DESIGN AND CONTROL OF MULTILEVEL INVERTER FOR SOLAR PV APPLICATION

A Thesis Submitted
In partial fulfillment of the Requirements
for the degree of

MASTER OF TECHNOLOGY

In

ELECTRICAL ENGINEERING
Specialization
In

Power System Engineering

By

MARUFUL HAQUE ANSARI
(Roll No.1200100582)

Under the supervision of

Dr. MIRZA MOHAMMAD SHADAB
Guide
Assistant Professor
Deptt. of Electrical Engineering

ISARAR AHAMAD
Co- Guide
Assistant Professor
Deptt. of Electrical Engineering

DEPARTMENT OF ELECTRICAL ENGINEERING
INTEGRAL UNIVERSITY, LUCKNOW, UP (INDIA)
2022

DEPARTMENT OF ELECTRICAL ENGINEERING
INTEGRAL UNIVERSITY, LUCKNOW

CERTIFICATE

This is to certify that **Mr. Maruful Haque Ansari (1200100582*)***, has carried out the project work, presented in this report entitled **"Design & Control of Multilevel Inverter for Solar PV Application"** submitted in partial fulfillment of the requirement for the award of the degree of **Master of Technology** in **Electrical Engineering** with specialization in **Power System Engineering of Electrical Engineering**, **Integral University, Lucknow** during the academic year 2022-2023.

The dissertation work carried out by them is satisfactory. The report embodies result of the original work and studies carried out by them and the contents of the report do not form the basis for the award of any other degree to the candidates.

Dr. MIRZA MOHAMMAD SHADAB
Supervisor
(Assistant Professor)
Deptt. of Electrical Engineering

ISARAR AHAMAD
Co-supervisor
(Assistant Professor)
Deptt. of Electrical Engineering

DECLARATION

I **Maruful Haque Ansari**, hereby certify that the work is being presented by me in this thesis titled "**Design & Control of Multilevel Inverter for Solar PV Application**" by me in partial fulfillment of requirements for the award of Degree of Master of Technologies in Power System Engineering to Integral University is an authentic record of my original work carried out under the supervision of **Dr. Mirza Mohammad Shadab**, Assistant Professor, and **Isarar Ahamad** Assistant Professor, Electrical Engineering Department.

The matter presented in this thesis has not been submitted earlier in any other University/ Institute for the award of any degree.

MARUFUL HAQUE ANSARI
MTech in Electrical Engineering
(Power System Engineering)
Roll No. 1200100582

ACKNOWLEDGEMENT

First of all, I would like to thank Almighty God who has given me strength, patience, and ability to complete this project work.

It gives us the greatest pleasure to express our deepest attitude and warmest thanks to **Dr. Mirza Mohammad Shadab** Assistant Prof., and **Isarar Ahamad**, Assistant Prof., Department of Electrical Engineering, Integral University for kind supervision, patient guidance, valuable suggestions and support throughout this report. We are truly very fortunate to have the opportunity to work with them. We found this guidance to be extremelyvaluable.

We are very grateful to **Dr. Mohammed Asim and Dr. A. F. Minai** MTech. Dissertation Coordinator, and Department of Electrical Engineering for his constant support and able guidance at various stages.

We would like to thank entire faculty members, staff of the Electrical Engineering Department, and friends who devoted their valuable time and helped us in all possible ways towards successful completion of present work. We say thanks to all those who have contributed directly or indirectly to this work.

Last but not least, we would like to thank our parents for their constant support and encouragement. They have always wanted the best for us and we admire their determination and sacrifice.

DATE: 02-07-2022 MARUFUL HAQUE ANSARI

PLACE: LUCKNOW (1200100582)

ABSTRACT

The demand of solar energy sources has increased considerably to avoid environmental pollution and to congregate the future power demand. Pumping of power from photo voltaic system to the utility grid depends on the level of power generation. There are certain challenges in the integration of both types of systems directly. The high penetration of Photovoltaic system and distributed generators requires innovative planning for the operation and management of the electricity grid in order to sustain or even to improve the consistency and quality of power. The power electronic components play a vital role for synchronization of distributed generation to the existing grid. In the present scenario current controlled pulse width modulated voltage source inverters is widely used to accomplish the task.

In the thesis effect of irradiance on the performance solar panel is analyzed by simulation result. A new control strategy for single phase grid-connected inverters proposed in this thesis. The proposed method is based on reference current generation from the grid voltage. The proposed strategy full fill the main objective of a PLL, i.e., is to generate a signal in which the phase is the same as the phase of a reference signal along with this the cost of implementation of PLL is eliminated and the current is maintained close to unity power factor in this method.

In the present work the Hysteresis band current control (HCC) technique has been implemented for the controlled of voltage source inverters. After analyzing the result of all the controller, a new control strategy proposed for single phase grid system which reduce the harmonic distortion as compared to the other controller during change of band.

In this thesis after the case study reduction of harmonics is taken as the main objective of thework. The results of this work revels that the harmonics distortion of HCC.

Table of Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

1.1 Introduction

In this aggressive world, every country needs to be in the club of developed countries by faster development and advance technology. The disequilibrium of environment caused by rapid industrialization and ever mounting population are the major hindrance for a developing country like India. The use of fossil fuel for production of power is accountable for increase of greenhouse gases. Day by day the emission label is seems to be increasing like a never-ending process. Seeing the uncharacteristic changes in climate, an international joint effort is required to avoid the adverse consequences in an effective and economical way. For a country like India whose per capita consumption is increasing exponentially, the hunger for power cannot be fulfilled by the conventional sources while environmental issues are main concerned. Therefore, generation of power from green sources like PV System has become an essential part to conquer sustainability and reduce the consumption of fossil fuel.

The huge amount of reservoir of renewable sources available can be utilized to enhance the production of clean power and can be an alternate for the diminishing fossil fuel sources. But it needs advance technology and government initiative to harness power from the renewable. For the last 100 years, the industry has been ruled by fossil fuels. Our electricity comes predominantly from coal and natural gas, and our transportation fuel comes from gasoline and diesel – all of them are remnants of fossil deposits. The traditionally exploited fossil fuels are however fast depleting. This implies that over the next 50-75 years, a large part of the energy economy will be replaced by alternative fuels. In the future energy scenario solar power will be an essential component of the power sector in India. Due to the epitaxial growth of PV technology and government subsidies the unit cost of power generated from solar energy is now within affordable limit [1-6].

Pumping of power from photovoltaic system to the utility grid depends on the level of power generation. There are certain challenges in the integration of photovoltaic systems directly. The high penetration of Photovoltaic system and distributed generators requires innovative planning for the operation and management of the electricity grid in order to sustain or even to improve the consistency and quality of power. The power electronic components play a vital role for synchronization of distributed generation to the existing grid. In the present scenario current controlled pulse width modulated voltage source inverters is widely used to accomplish the task.

1.1.1 Electricity from Solar Energy

According to MNRE the total installed capacity of India is as on January 2019 is 350.162 GW.

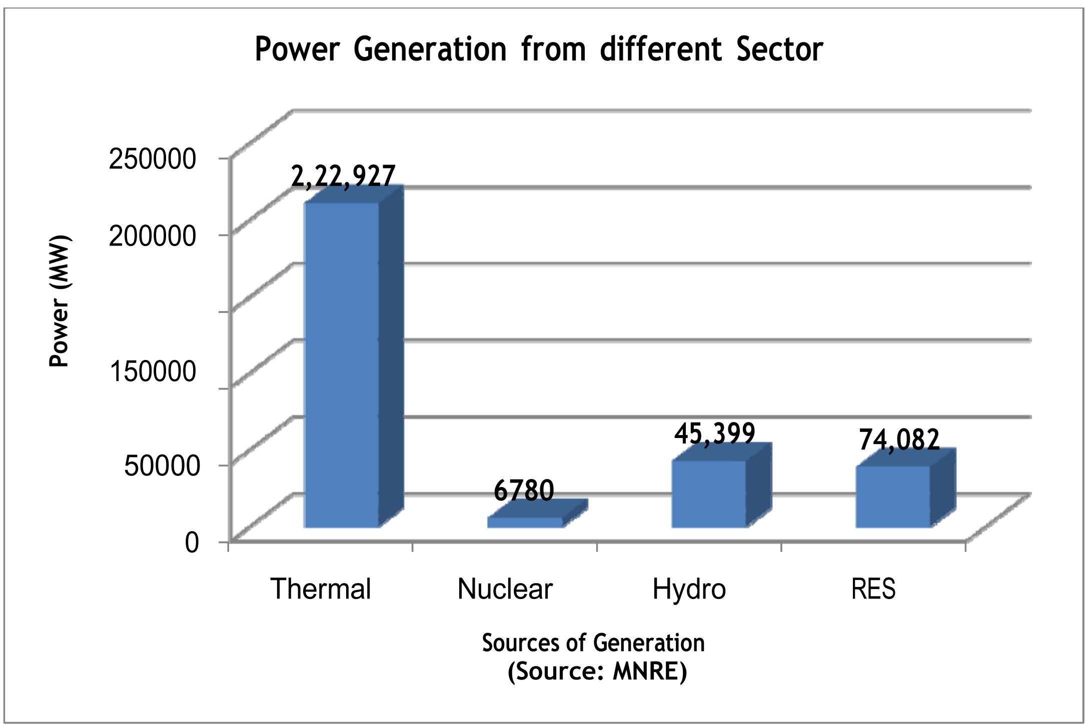


Figure 1.1 Total power generation in India from different sector

The power generated from different sources is given in the figure 1.1. As per the data the maximum power is produced from the thermal sector. As the resources of this sector are decreasing so it very difficult to full fill the energy needs for all the common people. Electric power consumption (kWh per capita) is increased significantly during the past year as shownin the figure 1.2 but we are still far behind in the world map although India is the 3rd largest power producer in the world.

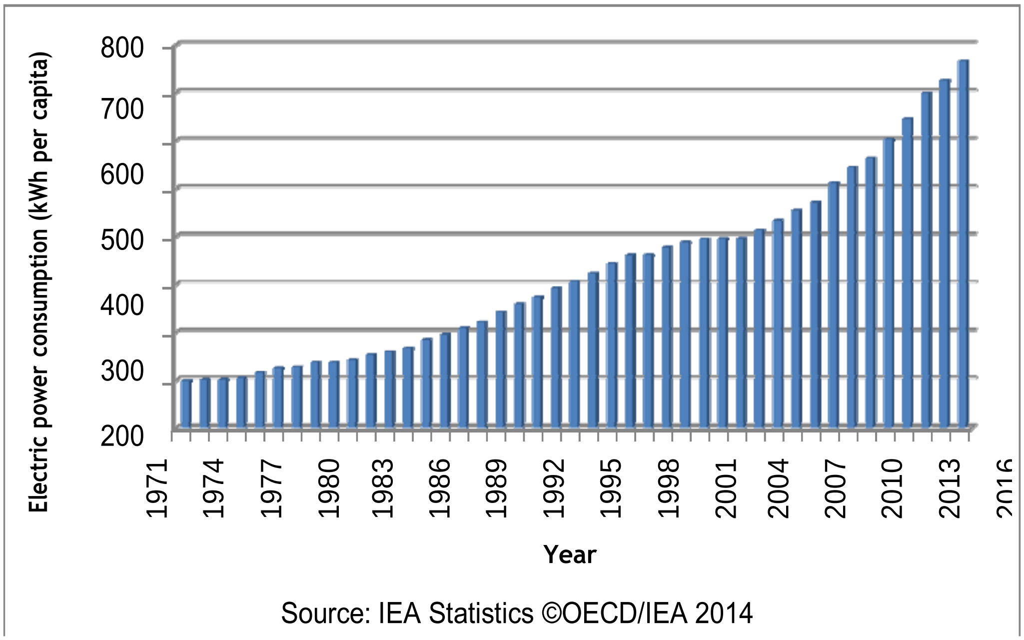


Figure 1.2 Electric power consumption (kWh per capita)

Figure 1.3 shows the per capita consumption of India with respect to some developed and developing countries which indicate we are far behind but as per central Electricity authority (CEA) the figure already touches 1149 kWh during 2017-2018.

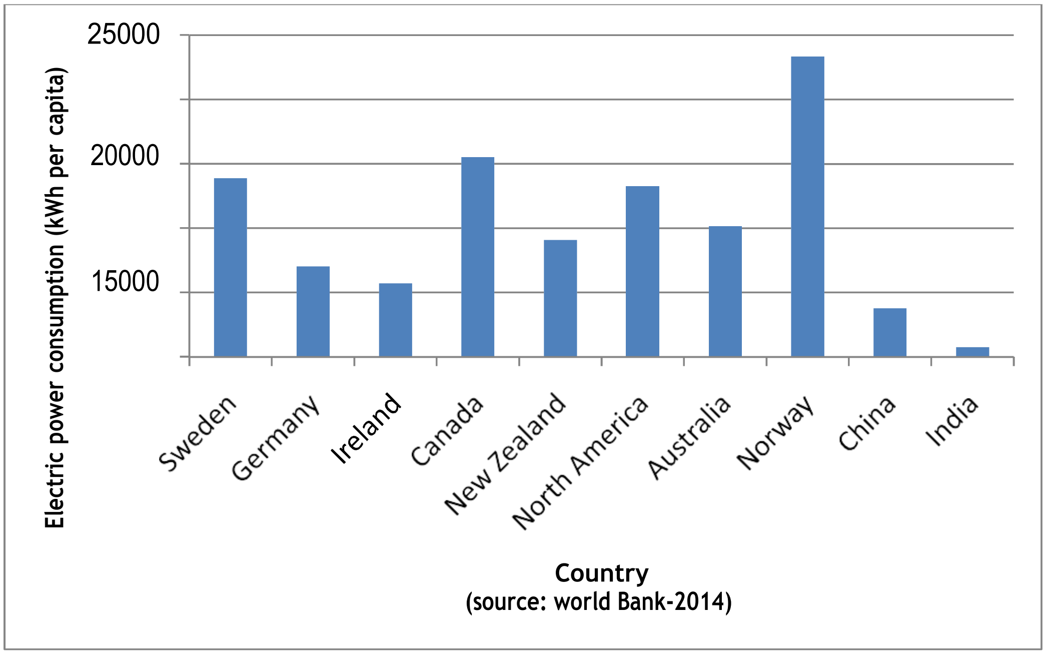


Figure 1.3 Per capita consumption of some different country

As of March 2019, total wind power installed capacity stood at 36,625.61 MW, solar power at 6,762.85 MW, Biomass at 4,831.33 MW, small hydro power at 4,273.90 MW while, waste to power at 115 MW, renewable energy installed capacity totaled 42,726.69 MW, respectively as shown in figure 1.4.

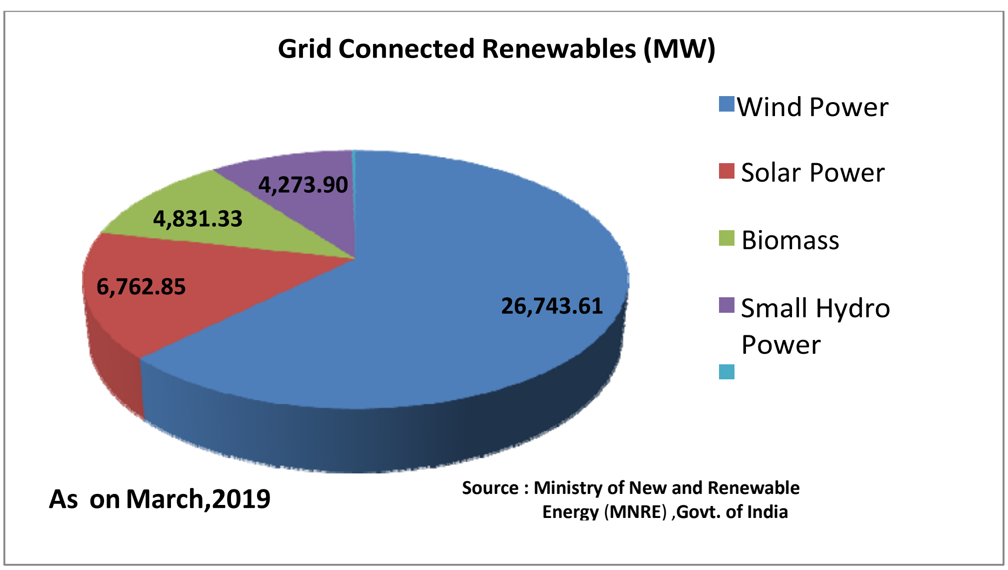


Figure 1.4 Grid Connected Renewable Energy Installed Capacity

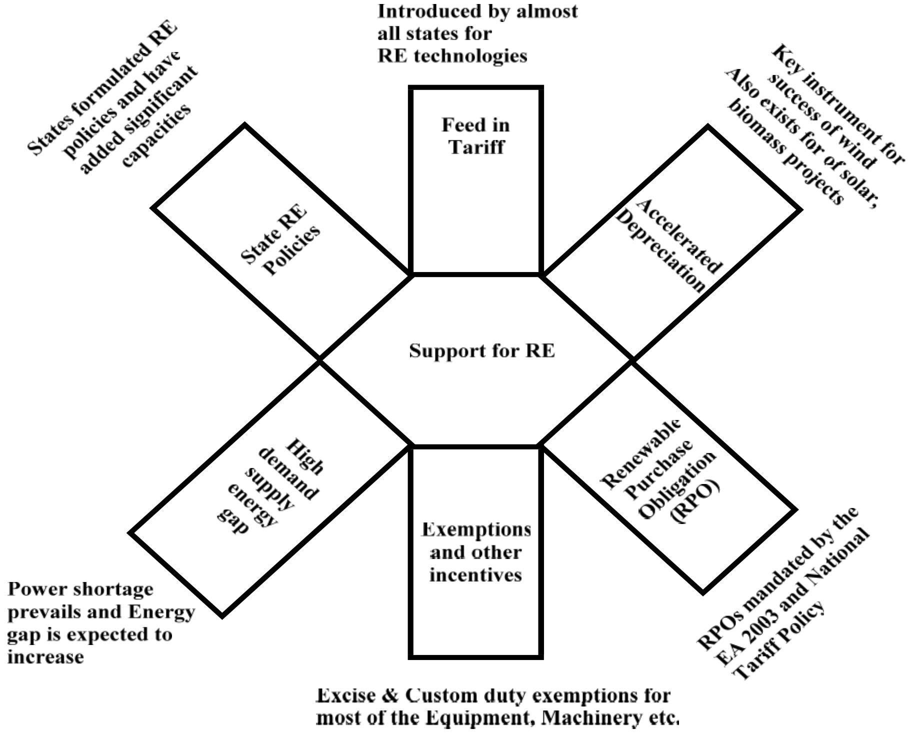


Figure 1.5 Government Support for Renewable energy (Source:MNRE)

Due to government initiative and support the energy production from renewable source is fourfold as compared to other sector. Figure 1.5 given below shows the government mechanism for support of growth of renewable in India.

