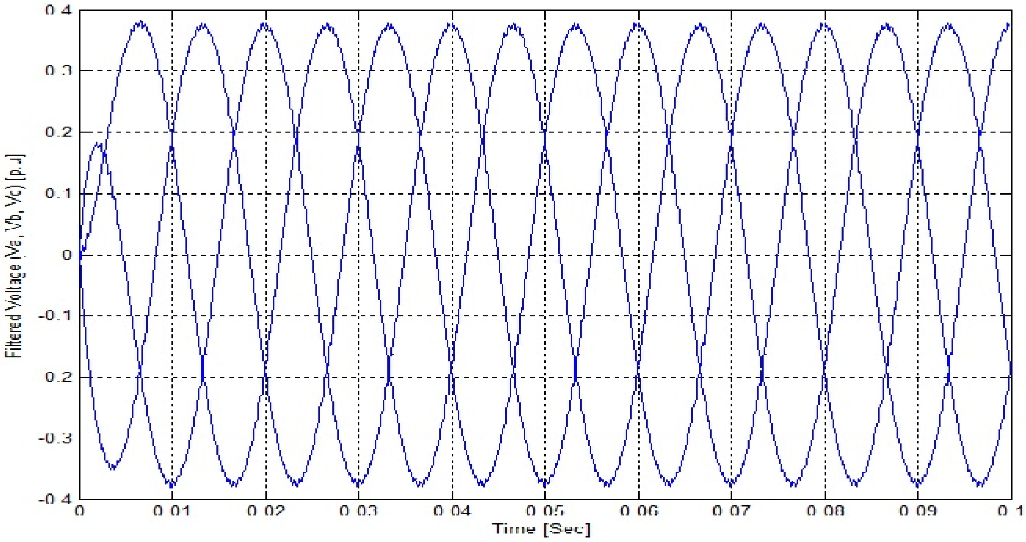


Figure 4.4.4: Filtered 3-phase voltage waveform at time constant 0.1ms

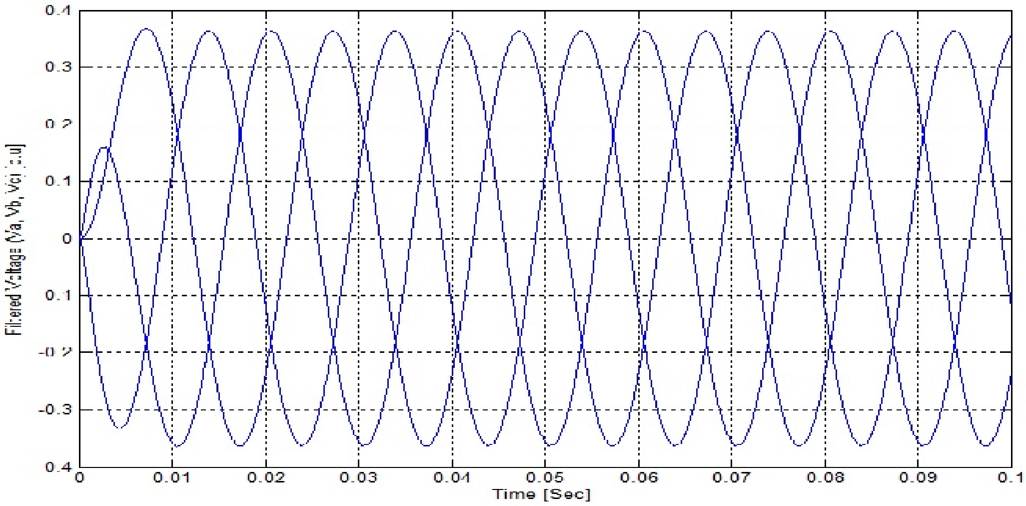


Figure 4.4.5: Filtered 3-phase voltage waveform at time constant 0.8ms

- **Pattern-2 outputs with 3-phase Transformer and 3-phase RLC load :**

