USE OF MULTILEVEL INVERTERS FOR THE INTEGRATION OF DIFFERENT KINDS OF RENEWABLE ENERGY SOURCES AND STORAGE TECHNIQUES INTO POWER GRID

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By
OSUMANU MUSAH MOHAMMED

In Partial Fulfilment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering

NICOSIA, 2018

OSUMANU MUSAH MOHAMMED

USE OF MULTILEVEL INVERTERS FOR THE INTEGRATION OF DIFFRERENT KINDS OF RENEWABLE ENERGY SOURCES AND STORAGE TECHNIQUES INTO POWER GRID

NEU 2018

USE OF MULTILEVEL INVERTERS FOR THE INTEGRATION OF DIFFERENT KINDS OF RENEWABLE ENERGY SOURCES AND STORAGE TECHNIQUES INTO POWER GRID

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By
OSUMANU MUSAH MOHAMMED

In Partial Fulfilment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering

NICOSIA, 2018

Osumanu M. Mohammed: USE OF MULTILEVE INERTERS FOR THE INTEGRATION OF DIFFERENT KINDS OF RENEWABLE ENERGY SOURCES AND STORAGE TECHNIQUES INTO POWER GRID.

Approval of Director of Graduate School of

Applied Sciences

Prof. Dr. Nadire ÇAVUŞ

We certify this thesis is satisfactory for the award of the degree of Masters of Science in Electrical Electronics Engineering

Examining Committee in Charge:

Assoc. Prof. Dr. Murat Fahrioglu	Committee Chairman, Department of Electrical and Electronic Engineering, METU
Prof. Dr. Mehmet Timur Aydemir	Supervisor, Department of Electrical and Electronic Engineering, NEU
Dr. Umar Ozgunalp	Department of Electrical and Electronic Engineering, NEU

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name: Osumanu Musah Mohammed

Signature:

Date:

ACKNOWLEDGEMENT

My sincere gratitude to God Almighty for the strength and protection. All Praise and Adoration belongs to Him who perfected His favor upon me by granting me life and good health to go through this project.

My utmost appreciation goes to my supervisor, Prof. Dr. Timur Aydemir for his guidance, encouragement and immense support to executing this project. My profound gratitude goes to the Chairman of the department, Prof. Bullent, and to my course advisor, Assist. Prof. Sertan. In addition, to all the lecturers and teaching assistants in the Electrical and Electronic Engineering Department, who contributed in various ways to making my study a success, especially Samuel Nii-Tackie, a PhD candidate at the Electrical department, God richly bless you all.

The success story of my graduate studies would be incomplete without acknowledging Ghana Education Trust Fund (GETFund) for the scholarship opportunity offered me to heighten this achievement. I wholeheartedly thank my coordinator, Mrs. Lamptey of GETFund, for her unflinching cooperation throughout my academic journey.

To my parents and family….

ABSTRACT

Globally, electrical energy demand keeps escalating beyond energy generation capacity. This energy, mostly from traditional sources such as, nuclear, thermal etc., come along with humongous adversities. These sources, however, do not exist everywhere globally. They are limited, and to generate a large capacity of power, more resources are required. Moreover, composite factors such as, cost of production, maintenance cost, environmental pollution, and other associated brunt, which dwell in their establishment have encouraged electrical power engineers to explore alternatively.

However, renewable energy sources, which are mainly derived from natural resources, and can be replenished naturally is penetrating as viable alternative to curb global thirst for power in addition to tenebrous environmental adversities. These energy sources exist everywhere globally, and the cost of production is low. More importantly, power from these sources are intermittent in nature due to variations in weather conditions. To overcome this, energy storage system is incorporated in the renewables integration not only to store excess power for future use, but also to mitigate power quality issues such harmonics and voltage and current fluctuations.

This project presents a conceptual topology on the use of multilevel inverters for the integration of different kinds of renewable energy sources and storage techniques into power grid. The ideology is demonstrated by the used of asymmetric source cascaded H-bridge multilevel inverter. The final simulation was developed using PSCAD/EMDTC model to demonstrate the feasibility results of the proposed subject.

Keywords: Renewable energy sources; renewables integration; energy storage system (ESS); cascaded h-bridge multilevel inverter; total harmonic distortions (THD)

ÖZET

Enerji talebi küresel olarak enerji üretim kapasitesinin ötesinde artmaktadır. Termal, nükleer vb. geleneksel kaynaklardan gelen enerjinin çok büyük avantajları vardır. Ancak bu kaynaklar dünyanın her yanında bulunmamaktadır. Kaynaklar sınırlı olup, yüksek kapasitede güç üretmek için daha fazla kaynağa ihtiyaç vardır. Üretim, bakım, çevresel kirlenme ve diğer etkenler nedeniyle elektrik mühendislerini alternatif kaynaklar araştırmaya zorlamıştır.