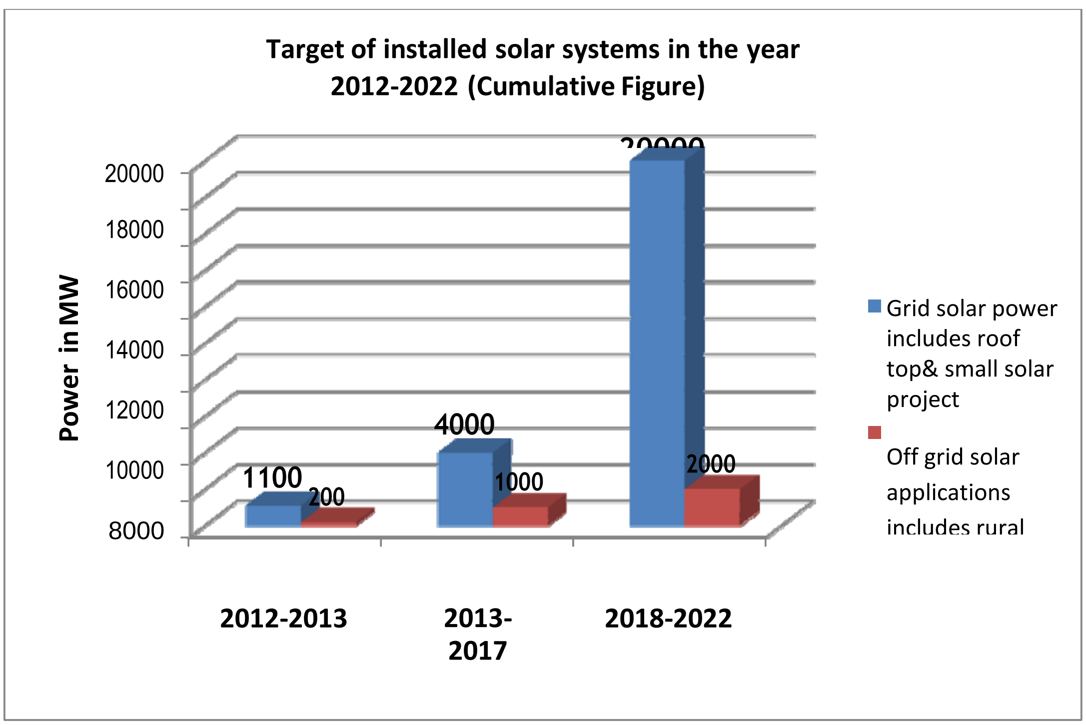


Figure 1.6 Target of installed solar systems in the year 2012-2022 (Cumulative Figure)

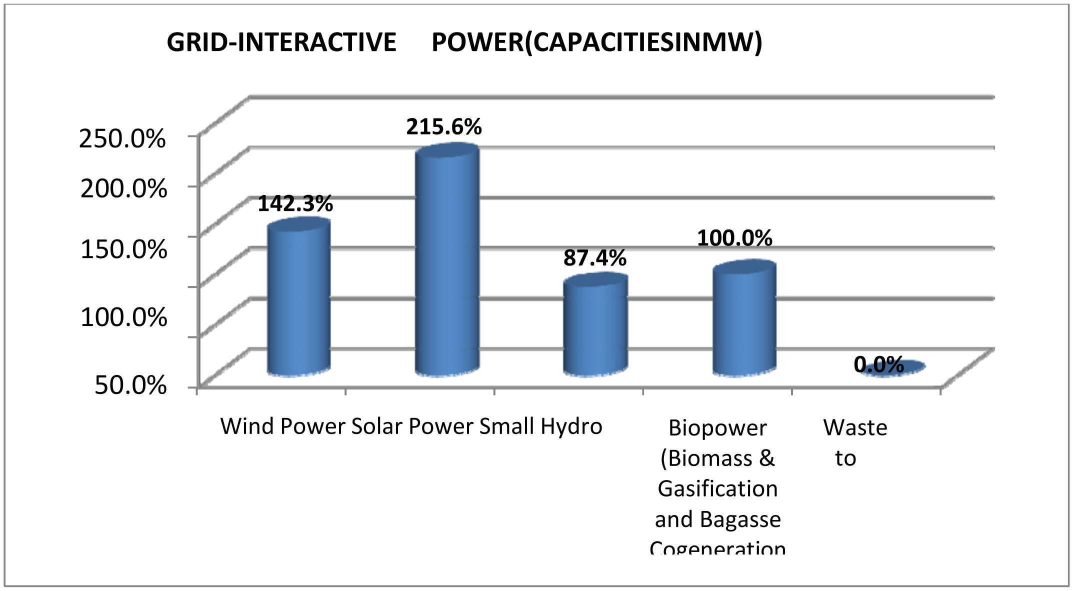


Figure 1.7 Target verses Achievement (Source MNRE)

Among all the energy sources the growth of solar power sector is more prominent. The cause may be the widely available solar power and development of solar PV technology. As per report of MNRE the unit cost of solar power is dropped from Rs 17.91 per unit in 2010 to Rs7 per unit now. In figure 1.6 the target for installing solar power is shown whereas fig 1.7shows the growth of solar energy as compared to renewable sources.

Another aspect of commercialization of renewable power is the changing economic. As per IEA (2002), the power producers are investing in the area of distributed generation because of development of technology, restriction for building of new transmission corridor, accelerating energy demand, liberalization of electricity market and seriousness about change of environmental condition [7-8].

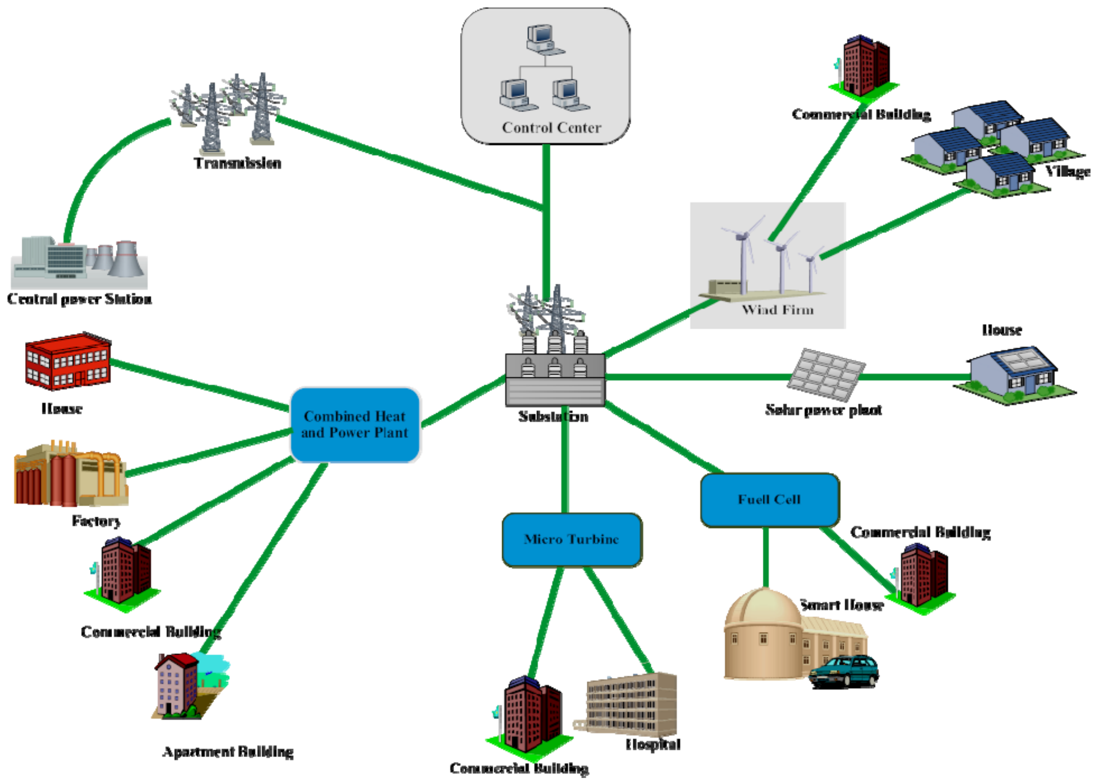


Figure 1.8 Different Distributed Sources with Utility DPGS with utility grid

Pumping of power from photo voltaic system to the utility grid depends on the level of power generation. The high penetration of Photovoltaic system and other distributed generators as shown in figure 1.8 requires innovative planning for the operation and management of the electricity grid in order to sustain or even to improve the consistency and quality of power.

The power electronic components play a vital role for synchronization of distributed generation to the existing grid. In the present scenario current controlled pulse width modulated voltage source inverters is widely used to accomplish the task [9-10].

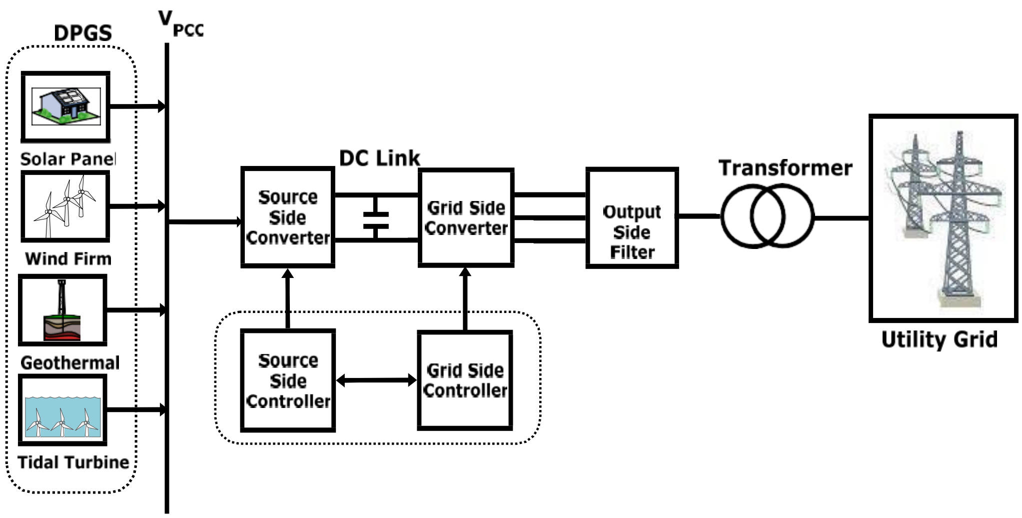


Figure 1.9 Integration of Distributed Power Generation Systems with Utility Grid

Figure 1.9 shows the integration of Distributed Power Generation Systems with Utility Grid.

Here, the source side converter is connected to control the input DC link voltage and the gridside converter is use to maintain the harmony between the highly intermittent source and theutility grid.

1.1.2 Role Of Renewable Energy

The demand for electricity is steadily increasing due to the increase in inhabitants and industrial development. Energy generated from natural sources such as coal or gas is not consistent with today's energy demand. Since coal (fossil fuel) is cheaply available, an enormous quantity of electrical energy is generated from fossil fuels. Fossil fuels cause significant damage to the environment by liberating carbon dioxide and mercury during energy conversion, which leads to global warming Gulagi et al. (2020). Sustainable energy sources can be used in power generation to overcome the challenges faced by generating electrical power from fossil fuels (Stonier & Lehman 2018).

Abdelrazik et al. (2018) dealt with the net generation of electricity from renewable sources which is expected to be equal to coal production by 2040. Nearly half of renewable energy is obtained from wind and solar power. Recent advances lead to renewable energy systems which are low cost. The average cost reduction for Solar Photovoltaic (PV) and shore winds forecast at 40–70% and 10-20 % by 2040. The growing global energy crisis is affected by the depletion of conventional energy sources (Albert & Stonier 2020), and also has the following drawbacks:

- Emission of harmful pollutants
- Carbon dioxide and mercury emissions are anticipated to increase by 35% and 8% by 2020 as the electricity generation is projected to increase

Global warming is estimated to raise the earth's surface temperaturefrom 3^0C to 6^0C by the end of this century as a result of the greenhouse effect. The power generated by conventional systems needs to be passed on tothe end-user on a long-term basic basis, requiring costly, complex infrastructure and exposing the entire system to higher energy loss and safety risks.

Kumar *et al.* (2019) encouraged investments in clean-energy production through PV systems. Modern topologies of power converters have provided various positive approaches for the relation to Photovoltaic (PV) systems. In view of fossil fuel price inflation and diminishing public acceptance of these energy sources, photovoltaic technology has become a truly sensible alternative. The PV has the advantage of converting sunlight directly into electricity and is also well suited for most geographical regions. Hence it is highly preferred compared to other Renewable Energy Systems (RES). In particular, solar power has been pollution-free, easily accessible from sunlight, and at a more acceptable level for the past two decades in terms of a minimum price.

There are many types of RESES available but the type of source to choose depends on location, usability, and availability. Some of the primitivesare as follows:

- Energy demand and significant energy alternatives lead to investment in photovoltaic power generation among all energy sources since energy can be produced between a few kW and several MW depending on geography.

- Most of the regions in the Indian subcontinent are blessed with daily global radiation of 4 -7 kWh/m^2/day.

The solar power system is usually the best choice for most suburban and rural applications as it requires less maintenance, providesnoise-less operations due to no moving parts, and occupies less space as rooftops can be used to install solar photovoltaic plates. The use of PVsystems in energy generation began in the 1970s and today, despite the high capital costs referred to by Khalid (2020), it is developing rapidly worldwide.

1.1.3 PV SYSTEM IN ENERGY CONVERSION

PV system performance depends largely on the efficiency of solar radiation, temperature, and conversion. Although PV systems have manydisadvantages, due to weather variations they suffer from varying system performance, high installation costs, and low module efficiency up to 20 %. Optimizing the sizing of stand-alone or grid-connected PV systems (GCPVS) is a convoluted problem of optimization that anticipates obtaining appropriate energy and economic costs for consumers.

Solar energy has the benefits of being employed almost in all placeswith the proper positioning of PV panels. In general, the advantages of Solar PV systems are:

- Low environmental effects
- easily mounted close to the consumer thereby reducing thetransmission line losses
- Reduces maintenance Costs
- environment friendly, since there is zero emission of carbondioxide gasses.

Basically, there exists two categories of PV systems such as (1) standalone and (2) grid connected. In a standalone PV system, additional batteries are required to store the excess amount of produced power. But in a GCPVS the grid functions as a battery with an infinite storing capacity. It takes care of fluctuations in seasonal load. The excess amount of electrical energy produced by the PV system can be stored in the grid without throwing away. Hence, the efficiency of a GCPVS will be higher than the stand-alone PV system. Therefore, the usage of grid PV systems is much desired over standalone PV systems Sabry *et al.* (2020).