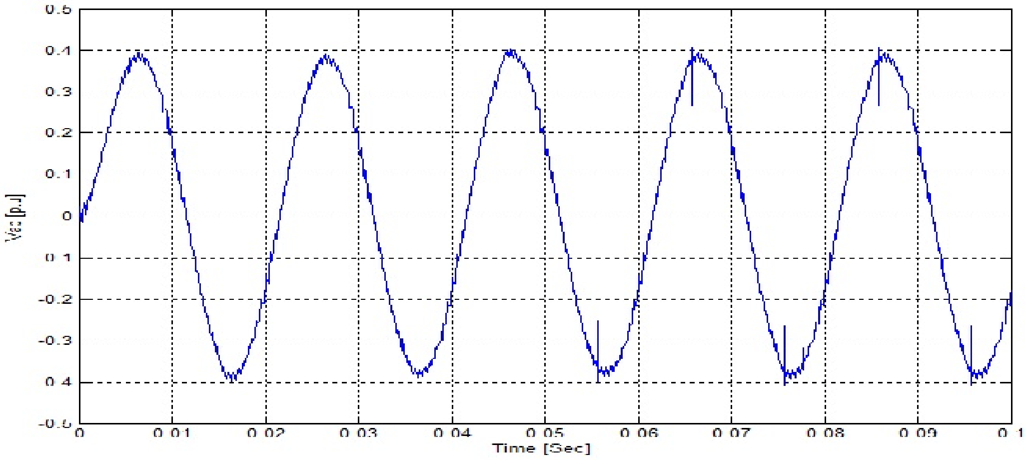


Figure 4.4.6: Voltage waveform (V_{ab})

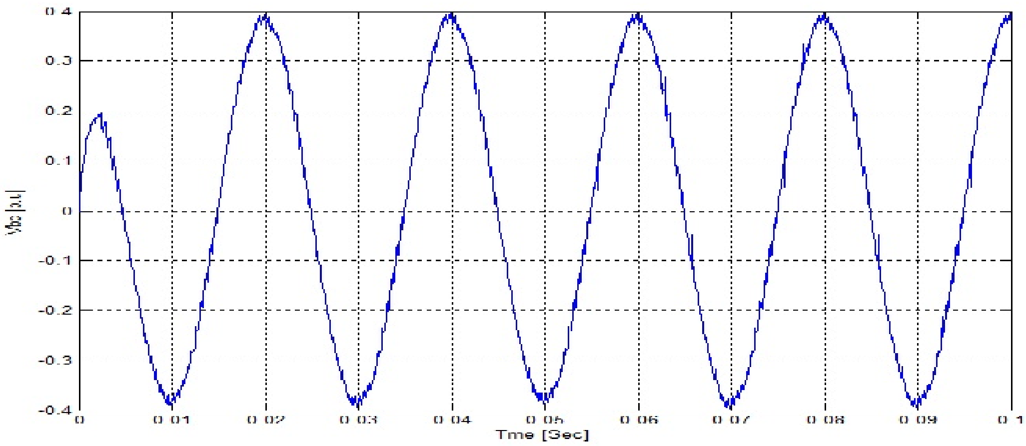


Figure 4.4.7: Voltage waveform (V_{bc})

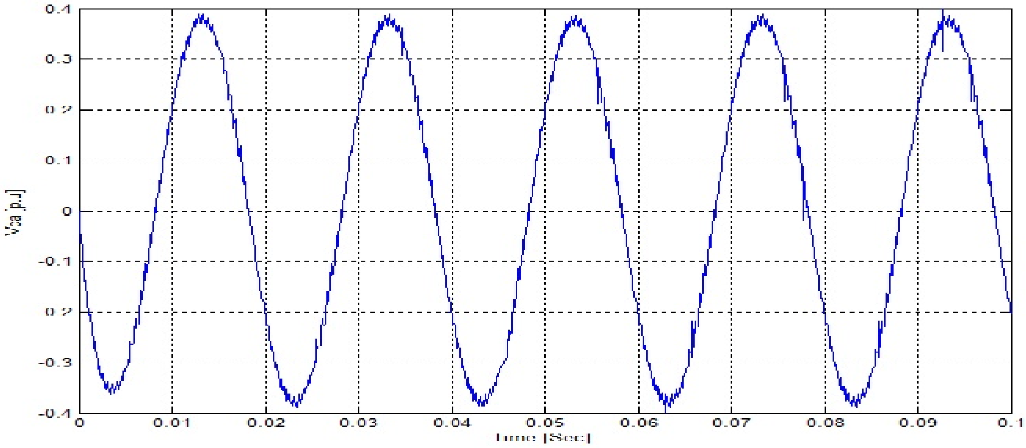


Figure 4.4.8: Voltage waveform (V_{ca})