Öte yandan, genellikle doğal kaynaklardan gelen ve doğal olarak yenilenebilir enerji kaynakları hem çevre problemlerini azaltacak hem de küresel enerji açlığını giderecek biçimde vazgeçilmez bir seçenek olarak yerini almaktadır. Dünyanın her yanında var olan bu enerji kaynaklarının üretim maliyeti de düşüktür. Ancak, hava koşulları nedeniyle bu kaynakların enerjisi sürekli değildir. Bunun üstesinden gelebilmek için enerji depolama sistemlerine ihtiyaç bulunmaktadır. Bu sistemler yalnızca fazla enerjiyi depolamak için değil, aynı zamanda harmonikler ve gerilim salınımı gibi güç kalitesi problemlerini azaltmak için de kullanılmaktadır.

Anahtar kelimeler**:** Yenilenebilir enerji kaynakları; yenilenebilir enerji entegrasyonu; enerji depolama sistemi (ESS); zincirleme bağlı h-köprü çok seviyeli evirici; toplam harmonik bozulum (THB)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$\boldsymbol{C_{boost}}$: Boost converter capacitor

$\boldsymbol{E_{boost}}$: Boost converter output DC voltage

$\boldsymbol{E_{source}}$: Input DC voltage

$\boldsymbol{F_{o}}$: Fundamental frequency

$\boldsymbol{F_{sw}}$: Switching frequency

$\boldsymbol{k_{p}}$: Proportional gain

$\boldsymbol{L_{bidirectional}}$: Bidirectional converter inductor

$\boldsymbol{L_{boost}}$: Boost converter inductor

N_{step}: The number of output levels

$\boldsymbol{S_{boost}}$: Boost converter switch

$\boldsymbol{S_{charge}}$: DC-DC bidirectional converter charging switch

$\boldsymbol{S_{discharge}}$: DC-DC bidirectional converter charging switch

$\boldsymbol{T_{i}}$: Integral time constant

$\boldsymbol{T_{sw}}$: Switching period

$\boldsymbol{V_{dc}}$: Output DC voltage

$\boldsymbol{V_{n}}$: The DC voltage sources applied to each H-bridge inverter

$\boldsymbol{V_{o,max}}$: The maximum voltage generated by the complete cascaded inverter

$\boldsymbol{V_{ref}}$: Reference voltage

$\boldsymbol{V_{stand}}$: The total maximum voltage the power electronic switches can withstand

LIST OF ABBREVIATIONS

AC:	Alternating Current
BESS:	Battery Energy Storage System
CAES:	Compressed Air Energy Storage
CHB-MLI:	Cascaded H-Bridges Multilevel Inverter
CPV:	Concentrating Photovoltaic
CSC:	Current Source Converter
CSP:	Concentrated Solar Power
DC:	Direct Current
DCMLI:	Diode Clamped Multilevel Inverter
EMTDC:	Electromagnetic Transients with DC
EMI:	Electromagnetic Interference
ESS:	Energy Storage System
FACTS:	Flexible AC Transmission System
FCMLI:	Flying Capacitor Multilevel Inverter
FESS:	Flywheel Energy Storage System
FRT:	Fault Ride Through
IGBT:	Insulated-Gate Bipolar Transistor
PHES:	Pumped Hydro Energy Storage
PSCAD:	Power System Computer Aided Design
PV:	Photovoltaic
PWHM:	Pulse Width High Modulation
PWM:	Pulse Width Modulation
SCES:	Super Capacitor Energy Storage
SMES:	Superconducting Magnetic Energy Storage
TES:	Thermal Storage System
THD:	Total Harmonic Distortion
VSC:	Voltage Source Converter

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Increased demand of energy for both industrial and domestic use has forced the power system to change significantly. These changes took place particularly in integrating different types of power generation facilities (Zhang et al., 2016). This has manifested into a reliable approach of power generation through renewable sources such as wind, biomass solar, geothermal etc. in addition to hydroelectric, nuclear, coal and the other existing energy sources to meet the escalating demand in an environmental friendly approach. Figure 1.1 shows renewables addition into power grid. Similarly, to resolve the surging demand for energy coupled with the need to eliminate greenhouse effect has prompted the emergence of renewable energy sources into the electrical network over the past years. The development, however, comes with power delivering deficiencies, especially when dealing with solar and wind power sources.