CHAPTER 2

LITERATURE REVIEW

2.1 Multilevel Inverters (MLIs)

These days, MLIs are being deployed in power systems because of their ability to meet the demand in power quality and power rating, as well as their reduced level of harmonic distortion and electromagnetic interference. There are several advantages of anMLI over the traditional two-level inverters where high switching frequency PWM is used MLIs are currently being considered as an industrial solution for high power quality and dynamic performance demanding systems, spanning through a power rangeof 1 to 30 MW Hence, MLIs are ideal for use in high voltage applications because they can generate low THD output voltage waveforms and can generate higher voltages witha limited device rating. The sources of sustainable energy, such as PV cells, fuel cells,and wind can broadly interact with a multilevel converter system. Mostly, the type of control algorithm utilized in the PWM of MLIs determine their operations, efficiency, power ratings, and application. Several studies have proposed various MLI topologies over the last few decades. Figure 2 shows the classification of the MLIsinto two main groups based on the number of employed DC sources in their topology. Until now, the most commonly used topologies in the industries are the neutral point. clamped (NPC) or diode clamped, the flying capacitor (FC), and the cascaded H-bridge(CHB).

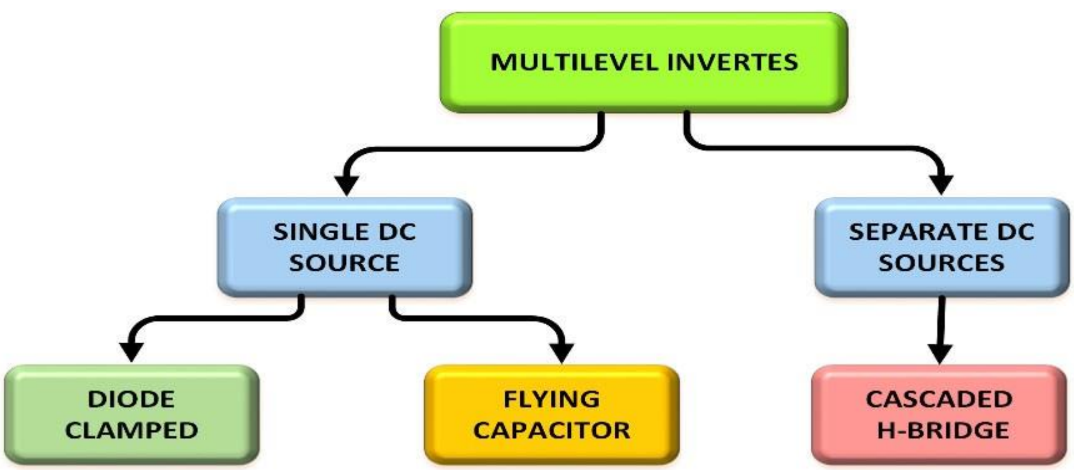
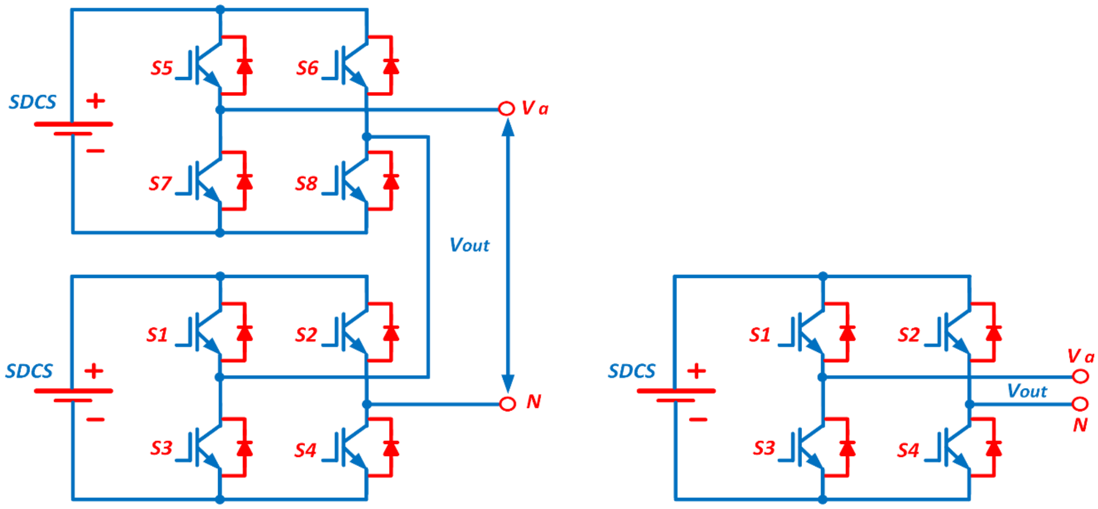


Figure 1 Multilevel inverters (MLIs) and their classification.

2.1.1 Cascaded H-Bridges MLI

The CHB-MLIs are produced from the serial connection of numerous single-phase H-bridge inverters with separate DC sources (SDCS). Each H-bridge consists of four unidirectional power switches and one DC source as shown in Figure 3. Each inverterlevel is programmed to produce three voltage outputs (+Vdc, 0, and −Vdc) via the connection of the DC source to the AC output; the desired output is achieved by connecting the four switches ($S1$–$S4$) in different manners. Switching the $S1$ and $S4$ switches to the ON position generates the +Vdc output, but when $S2$ and $S3$ are in the ONposition, −Vdc output is produced. To produce the 0-output voltage, either $S1$ and $S2$ or $S3$ and $S4$ must be in the ON position. A serial connection of the AC outputs of the full- bridge inverter is made in such a way that the generated voltage waveform will representthe sum of the outputs of all the inverters. In a cascade inverter, $m = 2s + 1$ is used torepresent the number of output phase voltage levels, with s being the number of different DC sources. This topology requires a smaller number of components when comparedto DCMLI and FCMLI because it does not have clamping diodes and clamping capacitors. In addition to that, it is free from the voltage balancing problem because it does not contain DC link capacitors. On the other hand, the multiple DC sources can be replaced either by separate renewable energy sources with separate converters or by single renewable energy sources with multioutput converters where the voltage balancing is themajor concern.

Proposals have been made for the use of multilevel cascaded inverters in applications for static var generation, as well as their usage as an interface with RES they have also been proposed for use in battery-powered applications. A cascade inverter can alsobe used for static var compensation via direct connection in series with the electric system. They are suitable for the hooking of RES to the AC grid as they need separate DC sources when used in fuel cells and photovoltaics. They have also been proposed to be usedin electric vehicles as the main traction drive because in such applications several batteries or ultracapacitors serve as SDCSs. The structure of this topology is flexible and can be used in different number of inverter levels. The generation of the different output voltages is achievable via the application of different ratios of the DC sources and reducing the inner voltage levels-related switching redundancy. Transformer-dependent CHBMLIs are developed to reduce the need for independent DC sources; it is like the CHBMLI structure but differs by the serial connection of the output voltage of the isolation transformer .



(a) (b)

Figure 3. (**a**) Five-level CHBMLI topology, (**b**) three-level CHBMLI topology.

2.1.2 Flying Capacitor MLI

There are close similarities in the topologies of the FCMLI and DCMLI just that the FCMLI relies on the use of floating capacitors rather than clamping diodes. For the FCMLI, the magnitude of the voltage steps in the output waveform is a direct function of the voltage variation occurring in the adjacent capacitors. The FCMLI topology for the ‘m’ level inverter is comprised of $'m — 1'$ DC link capacitors count. Figure 4 is a schematic of the 3-level FCMLI topology which contains four unidirectional power switches and a flying capacitor, in addition to a DC supply with two capacitors for obtaining voltage levels ($Vdc/2,\ 0,\ -Vdc/2$). Switches $S1$ and $S2$ must be in the ON position to generate the positive polarity output voltage while $S3$ and $S4$ are switched ON for the negative polarity output voltage. Switches $S1$ and $S3$ or $S2$ and $S4$ are turned on to generate the 0-level output voltage. In the FCMLI, the voltage synthesis is more flexible compared to that of a DCMLI. When there are more than five levels, the problem of voltage balancing can be addressed by making a proper selection of the switching combination. One major advantage of this topology is that the reactive and active power can be controlled while its major drawback is in the use of several capacitors, which makes the system expensive and difficult to assemble. Furthermore, the switching frequency losses in sucharrangements are high in real power transmission.

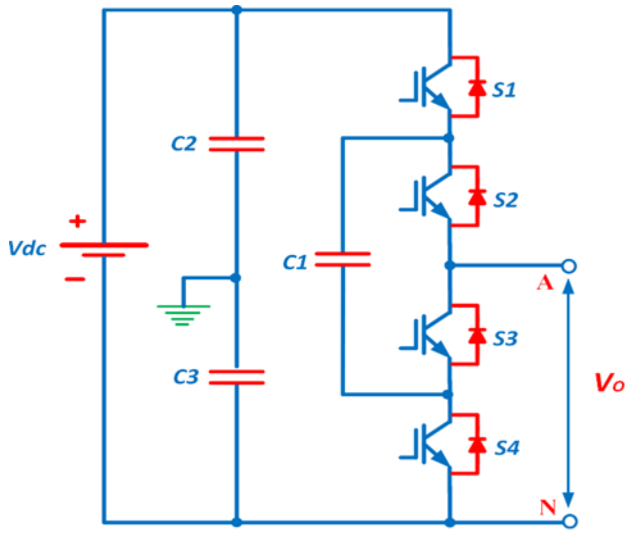


Figure 3. Three-level flying capacitor MLI topology.

2.1.3 Diode Clamped MLI

This type of inverter, also called a neutral point clamped inverter (NPC), was invented in 1981 by Nabae et al. [18]. Figure 5 depicts the DCMLI topology, which is used to generate an output voltage with three levels. The configuration for this topology contains four unidirectional power switches, two diodes, and two capacitors. The clamping diodes are connected in series to share the blocking voltage. In this topology, the output voltage is of three levels, which are Vdc/2, 0, and −Vdc/2; Vdc/2 is generated by keeping S1 and S2 switches ON while S3 and S4 are switched to ON to generate −Vdc/2. Switches S2 and S3 are turned on to produce the 0 level voltage. During the passage of the equivalent voltage through the DC link capacitors, it is expected that each active switching device has voltage stress that is clamped to the voltage of each capacitor through diode clamping [54]. In a real application, the blocking voltage is shared by serially connecting the clamping diodes. Then, only a voltage level of $V/(m — 1)$ dc is required to be blocked by each active device. For reverse voltage blocking, the voltage ratings of the clamping diodes must vary. If operating the DCMLI under the PWM technique, the major issue with the design in high voltage applications is the diode reverse recovery of these clamping diodes [55].

The DCMLI, in comparison to the other multilevel converter topologies, has a greater industrial application due to its high-power delivery capability, simplicity, and efficiency. It has found application in Static VAR Compensators (SVC), high voltage system interconnections [55,56], and variable speed motor drives. The need for a capacitance is annulled in the DCMLI converter as the components share a common DC bus. Hence, it can be used in high voltage back-to-back interconnection, adjustable speed drives, and other back-to-back topologies. However, the problems of this converter include difficulty in single inverter real power flow due to discharging or overcharging of the DC level without adequate control [57], as well as the issue of balancing and stabilizing the capacitor DC voltage in the DC link [41].
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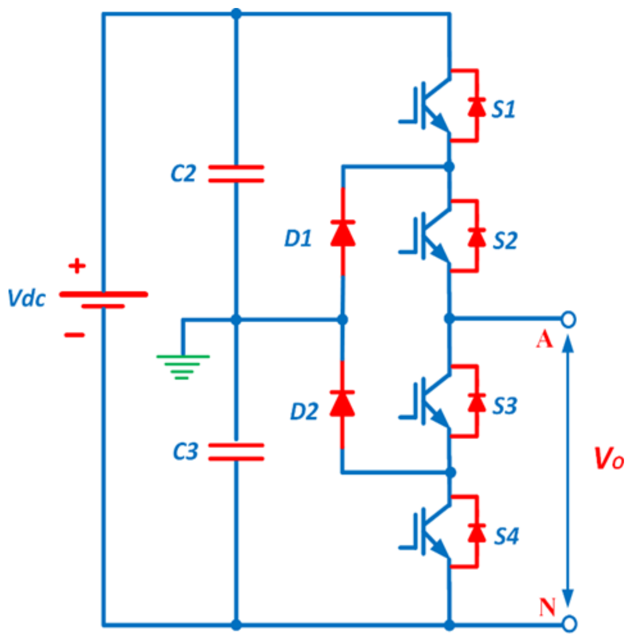


Figure 5. Three-level diode-clamped MLI topology.

2.2. Comparison between CHB-MLI, FC-MLI, and DC-MLI Topologies

In this section, a comparison between the three main MLI topologies, called the classical topologies, was made in terms of the advantages and disadvantages, as illustrated in Table 1.

Types of MLI	Advantages	Disadvantages
DC-MLI [18,35,41,55,57–61]	1. A good option for industrial applications 2. Exhibits high fundamental frequency switching efficiency. 3. Can pre-charge the capacitors as a group 4. Control method is simple. 5. The use of neutral clamping switches can solve the issue of voltage balancing and uneven loss sharing between the switching devices in neutral point clamped (NPC) converters	1. The complexity of voltage balancing circuit. 2. The unequal share of losses between inner and outer switches 3. Increased number of clamping diode as the level increased
	Reduces the number of required DC sources. Phase redundancies are available for balancing the	The complexity of voltage balancing circuit.

33

FC-MLI [22,35,41,57,59,62,63]	voltage levels of the capacitors. Appropriate for fault-tolerant application. Real and reactive power flow can be controlled. No need for filters to reduce harmonics.	Requires numerous capacitors for high levels High losses and switching frequency for real power transmission High installation cost.
CHB-MLI [22,23,59,64–67]	Modular and simple structure. Easy to extend to higher levels. Requires only unidirectional switches. Appropriate for fault-tolerant application.	Less number of output voltage levels. Requires more number of gate driver circuits. Requires several DC sources to increase the output voltage.

2.3 Modified Multilevel Inverter

Although MLIs have various advantages over other inverters, they have been extensively tested and developed to produce better efficiency by considering sizes and cost with all types and different voltage levels obtained. Thus, a modified multilevel inverter was invented by modifying MLI configurations and designing MLI with less count of power switches. With the reduced number of switched MLIs, the system has theadvantages of cost-effectiveness, lower component count, and less space occupancy [23].Considering this, the cascaded H-bridge MLI was adopted as a case study [68–71] because of its lower component requirement compared to the MLI topologies. A further modification was done on the CHBMLI framework to achieve a five-level output for single phase usage using a lower number of switching components rather than the required eight switches in the conventional design as depicted in Figure 6. Moreover, the system is completed by adding a filter at the output of the inverter for greater THD reduction. Thestudy by [72] investigated the relationship of the THD with changes in the switching frequencies and inverter levels; the study found the switching frequency of 6 kHz and theseven-level inverter as the arrangement generating the lowest THD. In this case, a five- level design was selected because of its lesser circuit complexity and less THD. Figure 6apresents the general structure of MLI while the modified version used in this study is shown in

Figure 6b. According to [36], MLIs are modular and easy to design [36]; they are suitable for use in high power and high voltage systems [73]; their simple configuration allows the generation of a higher voltage without the need for high rating components since the multilevel topology ensures that the overall device stress is distributed among the respective components. Hence, MLIs can be used for 10 kV rated DC-link voltage inverters. There is also a significant decline in the switching losses. The total ratedload losses can also be reduced by 60% using a five-level inverter. The use of higher number of inverter levels decreases the THD of the output, thereby increasing the signalquality

The extent of work done on this inverter type recently portrays their importance in this field. For instance, reference [76] suggested a three-phase five-level inverter that usessix switches, while reference [77] developed a single-phase inverter that has six switchesper inverter cell. In this system, the ratings of two of the switches differed from those of the other four (four switches are designed to withstand 400 V, while the others are exposed to 200 V). Hence, two different switch ratings are needed in this system. Furthermore, the study by proposed an 11-level inverter that has 14 switches, whilea system with fewer switches was presented by [73]; this system relies on low rating switches and exhibited the expected performance level via cross-connection of theswitches. The study also evaluated this approach on an 11-level inverter system. Various studies [79–83] have presented similar MLI architectures with a reduced number of switches. A topology that can combine individual battery cells that are serially connectedto achieve multiple voltage levels has also been presented; the system was developed with a reduced number of switches via the intelligent modification of the cell connection. Thistopology can also utilize capacitors and other DC sources and could be used in grid-connected PV systems [84]. Single-phase MLIs have been connected with grid-connectedPV systems in the studies by [85,86]. The study by presented another topology with alower number of switches (six switches); the system was designed by altering the polarities of the DC source as required. The performance of the system was evaluated aswell on a five-level single-phase inverter.