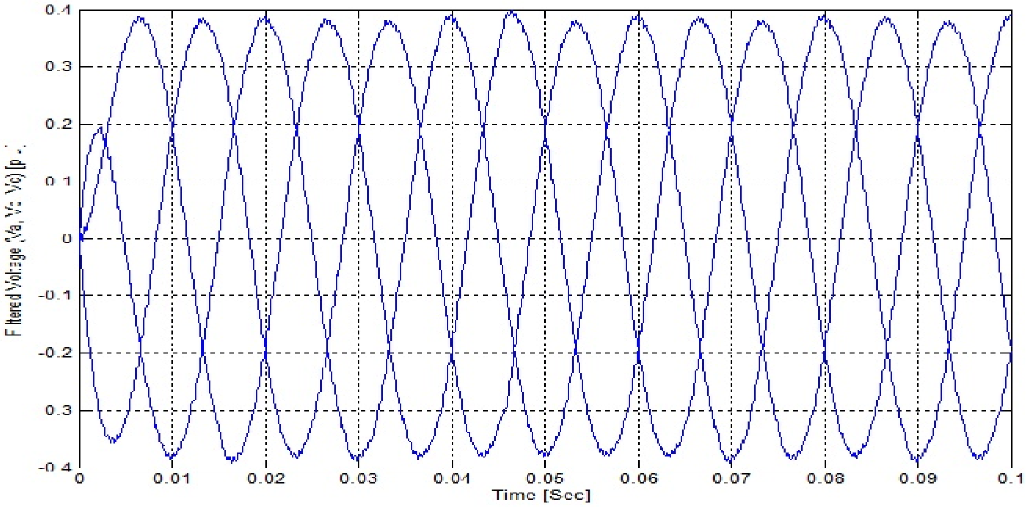


Figure 4.4.9: Filtered 3-phase voltage waveform at time constant 0.1ms

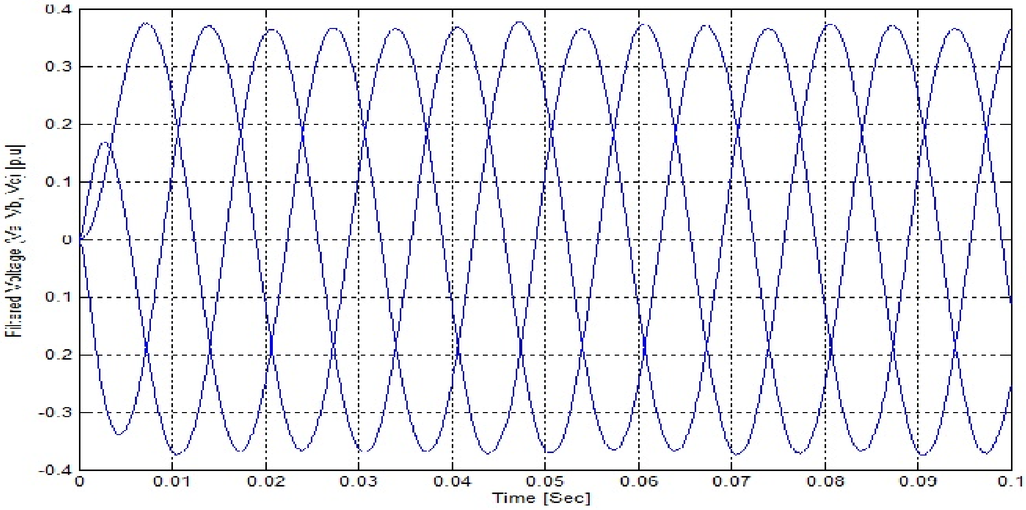


Figure 4.4.10: Filtered 3-phase voltage waveform at time constant 0.8ms

4.5 Generalised Matlab/Simulink model of SVPWM (With 3-phase Transformer and 3-phase Parallel RLC Load):

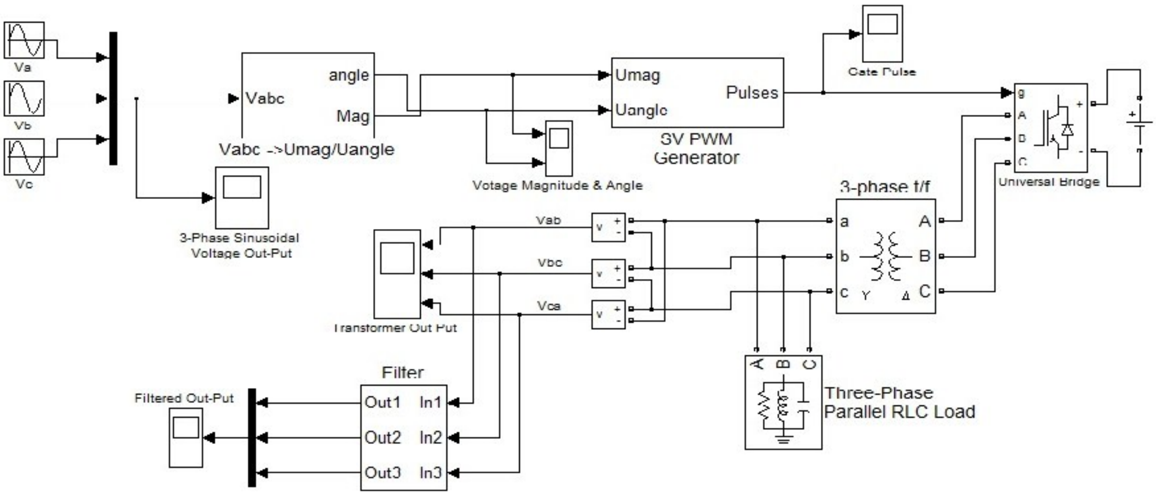


Figure 4.5: SVPWM inverter with 3-phase Transformer and Parallel RLC Load