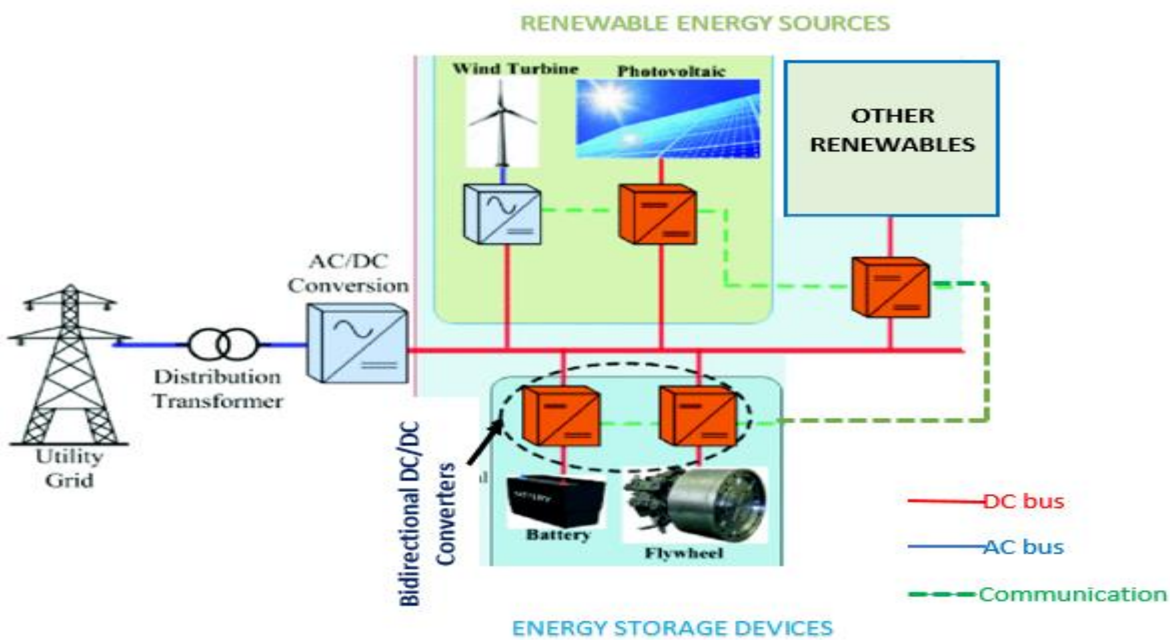

Figure 1.1: Schematic of renewables and ESS integration (Kumar et al., 2017)

This also, introduces instabilities in voltage and frequency along with harmonic, and pollution that need to be consistently controlled. Consequently, power operators are forced to balance demand and supply, and are sometimes compelled with no option than to cut out supply from renewable energy sources in order to maintain or minimize utility stability hence, losses occur.

Furthermore, intermittent capability of renewable energy resources like solar and wind in particular, has adverse effect on power network in addition to voltage and current harmonics, voltage and frequency and reactive power that affect the general assessment of the power system. For instance, solar radiation irregularities due to the unbalanced weather conditions during winter and stormy days, cause voltage instability at the output of the renewable system at the point of grid integration. For wind energy, fluctuations usually occur due to wind turbulence and also, wind turbine design. Basically, power flow from transmission systems to distribution systems. However, reverse power flow may be possible when the integrated power system has more power that the load of the grid (Shafiullah, 2016).

Fluctuation in renewable energy sources causes dynamic conditions in the network due to asymmetric renewable energy input. This introduces bidirectional power flow, which adjusts system voltage hence, affects transformer utilization. Reactive power is needed in network operations due to loads such as induction machines. In such conditions, induction generators used in wind turbines become very critical since reactive power control has significant influence on network parameters (Shafiullah, 2016; Guinane et al., 2012). Therefore, renewable energy resources in combination with energy storage component with vast intermittent capabilities is very essential to provide uninterrupted protection to crucial loads. Also, hybrid integration of renewable resources in addition to energy storage systems are very important probably, to mitigate photovoltaic shadowing and wind turbulence effects.

An obstacle in the way of integrating renewable energy sources in much higher capacities is their intermittent nature. This is a situation which has compelled several researchers in the field. In view of this, integration of an energy storage system to meet the demand surplus has been an attractive research area. Energy storage systems that store enough energy without much loss also help increase the stability of power systems (Mizutani et al., 2016). As a result, energy storage systems (ESS) could be a promising choice (Romlie et al., 2014). ESSs can ensure restoration of low voltages by providing the required reactive power to networks, and also, allow other sources of generators to follow scheduled generation to supply as per base loads (Hasan et al., 2013). ESSs have also been favorable to improve upon the power quality, in addition to storage of reserved electrical energy.

Multilevel inverters topologies are recognized as attractive amongst the modern day power engineering involving power converters. In recent years, their numerous considerable features have encouraged their penetration in several industrial applications such as renewable energy integration. These inverters produced smooth sinusoidal output waveform at reduced stress rate. More importantly, they possess viable factors such as high power and medium power applications in addition to ability to generate an output voltage with less distortion. Although, their applications include different control techniques which are necessary for harmonic mitigations and power factor corrections. However, the use of components such as, clamp diodes and capacitors in a large-scale applications, can sometimes effect difficulties in controlling real power flow in individual inverters.