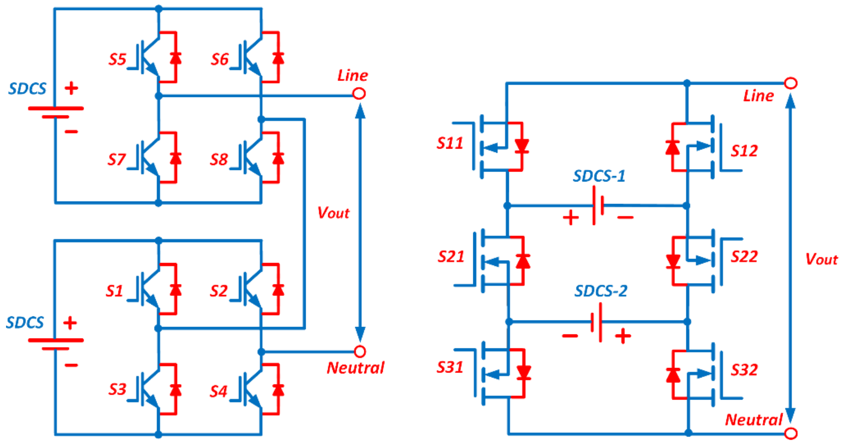


Figure 6. (**a**) Schematic of the MLI topology where each 4-switch block is considered an H-bridge.

(**b**) The modified structure of a 5-level inverter that uses 6 switches instead of 8.

2.4 Multilevel Inverters in Renewable Energy System Applications

Due to the MLI's capabilities of producing high-quality voltage waveforms through low switching frequency operation, they are thus preferred for high and medium powerapplications. MLIs have widely used in various applications such as power supplies (PSs) applications; renewable energy systems (RESs) such as photovoltaic (PV) systems, wind energy conversion systems (WECS) and fuel cells (FC); electric vehicles (EV); induction heating (IH) and numerous other fields. Many MLI topologies have beenintegrated with RESs in grid-connected systems for the addition of the power generatedby the RESs to the grid.

a. *Wind Energy Conversion Systems (WECS)*

An attempt to the use of a CHBMLI topology to interface split winding wind alternators (SWAs) to the grid was made by the experimented SWA-CHBMLI system was found efficient in interfacing a large wind turbine to the grid; the system also achieved better power quality at the PCC, thereby making the system more efficient. In recent years, scholars have been paying attention to MLIs designs with fewer numbers ofgate drivers and switches to reduce the required installation space and the cost of MLIs. A hybrid modular multilevel converter was presented byfor the

33

connection of large wind turbines to the grid. The system is a promising converter topology on the grid-side of a back-to-back connected full-scale converter of a WECS since it combined MMC and HB module features. It can improve the reliability of the entire WECS. A presented a novel two-stage CSD multilevel system that used a lower number of switches to achieve a high number of voltage levels; the system also addressed the issue of high voltage spikes under R-L loads as the system has a path for the reverse load currents. The system was considered suitable for integration in medium-voltage renewable energy systems. The use of a modular cascaded MLI in a fault-tolerant distributed control system has been evaluated by for the integration of wind turbines to the grid. The inverter was found capable of synchronizing with the grid frequency without any damage to the in-coming currents, which is a necessary condition after clearing a grid fault or when first connecting to the grid.

b. *Fuel Cells (FC)*

A hybrid cascaded MLI was designed for fuel cell application by using the variable frequency inverted sine wave carrier modulation technique (VFISPWM). This modulation technique aims to improve the output voltage while giving low THD and reduced switching losses. Another work by came up with a fuel cell- based system with H-bridge DC/AC inverter and a three-level boost converter. To make sure the system operates in stable conditions, two feedback control loops were designed and added to the system. The developed multilevel DC-DC converters can be used in RESs for power generation at a reduced cost. A hybrid cascaded multilevel inverter CMLI has been proposed by for fuel cell power conditioning systems. The developed system can generate high voltages at higher speeds with a high conversion efficiency while ensuring low switching losses. The developed system can be used in high-power fuel cell systems. The study by reported the development of an open-loop FC-based energy system interfaced with CHBMLI. The system was evaluated for performance under different loading conditions and from the results, the system performed better than the conventional inverter-based systems and was considered appropriate for use in FC based energy system where there is a need for more flexibility and power handling capability. A proton exchange membrane fuel cell interfaced with five-level diode clamped MLI was presented by [98]. This arrangement was intended to reduce harmonic distortion and increase system efficiency. The study by [99] presented a system for energy delivery from a fuel cell to the grid; the system was equipped with a single-stage multilevel current- source inverter (MCSI) for energy provision and for increasing the power quality in the grid. The study found the developed system as an alternative in smart grids or distributed generation systems because it can generate active power while reducing the line current harmonics and compensating the power factor.

2.5 Photovoltaic Systems (PVs)

Much attention has been given to PV-based power generation due to its numerous advantages, such as ease of allocation, longer life, absence of noise, lack of pollution, lesser installation time, high mobility and components' portability, and ability to produce power output that can meet peak load requirements. Hence, PV arrays have found many industrial applications, such as in battery recharging systems, solar hybrid vehicles, satellite power systems, solar-based water-pumping machines, etc. For this reason, many countries are investing heavily in renewable energy-based projects. However, there are certain problems associated with PV generation systems, such as low conversion efficiency and interference from climate conditions. The power of PV cells is directly a function of the solar intensity/radiation but depends less on the temperature . A complete PV system is comprised of solar panels, batteries, DC-DC voltage converters, and controllers. The work of the DC-DC voltage converters is to match the load characteristics with the characteristics of the solar panels. There are three categories of DC-DC voltage converters, namely boost, buck, and buck–boost converters. The expected voltage level determines the section of the appropriate form of DC-DC voltage converter. Batteries are used to make the PV systems act as the real feeder source such that it is possible to achieve constant voltage levels that correspond to different loads. Another use of the battery is for power saving and as temporary compensation for power fluctuations. A solar panel is made up of several PV cells that are connected either in series or parallel or as series-parallel external connections.

The photovoltaic power characteristics are nonlinear, as illustrated in Figure 7. The characteristics of a PV cell are analyzed using parameters such as open-circuit voltage (Voc) and short-circuit current (Isc). Regarding the Isc, it is the maximum value of the current produced by a cell; this parameter is sensitive to irradiance. On the other hand, the Voc is the maximum value of the voltage that a solar cell can produce at zero current. There is the equivalent circuit generic model to represent

PV cells. Which has a single diode with series resistance and a shunt resistance as shown in Figure 8. The current source represents photon-generated current (Iph) by PV, which is proportional to the solar irradiation. The resistance (Rs) represents the contacts and connections-related losses, while the leakage currents in the diode are represented by parallel resistance (Rsh).

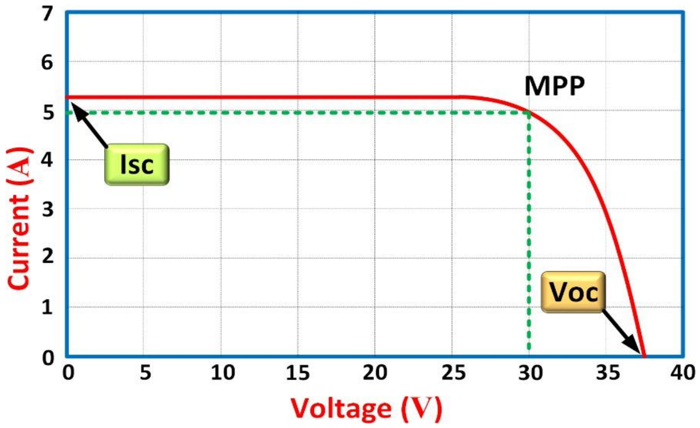


Figure 7. The current I– voltage V characteristics of a PV module.

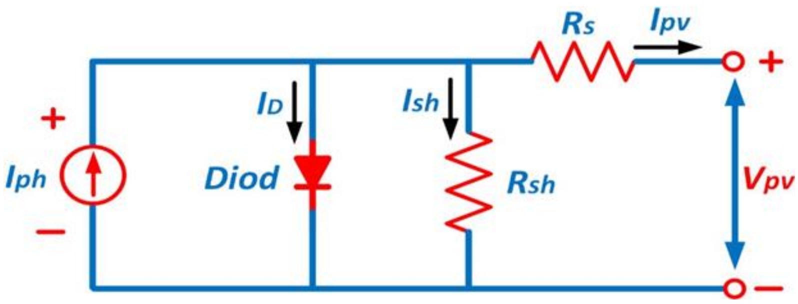


Figure 8. The equivalent circuit of PV cell

2.6 Multilevel Converters in PV Systems

The application of multilevel inverter (MLI) in PV systems to improve power quality and efficiency has received considerable interest recently. The selection of an appropriate converter for PV applications is one of the challenges since that has an impact on the behavior of the photovoltaic (PV) system. Therefore, many multilevel converters for the photovoltaic (PV) systems have been reported in the literature. The study presented an MLC for PV systems with integrated ESS. The developed MLC can provide constant power irrespective of the weather conditions. The proposed MLC showed a smooth transition from the charging mode to the discharging mode. Hence, the cascaded H-bridge (CHB) converter can be used in grid interconnections owing to its modular attributes, high-quality output waveforms, and ability to connect to medium voltage grids. A CHB-MLC with DC-DC stage isolation has been presented for large-scale PV systems. The proposed

CHB converter offered quality currents with low distortion. Its modular design ensured that it could operate in high voltage conditions and could improve the power quality. The study by presented an improved CMLI with a reliable configuration for reduction of current leakages in transformer less PV systems; conduction and switching losses were also reduced, making high switching frequency operation possible.

The study presented a CHB converter for use in PV systems; the system utilized an H6-bridge power cell rather than the H-bridge type. The system significantly improved the current quality and output voltage in partial shading conditions compared to the CHB type; this improved the system efficiency and the energy injected into the grid. A modular MMC was used in grid-connected PV systems. The proposed system can perform in both active and reactive power conditions, and this extends the applicability of the PV systems. A hybrid modular MMC for grid-connected PV systems was presented; this system can be used in high power systems by simply increasing the number of submodules per phase.

33

CHAPTER 3

MODULATION TECHNIQUES FOR MULTILEVEL INVERTER EQUAL PHASE METHOD

3.1 INTRODUCTION

The various modulation strategies of single phase and three phase inverters are discussed in this chapter. The important modulation methodologies which utilize pulse width modulation (PWM) and soft-computing approaches for three-level and multilevel inverters are briefly described in this chapter.

3.2 TWO-LEVEL AND THREE-LEVEL INVERTERS

The most important modulation strategies of three level inverters are described in this section. Both single phase and three phase inverter modulation methods are discussed in this section.

3.2.1 Single Pulse Width Modulation

In single pulse-width modulation, there is only one pulse per half-cycle and the width of the pulse is varied to control the inverter output root mean square (rms) voltage. The block diagram of the single pulse width modulation is shown in Figure 3.1. The output voltage waveform from the single pulse width modulated inverter is shown in Figure 3.2. The *rms* output voltage can be expressed as per the equation 3.1

$$V_o = V_s\sqrt{\frac{\delta}{\pi}} \tag{3.1}$$

where V_s is the DC-bus voltage of the full-bridge inverter and δ is the output pulse width. The pulse width δ can be varied from 0° to 180° and the *rms* output voltage V_o can be varied from 0 to V_s. The ratio of the reference signal amplitude A_r to the carrier amplitude A_c is known as the amplitude modulation index or simply modulation index (M). By varying the modulation index, the output *rms* voltage and total harmonic distortion can be controlled. The amplitude modulation index can be expressed as per the equation 3.2

$$M_a = \frac{A_r}{A_c} \tag{3.2}$$

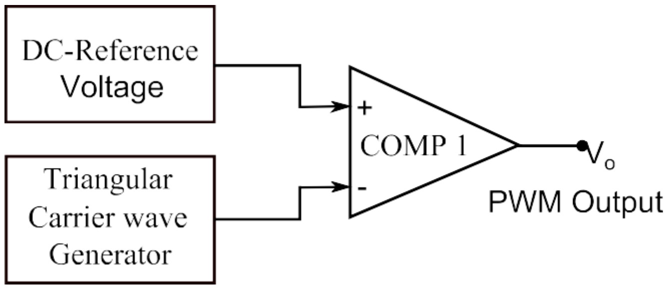


Figure 3.1: Block diagram of a single pulse width modulation

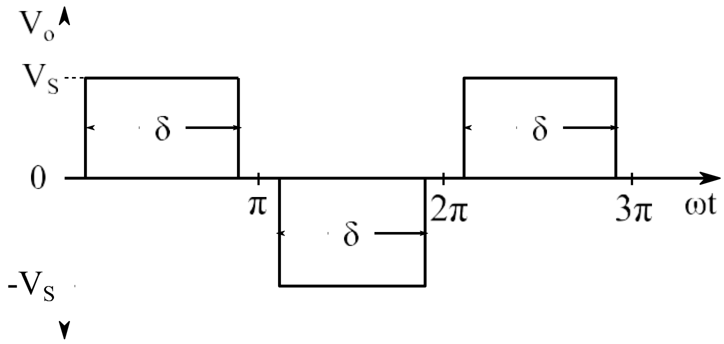


Figure 3.2: Output voltage waveform of a single pulse width modulation

The ideal output voltage of an inverter is a sinusoidal waveform. The practical waveform that obtained from the inverter output considerably changes from this ideal waveform. The harmonic components of the output voltage waveform obtained from the inverter output can be determined by Fourier
34 analysis. The instantaneous output voltage can be expressed using Fourier series

as per the equation 3.3.

$$v_o(t) = \sum_{n=1,3,5,..}^{\infty} \frac{4V_s}{n\pi} sin\left(\frac{n\delta}{2}\right) sin(n\omega t) \tag{3.3}$$

where δ is the pulse-width of the output voltage waveform. The duty cycle D is defined as $D = \frac{\delta}{\pi}$. The Fourier component b_n can be obtained from the above equation 3.3 as

$$b_n = \frac{4V_s}{n\pi} sin\left(\frac{1}{2}Dn\pi\right) \tag{3.4}$$

The amplitude of the fundamental component is obtained by substituting n=1 in equation 3.4 as

$$b_1 = \frac{4V_s}{\pi} sin\left(\frac{1}{2}D\pi\right) \tag{3.5}$$

Thus the rms value of the fundamental voltage can be expressed as:

$$V_{o1} = \frac{4V_s}{\pi\sqrt{2}} sin\left(\frac{1}{2}D\pi\right) \tag{3.6}$$

The rms value of the total harmonic component can be expressed as:

$$V_{rms}^2 = V_{o1}^2 + V_H^2 \tag{3.7}$$

where

$$V_{rms} = \sqrt{D}V_s \tag{3.8}$$

is the rms value of the pulse-width modulated output voltage.
∴ The rms total harmonic component can be expressed as:

$$V_H = \sqrt{DV_s^2 - \frac{8V^2}{\pi^2} sin^2\left(\frac{1}{2}D\pi\right)} \tag{3.9}$$

The equation 3.9 shows that the certain specific harmonics can be eliminated from the output voltage by judiciously selecting the duty cycle or pulse-width. The third harmonics can be eliminated from the output voltage by selecting a duty cycle of 66.67%. The above equations reveal that pulse-width modulation can be used for controlling output rms voltage and for improving total harmonic distortion.

3.2.2 Sinusoidal Pulse Width Modulation

The block diagram of sinusoidal pulse width modulation (SPWM) for a single phase full-bridge inverter is shown in Figure 3.3. The circuit schematic of a single-phase full-bridge inverter is shown in Figure 2.2b. The reference signal in SPWM is a sine waveform of the desired frequency. In sine pulse width modulation, the width of each pulse is varied according to the amplitude of a reference sine wave evaluated at the center of the same pulse. The total harmonic distortion of the inverter decreases significantly in SPWM. The output voltage waveform is shown in Figure 3.4. The *rms* output voltage of the inverter can be expressed as per the equation 3.10

$$V_o = V_s \left(\sum_{m=1}^{2p} \frac{\delta_m}{\pi} \right)^{1/2} \tag{3.10}$$

where p is number of pulses per half-cycle of the output, δ_m is the width of the m^{th} pulse, and V_s is the DC-bus voltage of the single-phase SPWM inverter. The amplitude modulation index of the inverter M is given by the equation 3.2, where A_r is the peak amplitude of the reference sine waveform, and A_c is the peak amplitude of the triangular carrier wave.