In this Simulink model 3-phase transformer with Delta-Wye configuration and 3-phase Parallel RLC Load is used. Parallel RLC load block implements a linear load as a series combination of R L C elements. At the specified frequency, the load exhibits constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage. The outputs waveform of pattern-1 and pattern-2 are shown in following figures:

- **Pattern-1 Outputs with 3-phase Transformer and 3-phase parallel RLC load:**

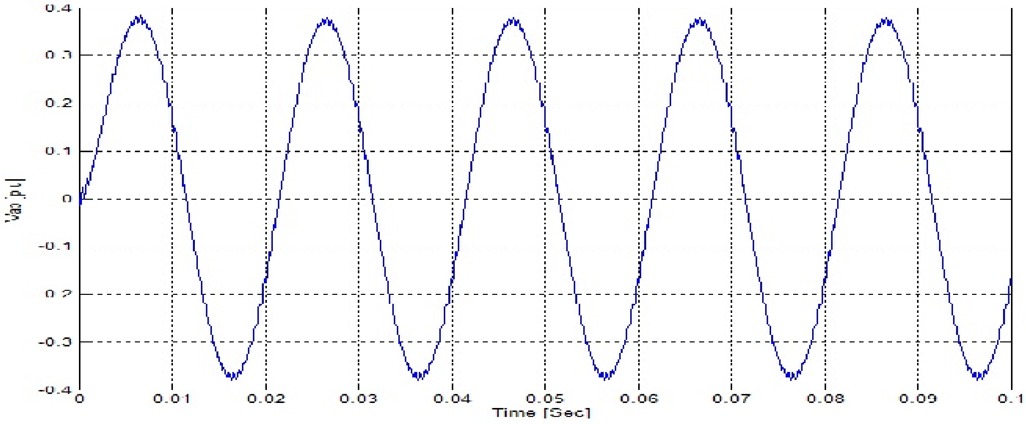


Figure 4.5.1: Voltage waveform (V_{ab})