This dissertation presents the study of the use of multilevel inverters for the integration of different kinds of renewable energy sources and storage techniques into existing utility grid. The introductory sections provide the concepts and the fundamental requirements of the proposed topic. The following sections explain renewable energy principles, energy storage techniques in addition to the benefits and setbacks of grid integration. The proposed topology consists of asymmetric DC sources, DC/AC cascaded H-bridge multilevel inverter, boost converter and DC/DC bidirectional converter for energy storage units. A boost converter will control and stabilize the DC sources from renewables. The cascaded H-bridge inverter and the DC/DC bidirectional converter shall manage the power flow between the renewables, the energy storage units, and the utility grid. When there is more available energy from the renewable sources, buck-boost converters will charge the energy storage units for future use.

On the other hand, the stored energy in the storage units must be supplied to the utility grid through the buck-boost converters and the multilevel inverter. This means the DC/DC buck boost converter must be able to operate in both directions in order to charge and discharge the energy storage units.

1.2 Literature Review

Several work have been carried-out over the years about renewable integration into the existing grid network. Composite factors pertaining to benefits, drawbacks and different solutions to overcome the problems are conducted. For instance, renewable integration into existing plants is proposed in (Tannous et al., 2016). The topology discussed the problems surrounding the introduction of renewable energy into existing power plants, and environmental concerns were raised. Integration of renewable sources of energy into power grid is presented in (Swain et al., 2017). In this paper, various considerable factors such as, appropriate features of inverters required to achieve this purpose were tackled. In addition, control measures to arrive at power stability, reliability and availability were presented.

More importantly, power electronics applications in renewable energy systems are explained in (Blaabjerg et al., 2006). The authors availed power electronic topologies for wind turbine (both offshore and onshore) and PV systems applications. Performance behavior to regulate voltage and frequency by the means of active and reactive power was clearly explained. Sekar et al., (2017) reviewed the power electronic converters suitable for renewable energy sources. The paper discussed DC-DC converters and multi-inputs converters, which are essential for renewables. For example, the main integration topologies applied on the integration of renewables is proposed in (Paulino, et al., 2011). In this presentation, inverter topologies like three phase full-bridge inverter, NPC inverter, fly-back inverter and Z-source inverter were presented. The paper also presented their benefits as well as their peculiar influence on renewables integration. Moreover, multilevel inverter topology necessary for renewable integration was proposed in (Amamra et al., 2017). The proposed six-level inverter was based on PWHM switching technique. The author realized that, low switching frequency technique reduces power loss and better to eliminate fundamental harmonics. In addition, it reduces the number of power electronic switches and appropriate gate drivers, making it more economical to use compare to other inverter topologies.

Impacts of renewable energy integration into high voltage network is proposed in (Shafiullah, 2016). The paper demonstrated that integration affects transformer loading throughout working period. Also decentralized control method of solar PV integration influences voltages regulation of the network. Liang, (2017) has discussed various emerging power quality challenges due to integration of renewable energy resources. They concluded that power quality issues such as harmonics, voltage and frequency fluctuations are the major setbacks of renewables integration.

Seasoned energy storage in renewable energy system is proposed in (Converse, 2012). The author proposed evaluation assessment before a storage system is designed. Peralta and Salles, (2017). Proposed advanced energy storage systems to increase the penetration of renewables. The paper discussed oil consumption and carbon monoxide emissions of increasing renewable energy. Thus, as compared to solar PV, wind energy has the ability to reduce diesel consumption and CO_2 emissions. A novel topology comprising of three boost converters and one bi-directional buck-boost converter was proposed for the control of energy storage for integration of solar PV by (Zhang et al., 2016). The proposed topology was designed to withstand variable conditions such as transient short circuit situations. Energy storage systems have impact on frequency fluctuations following faults microgrids including renewable energy sources. These impacts were evaluated and it was concluded that BES topology can reduce these fluctuations (Arif and Aziz, 2017). A grid connected photovoltaic inverter with battery-super capacitor hybrid energy storage is proposed in (Miñambres-Marcos et al., 2017). The proposed hybrid energy storage topology consisting of battery and super-capacitors is efficient in reducing charge/discharge rate in addition to producing almost a sinusoidal waveform for the grid injected current component. Also, power management and control of grid connected photovoltaic system with plug in hybrid vehicle load is presented in (Rahman et al., 2014). It was concluded that plug in hybrid electric vehicle (PHEV) has more ability to mitigate some recent crises on power demand when proper storage and control mechanism are used.

1.3 Thesis Objectives

During over generation, energy from renewable sources become needless, especially when the network stability is at risk. As a result, more energy losses occurs. However, this variability can be mitigated by the use of energy storage systems. These systems have the ability to improve power stability and reliability, also provide dynamic frequency support during transient load conditions. It is no doubt energy storage units play vital role in power system operation.