The frequency modulation index M_f of the sine pulse-width modulation is given by the equation 3.11.

$$M_f = \frac{f_{cr}}{f_m} \tag{3.11}$$

where f_{cr} is the frequency of the triangular carrier wave and f_m is the frequency

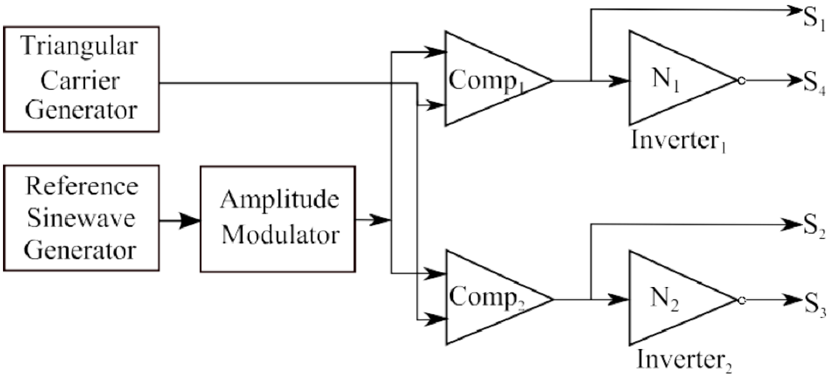


Figure 3.3: Block diagram of a Sinusoidal pulse width modulation

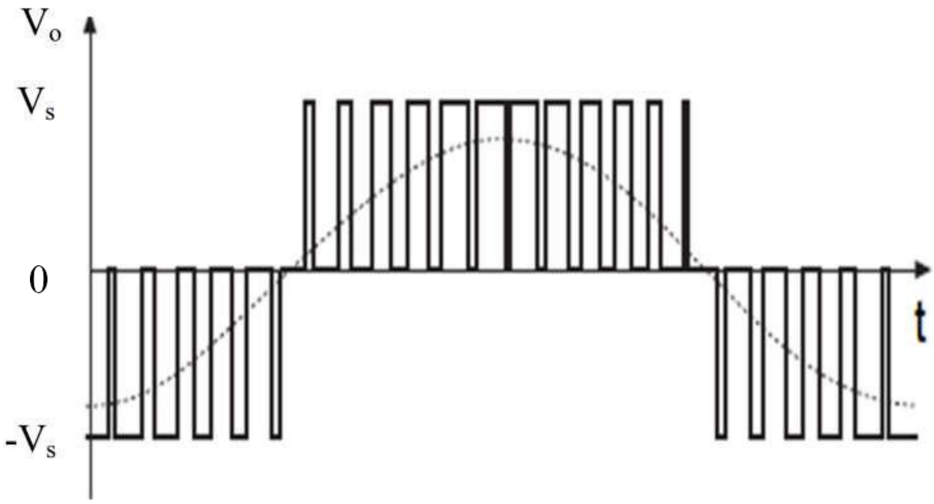


Figure 3.4: Output voltage of a Sinusoidal pulse width modulation

of the modulating sine waveform. The higher the frequency modulation ratio, the smaller will be the total harmonic distortion. However, the operating frequency is limited by the switching losses in the inverter. The inverter output frequency (f_o) is equal to the reference sine wave frequency (f_m). The spectral purity of the output waveform is highly dependent on the frequency stability of the modulating sine waveform. This necessitates a highly stable frequency synthesis of modulating sine waveform.

3.2.3 Space Vector Pulse Width Modulation

Space vector pulse width modulation (SVPWM) is quite different from conventional pulse width modulation schemes. This technique is primarily employed in three-phase inverter systems. The space vector pulse width modulation become highly popular in three-phase inverter systems because it is inherently suitable for digital implementation and it provides higher DC-link voltage utilization compared to the sinusoidal pulse-width modulation. A detailed description of the SVPWM is accomplished in (Van Der Broeck et al. 1988; Chen et al. 1999).

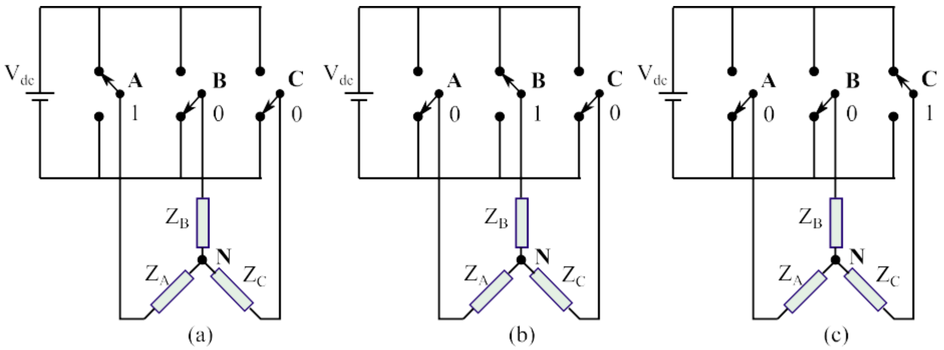


Figure 3.5: States of a two-level three-arm bridge inverter

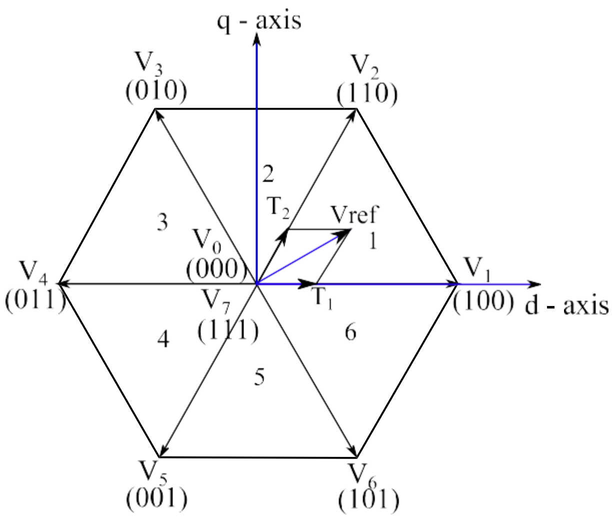


Figure 3.6: The space vector representation

In a three-phase full-bridge inverter system, the switching pattern for SVPWM consists of six active space vectors and two zero vectors. The

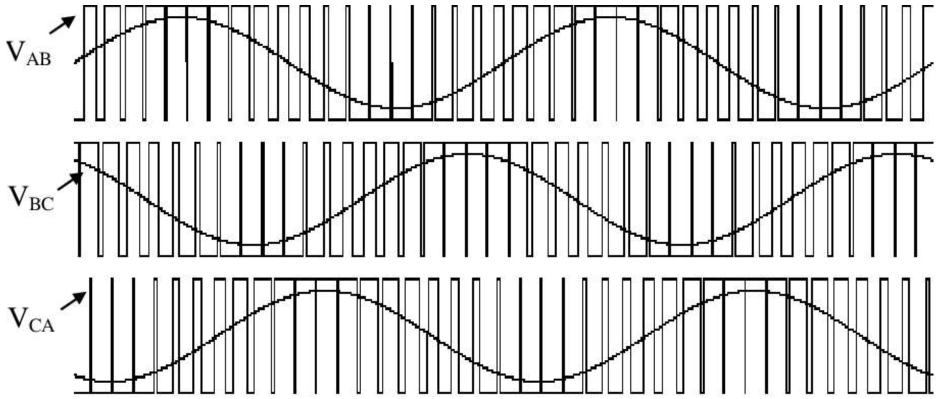


Figure 3.7: Space vector PWM output voltage waveform

Each switch can define a state of either '0' or '1'. The '0' state indicates that the inverter pole is connected to the bottom switch in the three-phase bridge and '1' state indicates that the inverter pole is connected to the top switch. In a three-phase two-level bridge inverter, it is possible to define 8 different states (000, 001, 010, 011, 100, 101, 110, 111). The zero output voltage can be obtained from the inverter by forcing the inverter either in 000 state or 111 state. Hence these two combinations of states are known as zero vectors. The remaining six states which contribute non-zero output voltage is known as active vectors. The requirement of SVPWM is to approximate the sinusoidal line modulating signal with eight vectors. The rate at which the space vector rotates is at the output frequency requirement of the inverter. At any instant the SVPWM switching pattern consists of two active vectors and one zero vector. An arbitrary space vector in the co-planar vector space is shown in Figure 3.6. The vectors $V_1, V_3, \&V_5$ are known as primary vectors and $V_4, V_6, \&V_2$ are their complementary vectors respectively. The SVPWM output voltage and current waveform for an R-load are shown in Figure 3.7.

3.3 MULTILEVEL INVERTERS

The major multilevel modulation strategies of inverters are described in this section. The most popular multilevel inverter modulation methodologies are listed below.

1. Multi-carrier pulse-width modulation
2. Nearest level modulation
3. Selective harmonic elimination type modulation

3.3.1 Multi-carrier Pulse Width Modulation

The carrier-based modulation schemes for multilevel inverters can be generally classified into two categories: phase-shifted multicarrier modulation (PSMC) and level-shifted multicarrier (LSMC) modulations (Wu and Narimani 2017). Both modulation schemes can be applied to the CHB multilevel inverters.

3.3.1.1 Phase Shifted Multi-carrier Modulation

In general, a multilevel inverter with m voltage levels requires $(m-1)$ triangular carriers. In the phase-shifted multi-carrier modulation, all the triangular carriers have the same frequency and the same peak-to-peak amplitude, but there is a phase shift between any two adjacent carrier waves, given by equation 3.12

$$\Phi_{cr} = \frac{360^\circ}{(m-1)} \tag{3.12}$$

The device switching frequency in PSMC modulation is high and is equal to carrier frequency $f_{sw_{dev}} = f_{cr}$. The total harmonic distortion in this modulation scheme is relatively low compared to a level shifted multi-carrier modulation schemes. Due to the high device switching frequency, the switching losses in PSMC modulation is high and not suitable for high power applications.

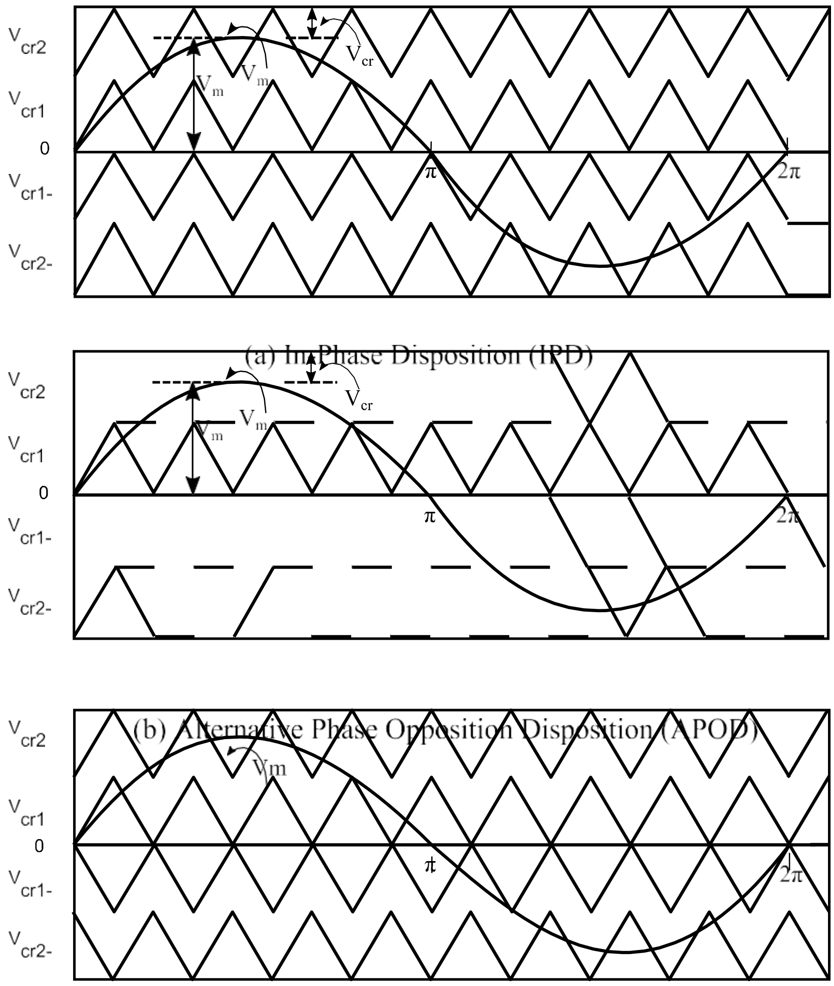
3.3.1.2 Level Shifted Multi-Carrier Modulation

The high-frequency triangular carriers are level shifted before being compared with a sinusoidal reference waveform to derive the switching pulses. There are three different forms of the level shifted multi-carrier modulation schemes existing in the literature (Wu and Narimani 2017).

1. Level Shifted Multi-carrier Modulation - In Phase Disposition (LSMC-IPD): - In this LSMC modulation schemes, all the $(m-1)$ carriers are in phase as shown in Figure 3.8 (a).
2. Level Shifted Multi-carrier Modulation - Alternate Phase opposition Disposition (LSMC-APOD): - Here all carriers are alternatively in opposite disposition as shown in Figure 3.8 (b).
3. Level Shifted Multi-carrier Modulation - Phase opposition Disposition (LSMC-POD): - In this LSMC modulation, all carriers above the zero references are in phase but in opposition with those below the zero reference as shown in Figure 3.8 (c).

The Level Shifted Multi-carrier Modulation is similar to the phase-shifted modulation, an m-level CHB inverter using level-shifted multi-carrier modulation scheme requires $(m-1)$ triangular carriers, all having the same frequency and amplitude. The $(m-1)$ triangular carriers are vertically disposed such that the bands they occupy are contiguous. The frequency modulation index is given by $M_f = f_{cr}/f_m$, which remains the same as that for the phase-shifted modulation scheme whereas the amplitude modulation index is defined by the equation 3.13

$$M_a = \frac{\hat{V}_m}{\hat{V}_{cr} \times (m-1)} \tag{3.13}$$



(a) In Phase Disposition (IPD)

(b) Alternative Phase Opposition Disposition (APOD)

(c) Phase Opposite Disposition (POD)

Figure 3.8: Level Shifted Multi-Carrier modulation for five level inverter

The device switching frequency in Level shifted multi-carrier modulation scheme is given by the equation 3.14

$$f_{sw_{dev}} = \frac{f_{cr}}{(m-1)} \tag{3.14}$$

The device switching frequency is relatively low in level shifted multi-carrier modulation and hence the switching losses are less compared to the phase shifted multi-carrier modulation.

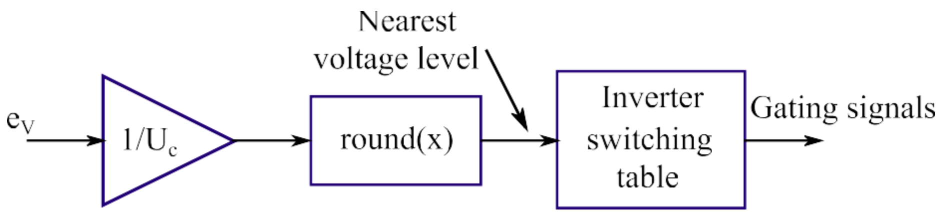


Figure 3.9: Block diagram of a nearest level modulation

3.3.2 Nearest Level Modulation

Nearest level modulation (NLM) is widely employed in modular multilevel converters (MMC). The topology of modular multilevel inverters are similar to cascaded H-bridge type with each sub-modules are the half-bridge type. The two primary modulation schemes used in MMC are carrier phase shifted sine pulse width modulation (CPS-SPWM) and nearest level modulation. When the number output voltage levels are high, nearest level modulation is preferred due to low switching losses in the NLM schemes.The block diagram of the NLM is depicted in Figure 3.9. The basic principle of nearest level modulation and single phase modular multilevel converter is shown in Figure 3.10. With N sub-modules are cascaded, in conventional NLM modulation can achieve $N+1$ output voltage levels can be achieved (Tu et al. 2011). The number of output voltage levels can be improved in the level increased NLM schemes proposed by (Hu and Jiang 2015).

The major benefits of NLM are its conceptual and implementation simplicity and the efficiency achieved with this method. The main disadvantage of this method is its high harmonic distortion at lower voltage levels (low modulation index).