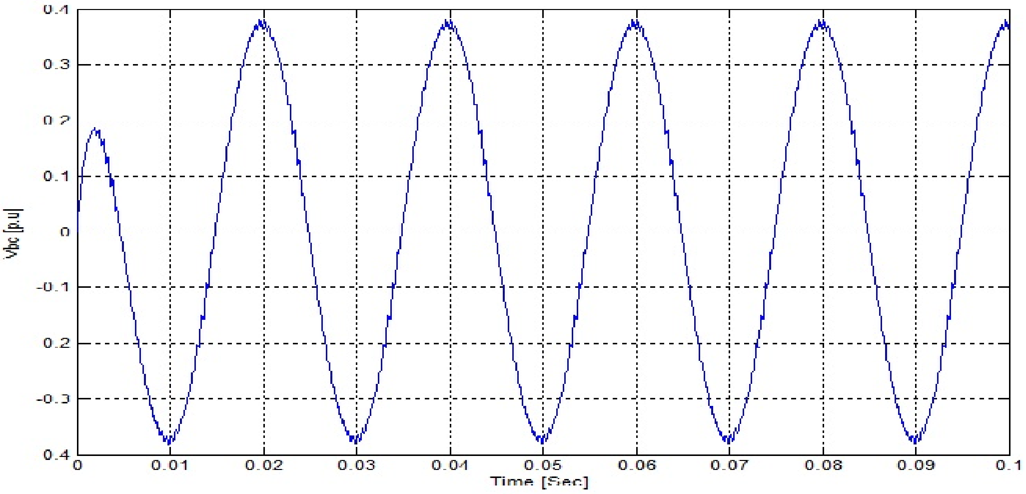


Figure 4.5.2: Voltage waveform (V_{bc})

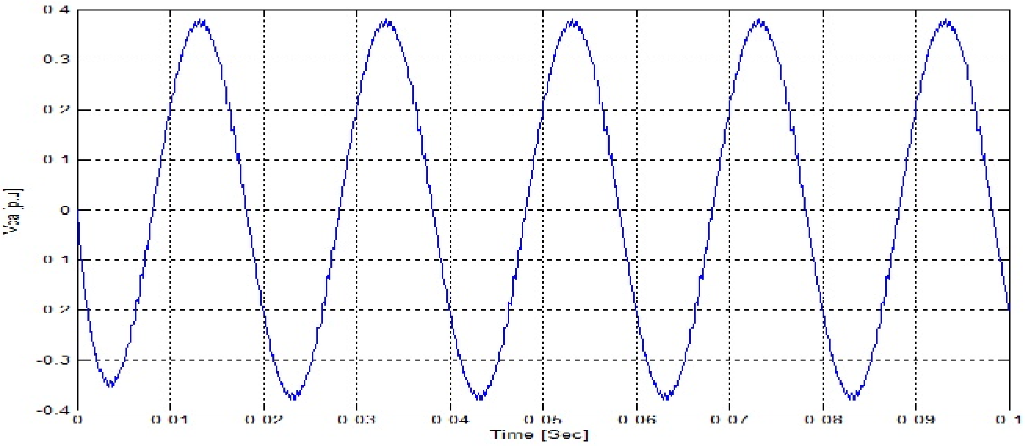


Figure 4.5.3: Voltage waveform (V_{ca})