The purpose of this project is to study an approach to integrating renewable energy sources with energy storage system into the grid using power electronics application approach. In order to understand the system operation, impact and implementation, a variety of methods would be used. This includes a comprehensive literature review to identify existing contributions on the subject, compare and contrast different opinions, and as guide to evaluate the project with the necessary recommendations for future studies. Also, it is aimed at providing power system applications in the areas such as:

- ***Renewable energy sources***: Globally, electrical energy demand keeps escalating beyond energy generational capacity. This energy, mostly from traditional sources such as nuclear, thermal etc., come along with humongous adversities. However, this project presents several forms of renewable energy sources and their benefits
- ***Energy storage techniques***: During over generation, energy from renewable sources become needless, especially when the network stability is at risk. As a result, more energy losses occurs. These systems have the ability to improve power stability and reliability, also provide dynamic frequency support during transient load conditions
- ***Renewables integration:*** The quest for renewables power generation in both developed and developing countries keeps escalating in proportion to power demand. As a result, this has motivated an alternative means to generate more power from renewable

resources and integrate into the existing grid. This dissertation is aimed at discussing efficient means of renewables integration

- ***Multilevel inverter application in renewables*:** This project offers the study of multilevel inverters and their different control techniques applicable in renewable energy sources, and also intends to increase the integration of alternative energy sources into power network
- ***Harmonics Elimination*:** normal power frequency is between 50 and 60Hz. However, frequency deviation can occur due to voltage and currents fluctuations.

A multilevel inverter based on cascaded H-bridge topology is proposed here to integrate asymmetrical renewable energy sources in the thesis. The proposed topology has been designed and simulated for two different sources. A boost converter has been used to increase the voltage level received from the renewable sources to a higher DC bus level and its closed loop control based on one quarter wave decay ratio technique.

1.4 Thesis Organization

In this thesis, **chapter one** presents the general introduction about the topic. It further throws more light on recent spate of renewable energy integration into the existing grid. It also includes the concept of energy storage systems and its introduction into power systems. Following literature review to capture the concept of the topic by reviewing of previous works, in addition to the chronological arrangements of the thesis.

Chapter two, discusses various forms of renewable energy resources such as solar, wind, biomass, hydropower and geothermal energy. It covers the main source of energy for renewables, the benefits and the setbacks. Moreover, the strategic process of renewable energy integration and the prevalence importance. In addition, the fundamental structures and the benefits of energy storage topologies are presented in this chapter.

Chapter three talks about multilevel inverters, types of multilevel inverters, advantages and disadvantages of multilevel inverters and applications of multilevel inverters in renewables integration as well as switching techniques necessary to reduce harmonics.

Chapter four demonstrates the methodology of the proposed technique. The design of the topology using cascaded H-bridge multilevel inverter with asymmetric inputs. It includes the control of the nine level waveform and the discussion of the simulation results.

Finally, **chapter five** is the concluding section, which tackles the overall outcome of thesis and gives some future work recommendations.

CHAPTER 2

RENEWABLE ENERGY SOURCES, RENEWABLE INTEGRATION AND ENERGY STORAGE TECHNIQUES

2.1 Renewable Energy Sources

Globally, electrical energy demand keeps escalating beyond energy generation capacity. This energy, mostly from traditional sources such as nuclear, thermal etc., come along with humongous adversities. These sources, however, do not exist everywhere globally. They are limited, and to generate a large capacity of power, more resources are required. Moreover, composite factors such as, cost of production, maintenance cost, environmental pollution, and other brunt, which dwell in their establishment have encouraged electrical engineers to explore alternative ways.

In recent years, renewable energy, which is particularly from natural resources, and can be replenished naturally, is penetrating as an alternative to the existing traditional forms of energy. Renewable resources exist over worldwide geographical areas, as compare to other traditional sources. This energy penetration is because of significant considerations which includes the desire to avert climate damage in addition to tenebrous economic factors. Against this background, global leaders seek to support renewables with attractive packages. Hence, investors are encouraged to invest in renewable energy, which invariably, create more job avenues. Among renewable technologies is a sustainable energy. A concept involving considerable future awareness to generate energy to meet the demands. There are several types of renewable energy, which almost present equal benefits to renewable technology. The common growing types are; solar energy wind energy, biomass, hydropower and geothermal as depicted in Figure 2.1. Their energy sources are directly or indirectly from the sun. They produced clean energy, and do not emit carbon emissions.