3.3.3 Selective Harmonic Elimination

A list of unwanted lower order harmonics in the inverter output

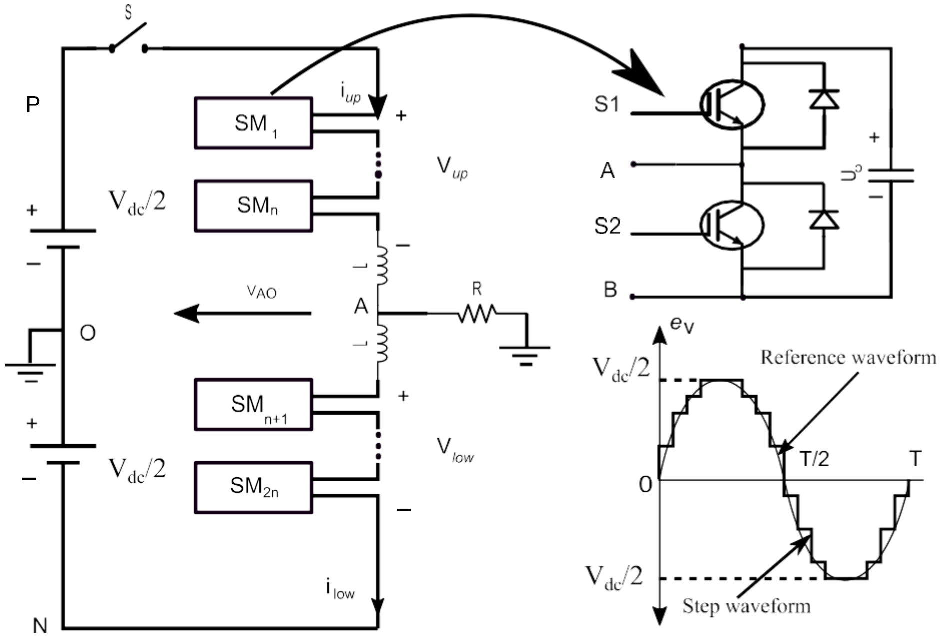


Figure 3.10: Basic principle of NLM in a modular multilevel converter

can be eliminated by using an off-line algorithm known as selective harmonic elimination (SHE) method. The switching angles are computed off-line and then stored in a look-up table (LUT). Based on the modulation index appropriate switching angles are fetched from LUT and applied to a gate driver circuit for implementation. Figure 3.10 shows an N-level cascaded H-bridge multilevel inverter topology ideally suitable for selective harmonic elimination. The output voltage of an 11-level cascaded H-bridge multilevel inverter with five switching angles $\theta_1, \theta_2, \theta_3, \theta_4$ and θ_5 is shown in Figure 3.11. Five H-bridge modules are cascaded to achieve 11-level output. The H-bridge modules P_1, P_2, P_3, P_4 and P_5 are turned-on at an angle $\theta_1, \theta_2, \theta_3, \theta_4$ and θ_5 respectively. The Fourier series representation of the output can be expressed as per the equation 3.15.

$$V(\omega t) = \frac{4V_{dc}}{\pi} sin(n\omega t) \times \sum_{n=1,3,5,..}^{\infty} (cos(n\theta_1) + cos(n\theta_2) + cos(n\theta_3) + cos(n\theta_4) + cos(n\theta_5)) \tag{3.15}$$

where $\theta_1, \theta_2, \theta_3, \theta_4$, and θ_5 are the switching angles of an 11-level CHBMLI

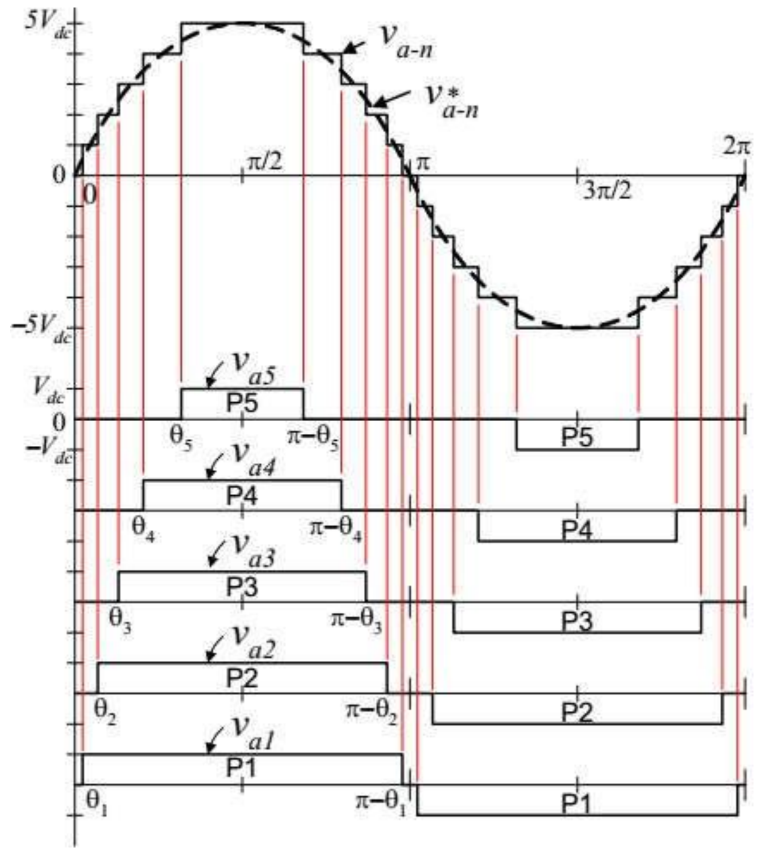


Figure 3.11: Output voltage of a single-phase 11-level cascaded H-bridge multilevel inverter

selected under the constraint $0 \leq \theta_1 \leq \theta_2 \leq \theta_3 \leq \theta_4 \leq \theta_5 \leq \frac{\pi}{2}$. In a single phase inverter, the dominant undesired harmonics such as the 3^{rd}, 5^{th}, 7^{th}, and 9^{th} are to be eliminated for improving the harmonic profile. In order to eliminate the above mentioned dominant lower order harmonics and to keep the fundamental components, the following transcendental equations 3.16 need to be solved.

$$\begin{aligned}
cos(\theta_1) + cos(\theta_2) + cos(\theta_3) + cos(\theta_4) + cos(\theta_5) &= M_a \\
cos(3\theta_1) + cos(3\theta_2) + cos(3\theta_3) + cos(3\theta_4) + cos(3\theta_5) &= 0 \\
cos(5\theta_1) + cos(5\theta_2) + cos(5\theta_3) + cos(5\theta_4) + cos(5\theta_5) &= 0 \\
cos(7\theta_1) + cos(7\theta_2) + cos(7\theta_3) + cos(7\theta_4) + cos(7\theta_5) &= 0 \\
cos(9\theta_1) + cos(9\theta_2) + cos(9\theta_3) + cos(9\theta_4) + cos(9\theta_5) &= 0
\end{aligned} \tag{3.16}$$

where M_a is the amplitude modulation index of the cascaded H-bridge multilevel inverter. The solution to the above transcendental equation 3.16 can be achieved using any one of the following methods:

1. Newton-Raphson Method (NR)
2. Resultant Elimination Method
3. Genetic Algorithm (GA)
4. Particle Swarm Optimization (PSO)
5. Ant Colony Optimization (ACO)
6. Imperialist Competitive algorithm (ICA)
7. Fuzzy Logic Controllers
8. Artificial Neural Network (ANN)
9. Ant-Lion Optimization (ALO)
10. Hybrid Optimization Methods

3.3.3.1 Newton Raphson Method

The Newton-Raphson (NR) technique is one among the widely used strategies for finding solutions of a system of a non-linear equations. This methodology has been applied to the numeric analysis of complex non-linear set of equations. It needs a good initial guess for an optimum solution. The switching angles are iteratively updated until a desired optimum solution is achieved. The convergence of optimum solution is not guaranteed in this iterative numeric method. The following steps can be utilized to solve the transcendental equations using the Newton-Raphson technique:

Step 1: Form a switching angle matrix with all switching angle lie between 0 and $\pi/2$.

$$\theta_{Old} = [\theta_1, \theta_2, \theta_3, \theta_4] \tag{3.17}$$

Step 2: Provide the value of modulation index M_a and the number of voltage level L. *Step 3:* Define a non-linear matrix F as given below:

$$F = \begin{bmatrix} cos(\theta_1) + cos(\theta_2) + cos(\theta_3) + cos(\theta_4) \\ cos(3\theta_1) + cos(3\theta_2) + cos(3\theta_3) + cos(3\theta_4) \\ cos(5\theta_1) + cos(5\theta_2) + cos(5\theta_3) + cos(5\theta_4) \\ cos(7\theta_1) + cos(7\theta_2) + cos(7\theta_3) + cos(7\theta_4) \end{bmatrix} \tag{3.18}$$

Step 4: Specify the corresponding harmonic amplitude matrix as

$$H_M = \left[\tfrac{(L-1)}{2} M_a, 0, 0\right]^T \tag{3.19}$$

Step 5: Define the derivative of the matrix F with respect to $\theta_1, \theta_2, \theta_3$ and θ_4. *Step 6:* Initial values for the switching angles are given as

$$\theta_{Old}(0) = [\theta_{10}, \theta_{20}, \theta_{30}, \theta_{40}] \tag{3.20}$$

Step 7: Solve for F and dF at the initial values of $\theta_{Old}(0)$

$$F + (dF \times \Delta\theta) = H_M \tag{3.21}$$

Step 8: Solve for $\Delta\theta$ from Equation 3.21 as

$$\Delta\theta = (dF)^{-1} \times (H_M - F) \tag{3.22}$$

Step 9: Update the value of the switching angle.

$$\theta_{new} = \theta_{Old} + \Delta\theta \tag{3.23}$$

Step 10: Repeat the process until the desired criteria is achieved.

3.3.3.2 Resultant Elimination Method

In parallel resultant elimination method, the original selective harmonic elimination equations are converted to elementary symmetric polynomial equations using multiple angle formulas and variable substitution. The order of the elementary symmetric polynomials are reduced to decrease the computational complexity of equations. The following six-step algorithm as described by (Yang et al. 2016) can be utilized for the computation and solution to parallel resultant elimination method.

Step 1: The Sylvester matrix S is formed as per the two input multivariate polynomials and the variable needs to be eliminated;

Step 2: The degrees of the variables $x_1, x_2, , x_n$ in the determinant of S are computed, and then, the total number of multivariate interpolation points are determined;

Step 3: For each x_i, $(i = 1, 2, ..., n)$, the distinct interpolation points are determined and the corresponding Vandermonde matrix V_i is generated by the interpolation points $x_0^i, x_1^i, ..., x_i^{d_i}$;

Step 4: The numerical values of the determinant of S are evaluated on every multivariate interpolation points and the vector $y = (y_1, y_2, ... y_D)^T$ is obtained;

Step 5: The linear equations **V** **a** = y are solved and the coefficient vector **a** is obtained;

Step 6: The resultant polynomial **F** is obtained as per the equation

$F = \mathbf{a}^T \quad \mathbf{B}$

where **B** is a basis which contains monomials generated by $x_1, x_2, , x_n$.

3.3.3.3 Genetic Algorithm (GA)

Genetic Algorithm (GA) is a search-based optimization technique based on the principles of genetics and natural selection. A genetic algorithm within the simplest kind uses 3 operators: reproduction, crossover and mutation.

Reproduction:

A fitness value $F(i)$ is allotted to every individual in the population wherever high value implies better fit. The $F(i)$ is normalized with a mean value of fitness, $F_n(i) = F(i)/F_{av}$. The individuals with higher than average fitness will have more than one offspring and with below average fitness will have less than one offspring on the average.

Crossover:

The main operator to work on the parents is a crossover, which is applied with a certain probability, called crossover rate. This operator takes the valuable information from both the parents and combines it to find a highly fit individual.

Mutation:

Mutation is a genetic operator used to maintain genetic diversity from one generation of a population of genetic algorithm chromosomes to the next. It is analogous to biological mutation. Mutation alters one or more gene values in a chromosome from its initial state. In mutation, the solution may change entirely from the previous solution. Hence GA can come to a better solution by using mutation. The mutation occurs during evolution according to a user-definable mutation probability. This probability should be set low. If it is set too high, the search will turn into a primitive random search.

3.3.3.4 Particle Swarm Optimization (PSO)

Particle Swarm Optimization is a population based optimisation algorithm invented by Kennedy and Eberhart where the population is called a swarm and each individual in the population are called a particle. PSO exploits the cooperation aspect and applies it to computer science and engineering optimization problems. It does this by modeling a social system. In this model, the system is populated with individual particles representing possible solutions to the problem. The particles themselves are not intelligent. They simply follow a predefined set of rules. Suppose the following scenario: a group of birds are randomly searching food in an area. There is only one piece of food in the area being searched. All the birds do not know where the food is. But they know how far the food is in each iteration. So what's the best strategy to find the food? The effective one is to follow the bird which is nearest to the food.

PSO learned from the scenario and used it to solve the optimization problems. In PSO, every single solution is a "bird" in the search space. We call it "particle". All of particles have fitness values which are evaluated by the fitness function to be optimized, and have velocities which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles. PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. In every iteration, each particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called pbest. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called gbest. When a particle takes part of the population as its topological neighbours, the best value is a local best and is called l best.

3.3.3.5 Ant Colony Optimization (ACO)

The first ACO algorithm was introduced by Marco Dorigo (Colorni et al. 1991). The development of this algorithm was inspired by the observation of ant colonies. The behaviour that provided the inspiration for ACO is the ants foraging behaviour, and in particular, how ants can find shortest paths between food sources and their nest. When searching for food, ants initially explore the area surrounding their nest in a random manner. While moving, ants leave a chemical pheromone trail on the ground. The pheromone quantity depends on the length of the path and the quality of the discovered food source (Oshaba et al. 2015). An ant chooses an exact path in connection with the intensity of the pheromone. The pheromone trail evaporates over time if no more pheromone is laid down. Other ants are attracted to follow the pheromone trail. Therefore, the path will be marked again and it will attract more ants to use the same path. The pheromone trail on paths leading to rich food sources close to the nest will be more frequented and will, therefore, grow faster. In this way, the best solution has more intensive pheromone and higher probability to be chosen. The described behaviour of real ant colonies can be used to solve optimisation problems in which artificial ants search the solution space by transiting from nodes to nodes. The artificial ant's movement usually data structure. The pheromone consistencies of all paths are updated only after the ant finished its tour from the first node to the last node. Every artificial ant has a constant amount of pheromone stored in it when the ant proceeds from the first node. The pheromone that has been stored will be evenly distributed on the path after artificial ants finished its tour. The amount of pheromone will be high if artificial ants finished its tour with a good path and vice versa. The pheromone of the routes progressively decreases by evaporation in order to avoid artificial ants stuck in the local optimal solution.

3.3.3.6 Imperialist Competitive algorithm (ICA)

ICA is an algorithm for optimization inspired by the imperialistic competition (Ali 2015; Abd-Elazim and Ali 2016). Like other evolutionary ones, this algorithm begins with an initial population. Population individuals are called country and are divided in two types: colonies and imperialists that all together shape some empires. Imperialistic competition among these empires forms the basis of the proposed evolutionary algorithm. During this competition, weak empires collapse and powerful ones take possession of their colonies. Imperialistic competition hopefully converges to a state in which there exists only one empire and its colonies are in the same position and have the same cost as the imperialist.

3.3.3.7 Hybrid Methods

Hybrid methods combine the merits of two methods to achieve the objective. Numerous such hybrid methods are currently existing with different objectives. Few important such methods are listed below. The proposed is provided in the results section.

- Genetic Algorithm and Artificial Neural Network (GA-ANN)
- Particle Swarm Optimization and ANFIS (PSO-ANFIS)
- Antlion Optimization and ANN (ALO-ANN)

3.3.3.8 Fuzzy Logic Controllers

The Fuzzy Logic controllers are extensively used in consumer appliances such as washing machines, induction heaters, and refrigerators. They also find applications in industrial processes, such as cement kilns and robotics. Fuzzy logic principles are utilized in Fuzzy logic controllers. Fuzzy logic uses linguistic variables rather than numbers and hence they are not accurate like conventional controllers. Fuzzy logic controllers do not follows accurate mathematical models instead utilizes the rule-based reasoning to formulate the control action. Fuzzy logic controllers in general consists of an input fuzzification block, processing block based on fuzzy rules and output defuzzification block (Ross 2005).

3.3.3.9 Artificial Neural Network (ANN)

An ANN is a complex interconnection of artificial neurons that can mimic a biological brain system. It has the flexibility to approximate an arbitrary operate mapping and might attain a better degree of fault tolerance. ANNs have successfully applied to Pulse width modulated inverters circuits for improving total harmonic distortion.

Chapter 4

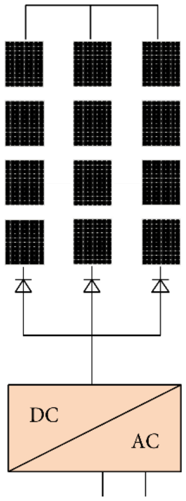
CASCADED MULTILEVEL INVERTER

4.1 ***Cascaded H-Bridges MLI***

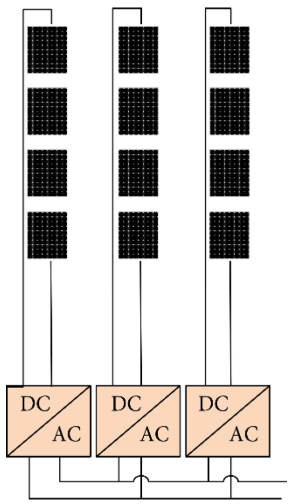
Cascaded multilevel inverter topologies have received a great deal of attention for grid-connected PV systems. Three-cascaded multilevel inverter configurations are proposed for grid-connected PV applications. These are the three-phase cascaded H-bridge multilevel inverter topology, three-phase cascaded voltage-source inverter topology using inductors, and three-phase cascaded voltage-source inverter topology using coupled transformers. Distributed maximum power point tracking (MPPT) of PV modules using perturbation and observation algorithm is used for all presented topologies. Each PV module is connected to one DC-DC isolated converter for best MPPT achievement. Simulation is achieved by using the SIMULINK environment. The simulation results show that the three proposed topologies function well in improving the grid's power quality. The grid currents are kept in phase with the grid voltage to ensure unity power factor, and the THD of the grid currents are within the acceptable range. The proposed topologies are experimentally implemented in the lab, and the switching pulses are generated with the help of the Macrolabia data acquisition system. Comparing the three topologies according to the number of switches, voltage, and current stresses on switches and THD of the generated voltages and grid currents and according to the efficiency has been achieved in this paper, both experimentally and by simulation. The simulation and experimental results and comparisons are presented to verify the proposed topologies' effectiveness and reliability.