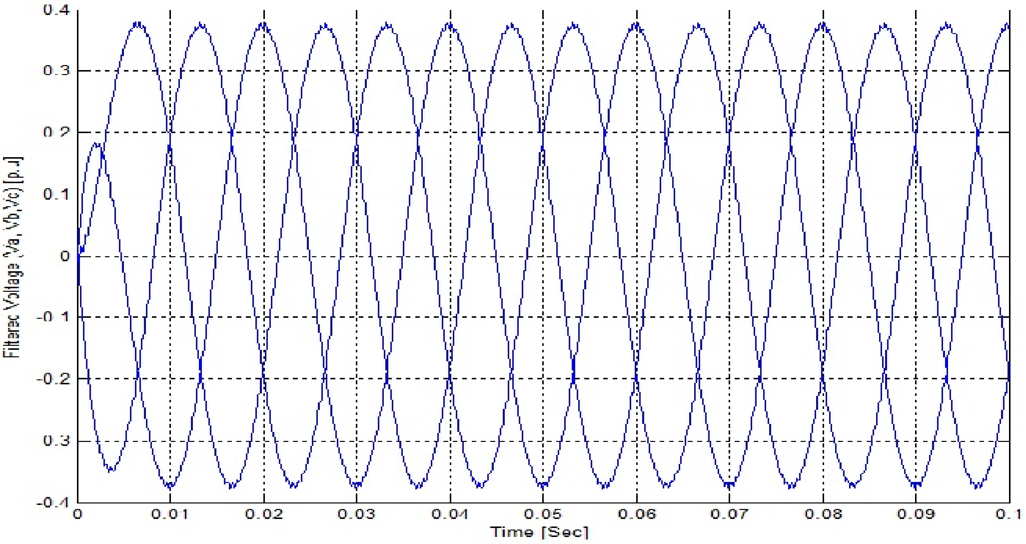


Figure 4.5.4: Filtered 3-phase voltage waveform at time constant 0.1ms

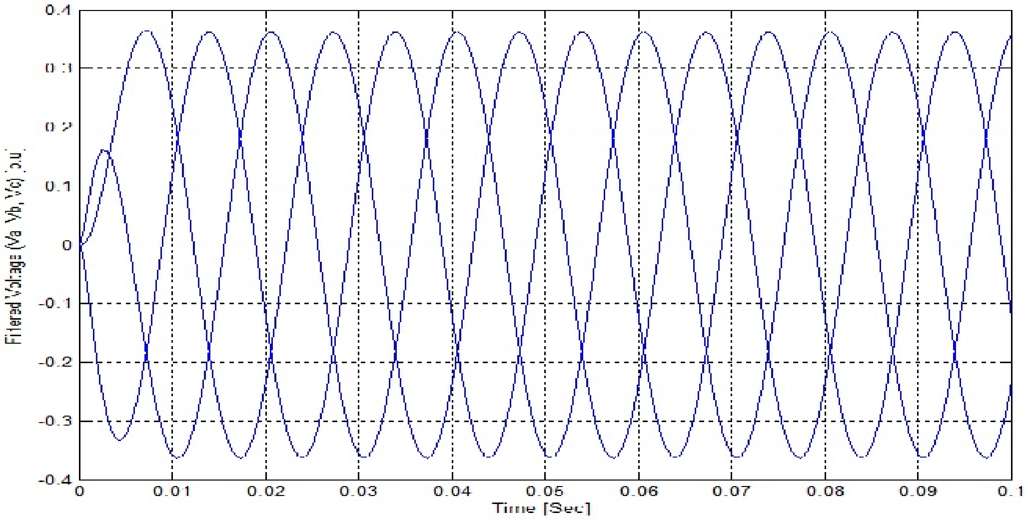


Figure 4.5.5: Filtered 3-phase voltage waveform at time constant 0.8ms

- **Pattern-2 Outputs with 3-phase Transformer and 3-phase parallel RLC load:**

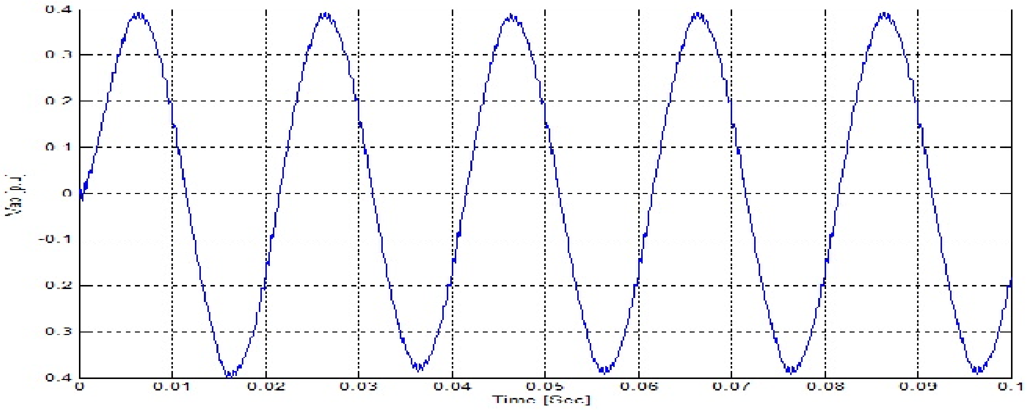


Figure 4.5.6: Voltage waveform (V_{ab})