The prospects of renewable energy concept come along with prosperous advantages. These favorable conditions have made their penetration massively acceptable. Unlike fossil fuel, which releases carbon monoxides when burnt, renewable energy has no extreme effect on the environment. More importantly, the energy from renewable sources can be easily stored using batteries for future use, especially during stormy conditions. This and more advantages drive the urge for renewable penetration, and some of these are:

- Renewable energy serve as additional sources to ensure power reliability.
- Energy from renewable sources is sustainable
- Renewable applications release no or less obnoxious materials into the environment as compare to traditional methods.
- They require less initial cost as well as maintenance cost.
- Renewable technologies are very clean without any climate damage.
- They require less maintenance unlike other sources

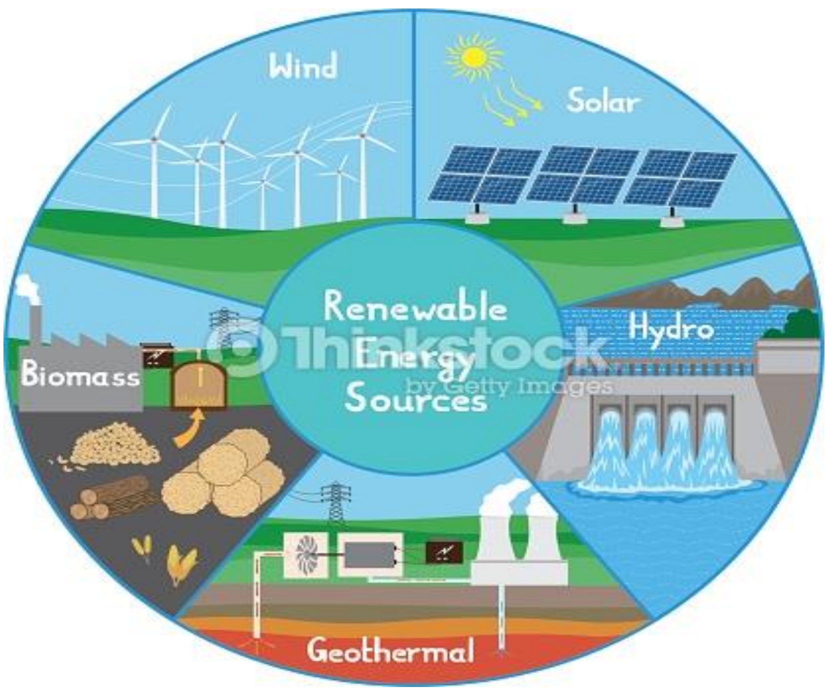

Figure 2.1: Renewable energy sources

However, energy from most renewable resources depend massively on sunlight. Factors as, winter, night etc., defy the unlimited availability claims of renewable energy. During these conditions, the sun's radiation dwindles or becomes unavailable to produce the required energy. This may lead to power instability and other power inefficiencies. Although, most renewable power structures include energy storage systems to store surplus energy produced during daytime. There are also few disadvantages, which are yet to be addressed, and they are:

- Renewable sources produce lesser electricity as compare to fossil fuel generators.
- Their source of energy depend on weather, which has dwindle conditions.

2.1.1 Solar energy

Generally, quite number of renewable energy are derived from the sun. The radiation from the Sun is converted into different forms of energy when it reaches the earth's surface. As the name implies, solar energy is, the energy from the sun, which can be harnessed into different forms of energy such as, electricity, heat etc. The concept of solar energy is propelled by two main technologies: Photovoltaic and Solar thermal. Photovoltaic (PV) involves the use of solar cells to convert sunlight into electricity. These cells are usually made of semiconductor materials, which allow free movement of electrons (current) when sunrays strikes their surface. Solar thermal on the other hand, is converging the sunrays mostly by the use of solar collectors to produce heat energy for both domestic and industrial applications. In both technologies, it is noticed that the amount of energy produced is depends hugely on solar radiation. In spite of that, prominent concentrating technologies (concentrated solar power, CSP and concentrating PV, CPV) to be able to trap the maximum radiations for PV and solar thermal applications have emerged (Renewable energy sources presentation, 2008).

Undoubtedly, solar energy is leading the race of renewable energy invasion in the world's electricity market. It is abundantly available in most countries, and provides a reliable supply. Solar energy offers several advantages, which have persuaded investors to consider its patronage. A notable regarded as a clean source of renewable energy. Although, solar power station requires low maintenance in addition to reduction of greenhouse effect. Nevertheless, sunlight is the main source of solar energy, which is not available at all days. Also, manufacturing process of silicon materials may expose certain harmful substance to the environment.

2.1.2 Wind energy

Wind energy is energy generated by wind power plant. Wind speed is allowed to drive a wind turbine, which is coupled to a generator to produce electricity. Wind power plants are growing significantly with annual capacity factor of 20% - 40%. The capacity of wind power depends on wind speed, and therefore, it is suitable in areas such as Europe and USA where wind speed is more stable. Currently, the world electricity consists of 1% of wind energy. This includes both offshore and onshore wind farms. However, the integration of wind energy comes along with challenges. Wind is intermittent, and therefore, the turbines cannot work to their full capacity persistently. In addition, some wind turbine generators are not capable to controlling reactive power (Liang, 2017). This, together with other factors, eventually, increase the initial cost of construction.