4.1.1 Introduction

According to the interconnection of the photovoltaic (PV) inverters in the grid, four types of topologies are possible. These are the centralized inverter topology, string inverter topology, multistring inverter topology, and AC module topology. All of these topologies are shown in Figures 1(a)–1(d), respectively. They each have merits and demerits compared to each other. AC module topology is based on using one PV module per converter; therefore, it is the most modular and has the best MPPT capability. Any mismatching between PV modules can be removed using the AC module inverter topology. In addition, it is easy to enlarge by simply adding one PV module connected to one converter. Another advantage is that it can be used by persons without knowledge of electrical installations.



(a)



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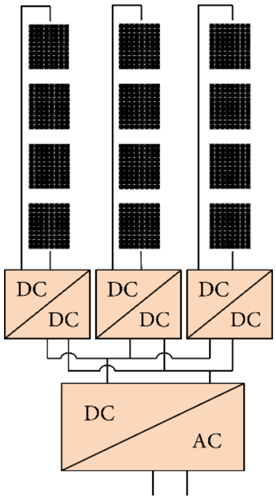
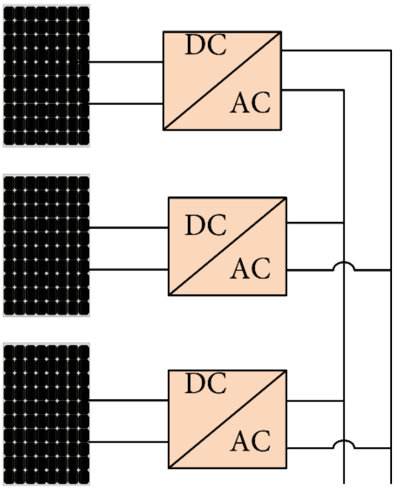


(c)



(d)

Figure 1_ Grid-connected PV system topologies.

Recently, many multilevel inverter (MLI) topologies have been proposed and have gained attention in many applications, especially in grid-connected PV applications. The most common MLI topologies can be classified into three types: neutral-point MLI, flying capacitor MLI, and cascaded H-bridge (CHB) MLI.

Cascaded MLI features have gained attention as an attractive solution for many applications, such as use of CHB MLI in standalone systems, static VAR compensations, and grid-connected PV system.

The topology presented in is an example of string inverter topology described in Figure 1(b). The authors proposed a three-phase cascaded H-bridge MLI and PV strings. The topology enables a large increase of the total power capacity of the PV system. However, this system is based on the string inverter topology in which multiple PV strings are connected to an H-bridge cell, and the H-bridge cells are then cascaded to generate multilevel voltage. Therefore, this type of topologies suffers from poor MPPT because of partial shading and module mismatch.

The topology presented in is an example of multistring inverter topology that is described in Figure 1(c). The presented configuration consists of string PV modules that are connected to one DC-DC converter and then to the H-bridge cell. Three H-bridge cells were cascaded to generate seven-level voltage. The DC-DC converter is responsible for tracking MPP and for amplifying the DC voltage if needed. This system suffers from the same disadvantages of not accurately tracking the MPP of the PV modules. In addition, the power rating of the DC-DC converter will be high, which increases the system cost. From another point of view, an example of the AC module inverter topology shown in Figure 1(d) is presented. A modular cascaded H-bridge multilevel PV inverter for three-phase grid-connected applications. The AC module inverter topology uses only one PV module for each H-bridge cell. To realize the improved use of PV modules, and to maximize solar energy extraction, a distributed maximum power point tracking control scheme is applied to the three-phase multilevel inverter, which allows for the independent control of each DC-link voltage. With increasing the number of PV modules, the number of H-bridges is increased. The AC module topology is very suitable to improve system efficiency, since the best utilization of PV modules could be obtained; however, the system will be costly and the control will be complex if the number of PV modules increases.

Another type of cascaded MLI topology is based on the conventional two-level voltage-source inverter (VSI). It has been used in many motor-drive applications. This cascaded MLI can also be used for grid-connected renewable energy applications. The three-phase currents in each unit are not balanced, which means the current stresses on each leg are not equal.

Three-cascaded multilevel inverter configurations are used for grid-connected PV applications. These are the three-phase cascaded H-bridge MLI topology, three-phase cascaded VSI topology using inductors, and three-phase cascaded VSI topology using coupled transformers. Distributed maximum power point tracking is used for all presented topologies. The AC module inverter topology has a great advantage in fully optimizing the MPPT. Therefore, the

AC module inverter topology is considered for all presented topologies in which only one PV module is considered for every DC-DC converter. The presented topologies are built in the SIMULINK environment and simulated with a grid interface. In order to validate the quality performance of the presented topologies as well as accurate control, the three topologies are experimentally implemented in the lab, and the switching pulses are generated with the help of the Macrolabia data acquisition system. The presented topologies have been compared to each other by simulation and experiment. The experimental results have verified the effectiveness and reliability of the proposed topologies.

4.1.2 Three-Phase Cascaded H-Bridge MLI

The proposed configuration is a multilevel inverter consisting of two power-processing stages: DC-DC converter and inverter. The proposed configuration is shown in Figure 2. As shown in this configuration, each PV module is connected to one DC-DC converter—unlike the AC module inverter topology described in [5], in which each PV module is connected to one H-bridge for optimal MPP tracking. This in turn can lead to increasing the total system cost and increasing the switching losses. The DC-DC converter is able to track MPP for each PV module and hence improve efficiency and for voltage amplification if needed. In this paper, the DC-DC isolated converter is used. The presence of a high-frequency isolation transformer within the DC-DC converter is for safety purposes. In addition, it is known that the H-bridge suffers from leakage current that may be introduced due to the presence of parasitic capacitance between the PV panel and the earth. This leakage current will cause distortion to the grid current, higher losses, and safety and electromagnetic interference problems. Therefore, the galvanic isolation will solve this problem and prevent leakage current.

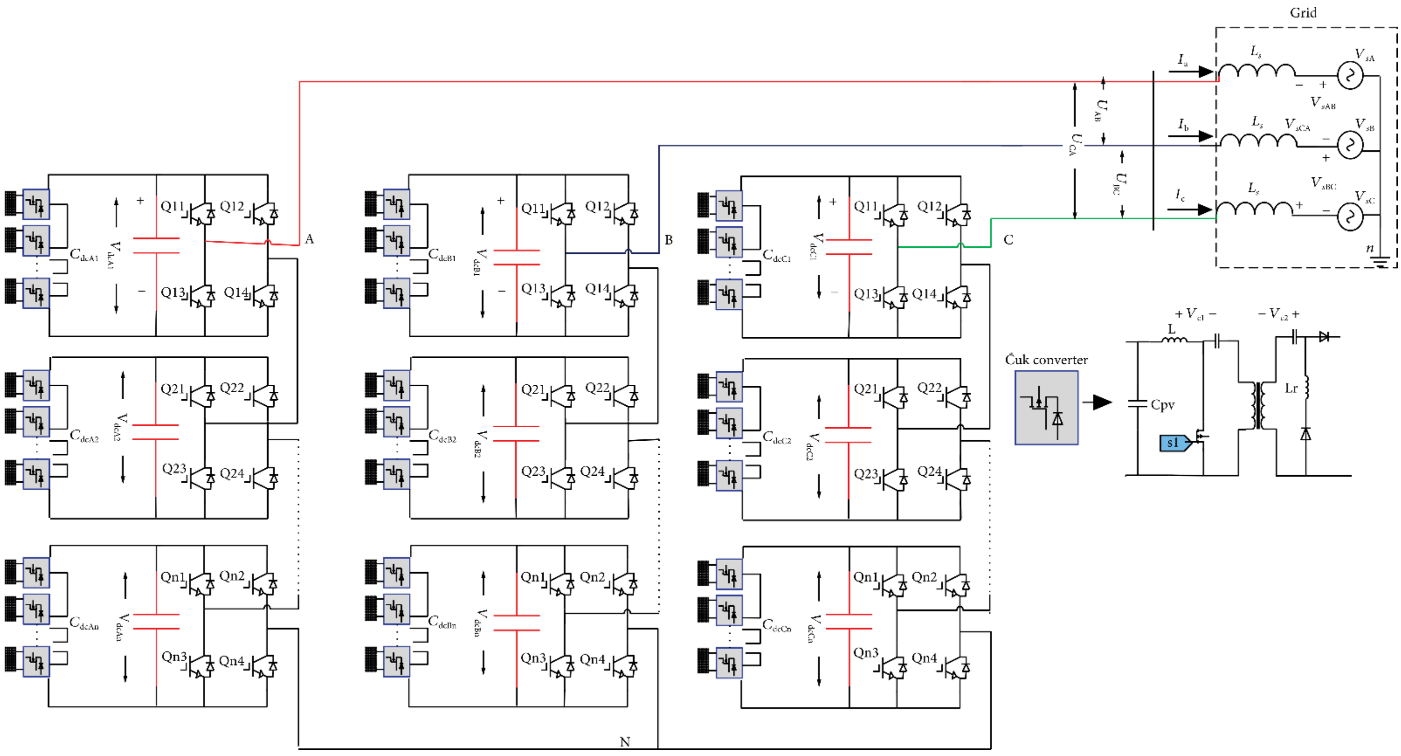


Figure 2_ Three-phase cascaded H-bridge MLI.

4.1.3 Three-Phase Cascaded Voltage-Source MLI Using Inductors

The proposed three-phase cascaded VSI topology is displayed in Figure 3. The system is used for grid-connected PV applications and consists of the three two-level VSI units. The three units are then connected in such a manner as to generate seven-level line-to-line voltage as mentioned in the Introduction. The circulating current is limited by using a current-limiting inductor. Each VSI unit is connected to PV modules via the DC-DC isolated converter. Each PV module is connected to one DC-DC converter. The DC-DC converter is responsible for tracking MPP and for voltage amplification if needed. In addition, it is used for isolation purposes due to the presence of a high-frequency transformer.

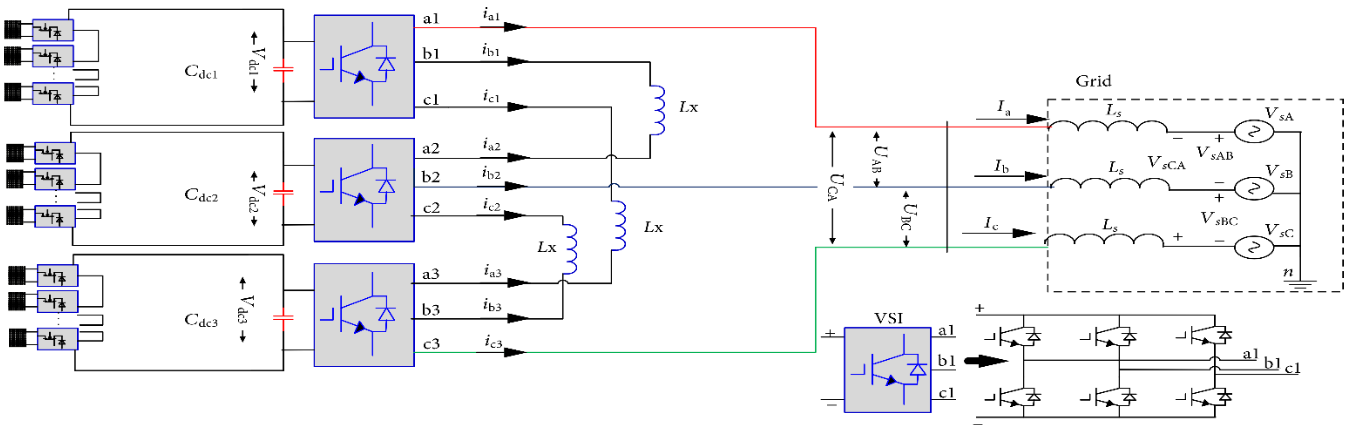


Figure 3 Three-phase cascaded VSI using inductors.

4.1.4. Three-Phase Cascaded Voltage-Source MLI Using Coupled Transformers

The proposed three-phase cascaded voltage-source inverter topology is seen in Figure 4. This system consists of the three two-level voltage-source inverter units. The three units are then connected in such a manner as to generate seven-level line-to-line voltage. This topology was proposed to solve the unbalanced three-phase currents inside each two-leg unit of the topology depicted in Figure 3. The authors [18] solved the problem of unbalanced three-phase currents in each unit by using intermediate transformers instead of inductors. The coupled transformers are characterized by their high magnetization inductance, which reduces the circulating current inside the converter. Each VSI unit is connected to PV modules via the DC-DC isolated converter. Each PV module is connected to one DC-DC converter. The DC-DC converter is responsible for tracking MPP and for isolation purposes.

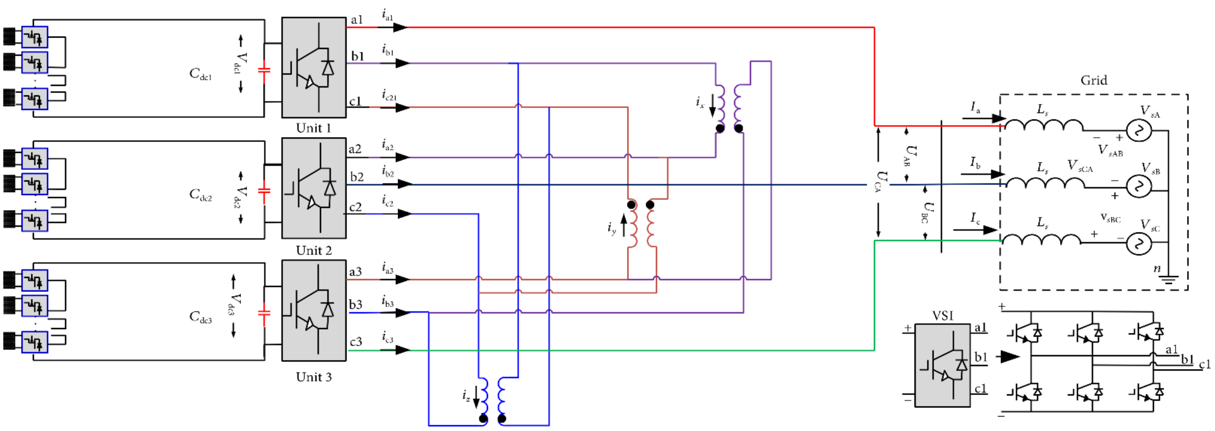
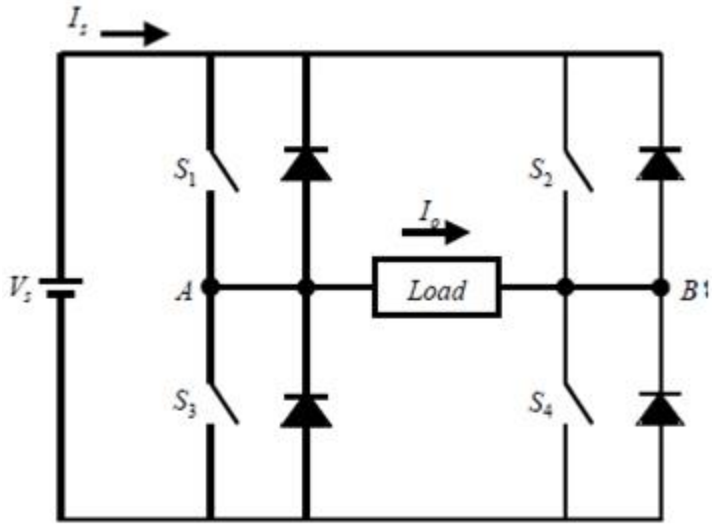


Figure 4 Three-phase cascaded VSI using coupled transformers.

3.2 Features of Cascaded H-Bridge Multilevel Inverter



4.2.1 H-Bridge Cell

- Each H-Bridge Cell consists of four switches and four diodes as shown in the picture.
- Like every H-Bridge, different combinations of switch positions determine different voltages such as V+, V- and 0.
- Two switching combinations are present for 0 volts.
- S1 and S2 are connected to positive voltage and S3 and S4 are connected to negative voltage.