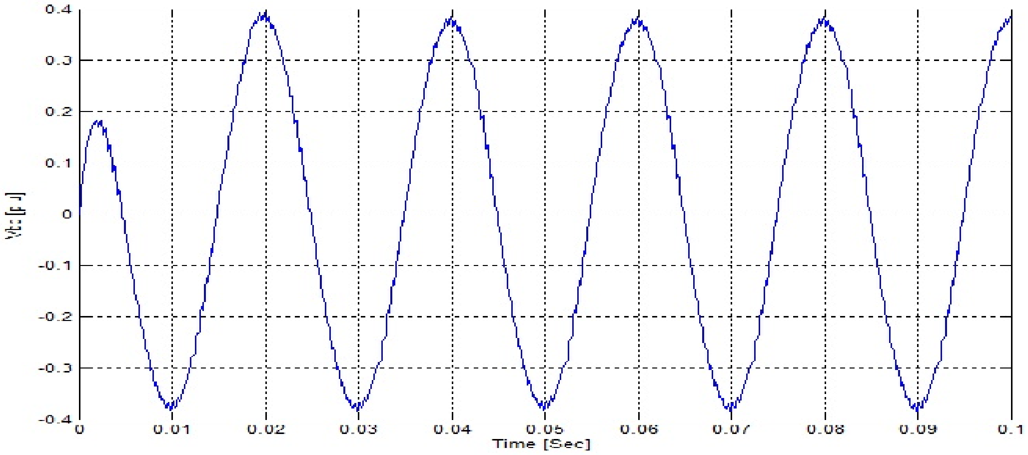


Figure 4.5.7: Voltage waveform (V_{bc})

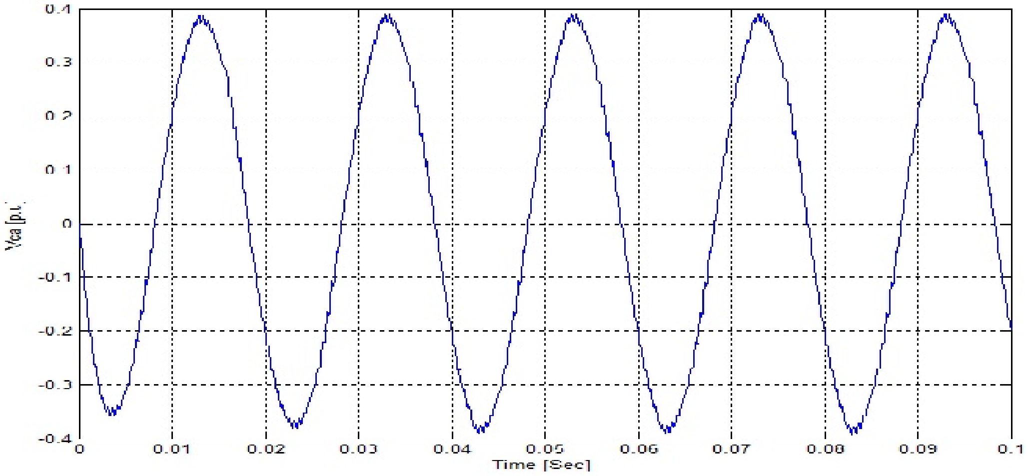


Figure 4.5.8: Voltage waveform (V_{ca})