2.1.3 Geothermal energy

Several technologies are used to pump water to deep underground through hot rocks to produce steam. This steam from underground springs is then used as a prime mover to drive a turbine coupled to a generator to generate electricity. In Europe and other advanced places, deep wells are constructed in hot rocks, where the fluid is heated to produce steam to turn heat turbines. Geothermal process consists of three main technologies namely; flash steam (hot water is brought to land surface under high pressure), dry steam (steam is used directly in the turbines. eg. Is Geysers with an annual capacity of 750MW), and binary cycle (it allows cooler reservoirs to be used other than flash and dry steam methods) (Renewable energy sources presentation, 2008). Geothermal energy has gained significant popularity in today’s energy demand with USA and Philippines been the highest in geothermal construction. The main advantage of geothermal power reside in low operating cost in addition to independent of weather conditions. However, geothermal power station is expensive. Also, the construction is restricted by land stability/availability.

2.1.4 Biomass and biofuel

Biomass is energy from organic materials, mostly from plans and animals. Plants to convert energy from the sun into chemical energy use the process of photosynthesis. When animals eat plants, this converted energy is transferred into them. Within biomass is a biofuel, which is produced from photosynthetic plants. Biofuel can be used to produce biodiesel. Which when mixed with mineral diesel, can be used in diesel engines. In biomass plant, plants and animals waste are burned to produce steam to drive a turbine coupled to a generator to generate electricity. Biogas, which is also derived from biomass as a result of biological breakdown of organic materials is rich in methane gas, and can be used to generate heat and/or fuel for both domestic and industrial purposes. Biomass offers a significant benefit making it more considerable source in renewable energy field. It is available every place in the world. However, to produce large megawatts of biomass power, more organic materials are required which could constitute deforestation.

2.1.5 Hydropower

This is energy derived from the movement of falling water. The water is made to flow, and it is collected in a dam. This water in the dam is then flow through a penstock due to kinetic energy under high speed. At the end of the penstock is a turbine coupled to a generator. The turbine is then turned by the gravity of the moving water to produce electricity. Unlike air, water is denser therefore; its movement generates more energy than wind. Energy from hydropower can be controlled to meet the demand level, simply by adjusting the flow of the water through the penstock. In today's engineering world, there have been several considerations regarding the construction of hydro power plants. The traditional dams require reservoir to store the water in flow. This reservoir however, endangered the environment. As a result, a new technology, run-of-the-river hydroelectric generation has emerged. Similarly, it also thrives on dams but with no reservoirs. In this method, the moving water through the penstock, which drives the turbine is made to return into the dam for a repeated process.

Also to the hydropower is tidal power technology, which converts the energy of the tides into electricity. This technology is more considerable than solar and wind, since tides are much predictable within a calendar year. Its operation is similar to hydropower. A method known as barrages is used to capture tidal energy with tidal stream to drive a turbine coupled to a generator to produce electricity. This technology is popular based on installation cost and environmental adversities. In general, hydropower derives several benefits, it constitutes to almost 19% of world's electricity (Renewable energy sources presentation, 2008). It is clean source of energy. Its operation requires no burning of fuels. But, to produce more power, land degradation becomes a problems, also aquatic and terrestrial animals are affected.

2.2 Renewable Integration

The quest for renewables power generation in both developed and developing countries keeps escalating in proportion to power demand. This is because of recent increasing oil prices in addition to the desire to restore climate parity. As a result, this has motivated an alternative means to generate more power from renewable resources and integrate into the existing grid. The integration of renewable energy resources involve synchronization fundamentals into the existing power grid, and this is normally done with the help of power electronic converters. The converters must be capable of allowing integration. Thus, to ensure grid interconnections at all levels, aimed at improving grid dynamic capabilities, stability and system reliability. The Figure 2.2 shows a typical example of renewable energy resources integration into the existing grid network. On this figure, converters and reciters interconnected several sources of renewables onto the DC-bus. There is also an inverter, which finally integrate the generated power into the AC grid (Paulino, et al., 2011). Additionally, there is a bidirectional buck boost converter, which controls the charge and the discharge of the energy storage unit, and a smart meter for power consumption measurement.