4.2.2 Single Phase Multilevel Inverter

- The number of output levels from a multilevel inverter depends upon the number of separate DC sources attached to it.
- The relation is m=2s+1
- All the outputs from H-Bridges should be quarter symmetric to generate a sin like wave.
- No even harmonics are present.

4.2.3 Three-Phase Multilevel Inverter

- Three-phase Multilevel Inverter is simply like three single phase inverters connected in wye configuration. Three H-Bridges are connected together.
- Delta configuration can also be used.
- Maximum number of line voltages is 2m+1 where m=no. of phase voltages.
- Triple harmonics are eliminated themselves.

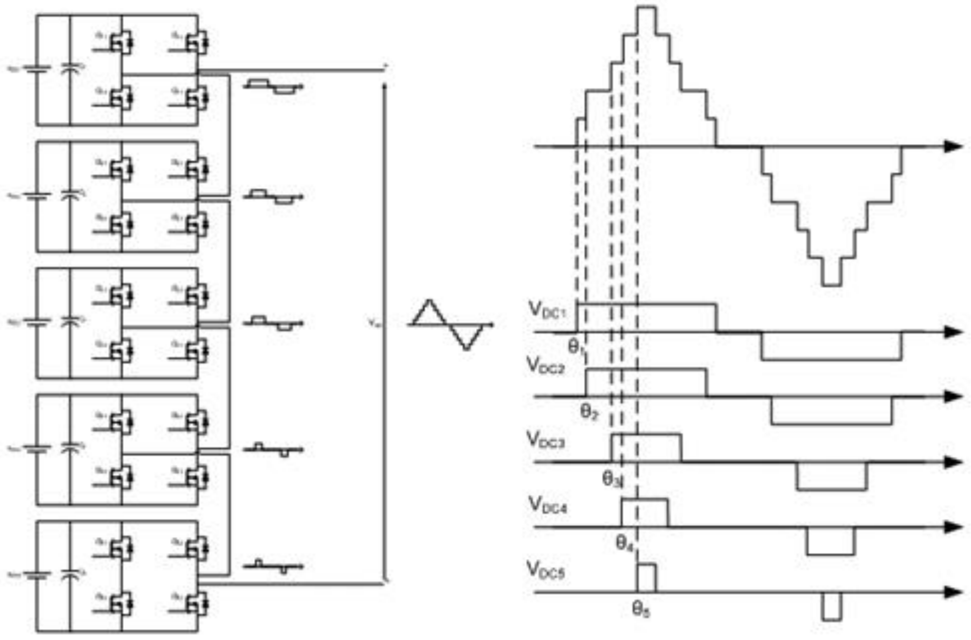
4.2.4 Real Time Switching

In ideal cases the switching time is considered zero and the switching devices turn on and off as soon as you command. But in real time application, switching time is an important phenomenon. To avoid this Blanking time is introduced. The switch turns off just immediately, but the other switch turns on after a certain delay.

4.2.5 Separate DC Source

One of the major issues with Cascaded H-Bridge Multilevel Inverters is that we need separate DC sources with each leg. Well, it might look that separate DC source will create a mess or increase the components, but it is fairly necessary. Because same DC sources can give multiple configurations that result in short circuit. However, this issue has also been resolved. Now lesser number of DC sources can be used and SDC topology has also been proposed.

4.3 Advantages of Cascaded H-Bridge Multilevel Inverter



As the name suggests this multilevel inverter uses full H-Bridges connected is series to produce inverted AC from separate DC sources. These DC sources can be any natural resource such as sunlight or wind energy or anything.

- It does not need any capacitors or diodes for clamping.
- The wave is quite sinusoidal in nature even if you don't filter it.

This was all about cascaded H-Bridge multi -level inverters. Due to their advantages, they are often used now-a-days. More of the inverters types are still there which are extensively used and will be discussed in the upcoming tutorials.

CHAPTER-5

The multilevel inverter has generated a lot of attention in the high-power business lately. They offer the most recent collection of elements that may be used to simplify reactive power adjustment. Without the use of transformers or series-connected synchronized switching devices, multilevel voltage source inverters' distinctive configuration enables them to reach high voltages with minimal harmonics. The Diode clamped, flying capacitor, and Cascaded H-bridge inverter is the three main different inverter structures which are used in industrial applications with separate dc sources [1-5]. A diode-clamped multilevel (m-level) inverter (DCMLI) consists of (m-1) capacitors on the dc bus and produces m levels in the phase voltage. Some of the features are as follows:

- Blocking diodes with a high voltage rating.
- Unbalanced capacitor voltage.
- Unequal switching device rating.

However, the voltage level for the flying capacitor converter is identical to that of the diode-clamped converter. In flying capacitors, the order is numbered differently from that of the diode-clamped inverter [6-8]. Additionally, this has the following qualities:

- Balancing capacitor voltages.
- A Large number of capacitors.

A cascaded-multilevel inverter is made up of many H-bridge inverter components. With the use of multiple different dc sources, such as fuel cells, batteries, or solar cells, this multilayer inverter can provide the desired [9-11]. voltage. It has some characteristics:

- The cascaded inverters require distinct dc sources for power conversions from ac to dc or vice versa. It is appropriate for a range of renewable energy sources, such as solar, fuel cells, and biomass.
- It is not feasible to connect two converters back-to-back with DC sources because a short circuit might be created.

Cascaded H-bridge inverters solve the capacitor voltage balancing issue that plagues flying capacitors and diode-clamped inverters. Asymmetric and symmetric cascaded multilevel inverters are the two classes into which the cascaded topologies are divided. Due to the varying amplitude of its dc voltage source, the asymmetric CMLI produces a greater number of output levels than the symmetric CMLI [12]. The cascaded H-bridge multilevel inverter uses asymmetric voltage methods to raise the no output voltage levels. Voltage levels can be raised by using cascaded bridge MLI. Cascaded multilevel inverters' primary advantages are their uniform design and packaging. This results in a quicker and less expensive production process [14]. This has the drawback of requiring a separate dc supply for each H-bridge and having a large number of power switches. Sine Property methods may be used to precisely control the majority of cascaded inverter characteristics.

II. 3-LEVEL CASCADED H BRIDGE INVERTER

Each H-bridge in a basic H-bridge inverter includes four semiconductor switches, and the four cells [15] can output voltage with either positive or negative polarity or zero volt due to the switching behaviour of the switches as shown in Fig. 1.

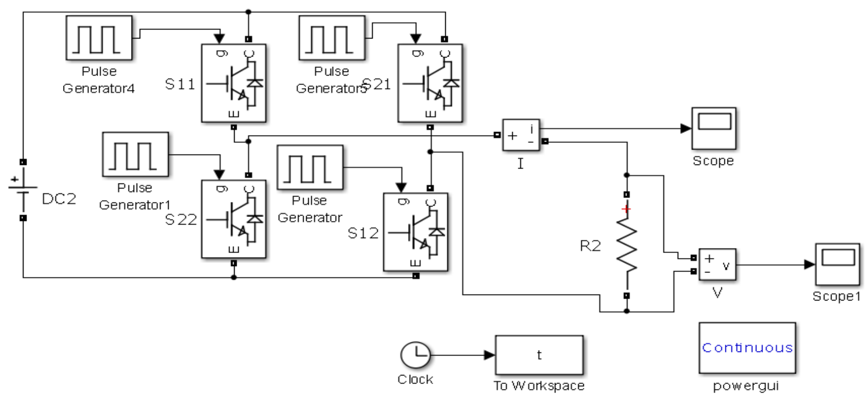


Fig.1 MATLAB circuit for 3-Level Cascaded H-Bridge Multilevel Inverter

Three levels are the lowest possible number of voltage levels for a multilevel inverter using a cascaded arrangement. Full-bridge inverters, also known as H-bridge cells, are used to illustrate how switches change ON and OFF by the switching voltages of a single H-bridge since they are necessary to obtain a waveform with three levels as shown in

Table 1: Output Voltage Values for H-bridge

Switching Voltage	**S11**	**S12**	**S21**	**S22**
0	1	1	0	0
Vdc	1	0	0	1
0	0	0	1	1
0	0	0	1	1
-Vdc	0	1	1	0
0	1	1	0	0

Table1. Three output switch levels, +V, -V, and zero, can be taken into consideration for voltages across the load according to a single H-bridge, which performs four switching operations.

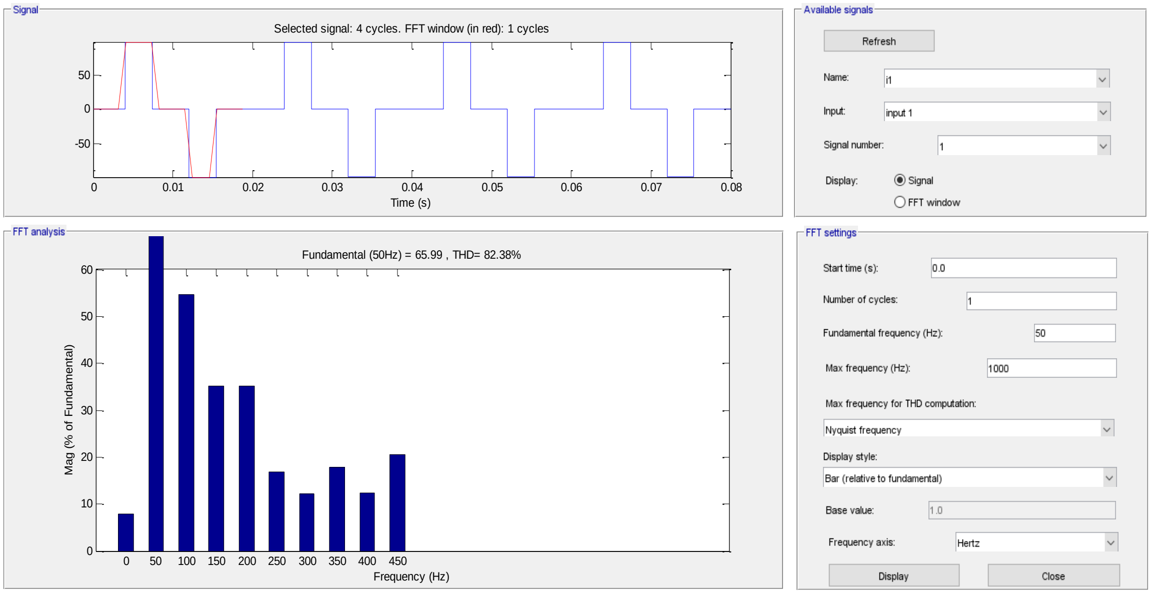


Fig.2 3 level inverter Simulated waveform of output voltage and THD

III. 1. 5-LEVEL CASCADED H BRIDGE INVERTER

The performance analysis has been analyzed of 5 level inverter is shown in Fig.3. This inverter consists of the series connection of two H –bridges fed with two voltage sources. The output voltages of the inverter are the sum of all voltages that appear at each cell output. The output voltage is given by $V=V_1+V_2$, Where V_1 appear across the first cell and V2 appears across the second cell. For a five-level inverter the output voltage ie. 2V, V, 0, -V, -2V.

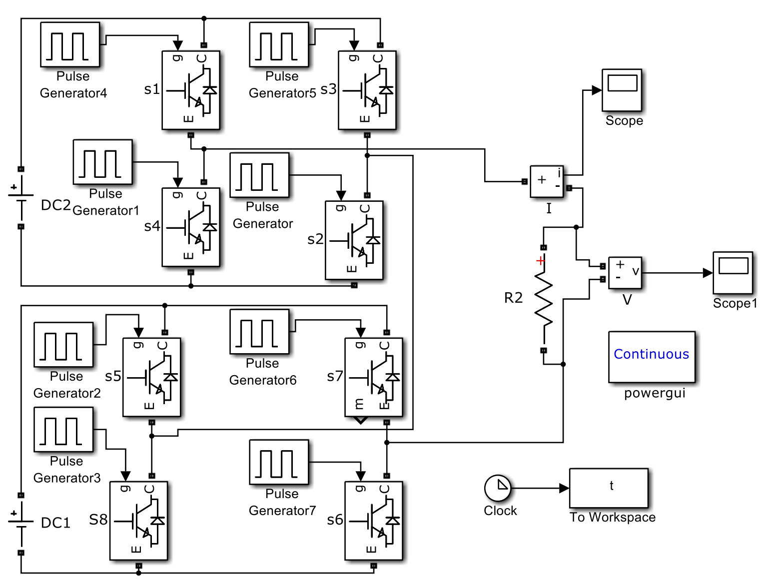


Fig.3

MATLAB circuit for 5-Level Cascaded H-Bridge Multilevel Inverter

III. 2. WORKING OPERATION OF FIVE-LEVEL INVERTER

Mode1: In mode1 operation switches S_1, S_3, S_5, and S_7 are on. The output voltage obtained across the load is zero.

Mode 2: In mode2 operation switches S_1, S_3, S_5, and S_8 are on. The output voltage obtained across the load is $+V_{dc2}$.

Mode 3: In mode3 operation switches S_1, S_4, S_5, and S_8 are on. The output voltage obtained across the load is V_{dc1} $+V_{dc2}$.

Mode 4: In mode 4 operation switches S_2, S_4, S_6, and S_7 are on. The output voltage obtained across the load is $-V_{dc2}$.

Mode 5: In mode 5 operation switches S_2, S_4, S_6, and S_8 are on. The output voltage obtained across the load is 0.

Mode 6: In mode 6 operation switches S_2, S_3, S_6, and S_7 are on. The output voltage obtained across the load is $-V_{dc1}$ - V_{dc2}.

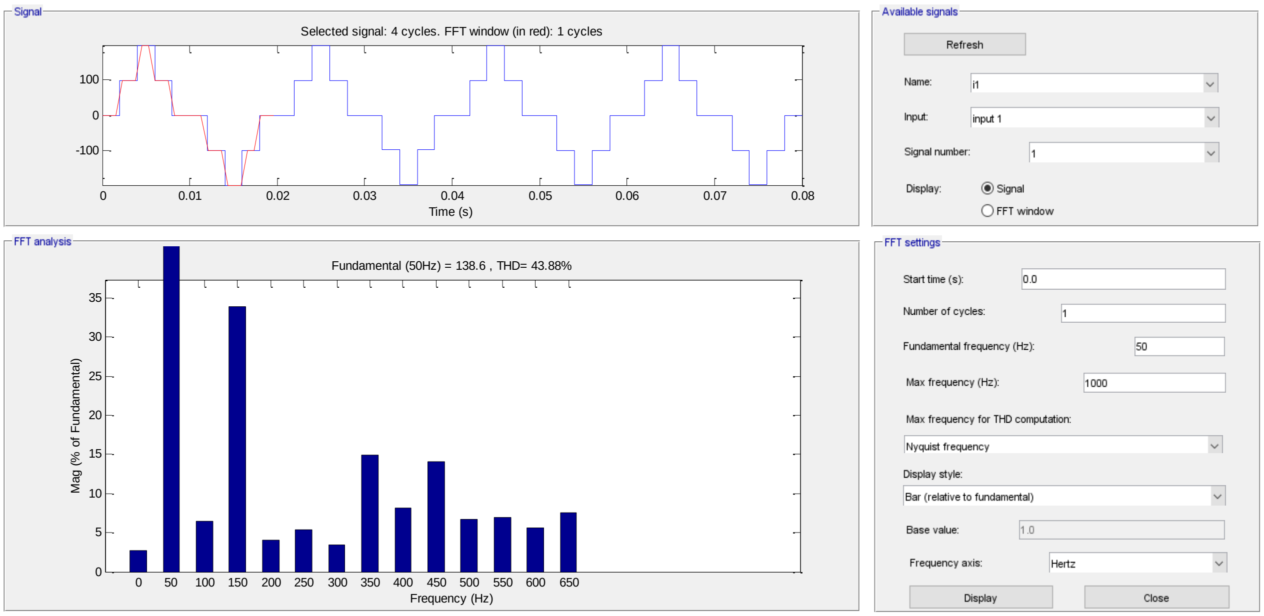


Fig.4 5-level inverter Simulated waveform of output voltage and THD

Table. 2 THD analysis of 3 & 5 level inverter

S. No	Types of multilevel Inverter	Total Harmonics Distortion with R Load
1	3 level	82.3%
2	5level	43.68 %

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PUBLICATION

1. **MARUFUL HAQUE ANSARI, MIRZA MOHAMMAD SHADAB, ISARAR AHAMAD, "ANALYSIS AND IMPLEMENTATION OF CASCADED MULTILEVEL INVERTER TOPOLOGIES" ACCEPTED IN INTERNATIONAL JOURNAL OF REASERCH IN ENGINEERING AND SCIENCE (IJRES)**