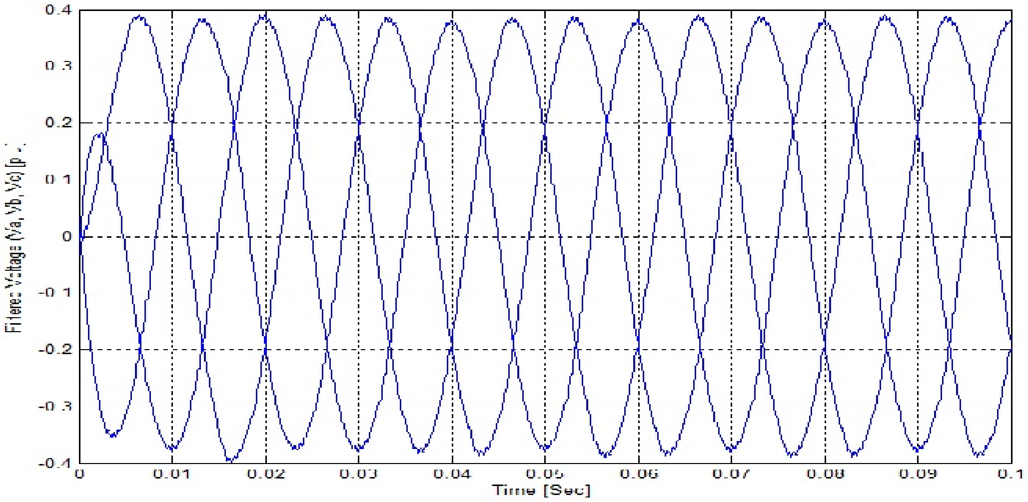


Figure 4.5.9: Filtered 3-phase voltage waveform at time constant 0.1ms

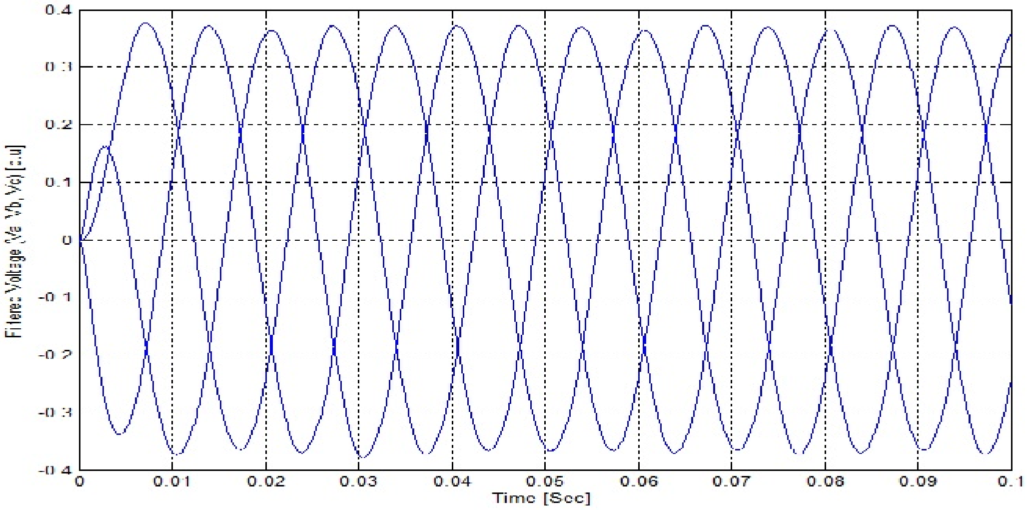


Figure 4.5.10: Filtered 3-phase voltage waveform at time constant 0.8ms

Chapter-05

CONCLUSION AND FUTURE SCOPE OF WORK

5.1 CONCLUSION

The review has covered a few different inverter topologies for photovoltaic applications. The task for such an inverter is to amplify the photovoltaic low voltage up to the higher-level voltage of the grid and to convert it from DC into AC. Moreover, the three-phase voltage source inverter should be designed with Space Vector Modulation (SVM) as switching pattern by using MATLAB/Simulink for the grid-connected PV system. The theory of the Space Vector Modulation for a 3-phase inverter is presented by this thesis. This theory has been further extended to other 3-phase converter systems and nowadays became a standard for industry. The model of a three-phase a voltage source inverter is discussed based on space vector theory. It has been shown that the SVPWM technique utilizes DC bus voltage more efficiently and generates less harmonic distortion and easier digital realization in a three-phase voltage-source inverter. For converter's gating signals generation, the space-vector pulse width modulation (SVPWM) strategy reduces the switching losses by limiting the switching to the two thirds of the pulse duty cycle. A theoretical study concerning the application of the SVPWM the three-level voltage inverter and simulation results are presented to prove the effectiveness of the SVPWM in the contribution in the switching power losses reduction, out voltages with less-harmonics. The obtained simulation results were satisfactory. As prospects, future experimental works will validate the simulation results.

5.2 FUTURE SCOPE OF WORK

With the inverter proposed in this model satisfactory results are obtained from the simulations shown. A hardware circuit now needs to be developed which remains as a future scope of work. A VSI fed inverter design for SVPWM has been proposed. A CSI fed inverter design can be taken up for future work. Filters are used with fixed time constants. Optimization of the filter now needs to be carried out. A series and a parallel RLC load have been connected. No preference has been pointed out regarding its choice.

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