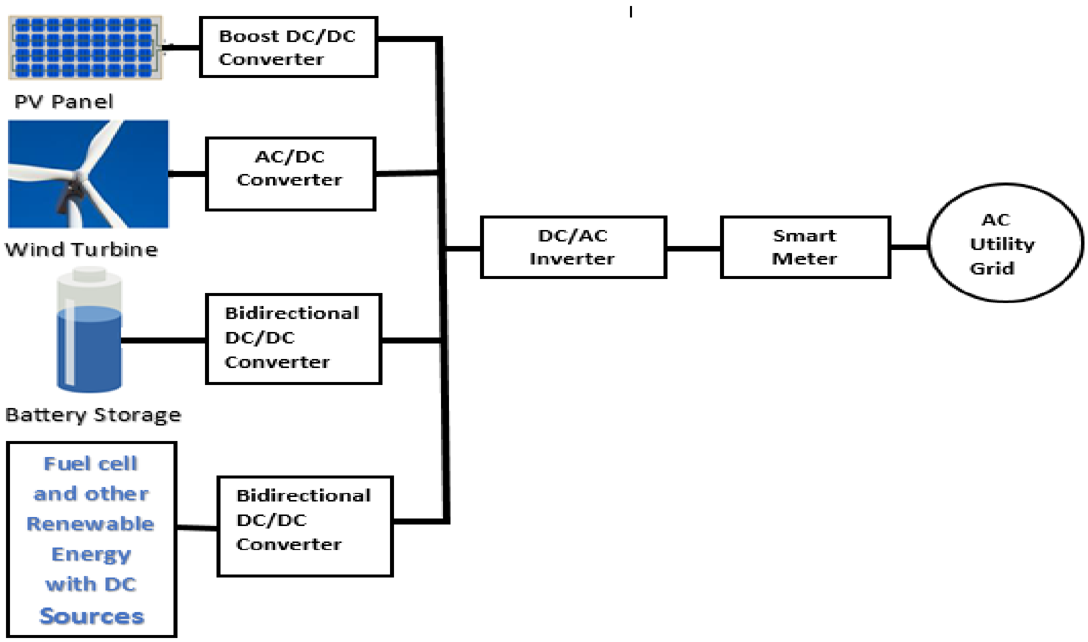

Figure 2.2: Typical example of integration of renewable energy sources into the grid

Renewable energy integration is centered on incorporating renewables, distributed generation, energy storage components and FACTS equipment in addition to feedback demand into the power system network. Policymaking and system planning is being employed to achieve integration progress. Thus, to address regulatory policies, technical, economic and other performance assessment of renewable and distribution systems (Bhoyar and Bharatkar, 2013). More importantly, system reliability is a major concern to vary generation and distribution capabilities to provide adequate and stable power to major load points. Renewable resources utilization create unbalanced conditions in power system parameters, which can cause adverse effect to equipment in addition to power quality issues. Against this background, it is paramount imperative to assess system reliability, unbalanced situations and appropriate financial resolutions to ensure system feasibility.

There are several technologies to integrate renewable energy into the power network. Integration can be done in combination with energy storage system, smart grid technologies and flexible technologies. Smart grid technologies involve the variation of renewable integration into the power network including load control to enhance system operation in order to manage technologies such as fault ride through (FRT) capabilities. Flexible technologies comprise of production optimization for dispatchable and non-dispatchable energy resources. Moreover, energy storage technologies are to avert periodical fluctuations through existing storage topologies. These technologies improve system reliability and make renewable integration more attractive.

Renewable integration addresses several issues ranging from power demand to environmental problems. In summary, the aims of renewable energy integration are:

- To protect the environment from pollutions. Since renewable sources are clean energy sources.
- To provide security and reliability to micro-grid applications in critical area of power systems.
- To enable plug in hybrid electric operation in order to reduce oil prices.
- To provide additional power into the grid hence, the price of electricity is reduced.
- To support energy and renewable energy efficiency.

2.3 Energy Storage Systems

Power from renewable energy sources is dynamic, and may have some undesirable fluctuations that can be eliminated by the use of energy storage systems. These fluctuations could be because of anomalous weather conditions, which is a relevant source of energy for almost all renewables. The normal transmission and distribution lines transport power in unidirectional way to consumers. Due to this, generation must be proportional to demand. This is because high power demand may cause variations in power plants, and inadvertently affect power generation and transmission. This inaccuracy can be resolve by the means of energy storage system. Energy storage system (ESS) is needed in today's power generation network. This system not only provides adequate reserved power for consumer satisfaction, but also enhances system reliability, flexibility as well enables transmission lines to sustain variable loads. ESS is essential for distribution energy resources system. It is usually small in capacity, and provides quick responds to load fluctuations. In applications such as solar PV and wind, it provides urgent intermittency to restore weather fickle in power system.

Furthermore, hybridization of two or more different energy storage systems is known to be one of the renowned solution for irregular solar radiation in photovoltaic renewable applications. For example, battery-super capacitor hybridization is relevant topology, which produces almost sinusoidal waveform for grid current injection in PV system (Miñambres-Marcos et al., 2017). Also, hybridization aid in integrating two or more renewables sources to meet demand/consumer requirement.

2.3.1 Types of energy storage systems

Basically, electrical energy is generated from renewable resources. This energy can be converted and stored in the form of electrical, mechanical, kinetic, potential and electrochemical form of energy. In power network, this energy conversion and storage concept includes power conversion units. In electromagnetic storage, we have super capacitor energy storage (SCES) and superconducting magnetic energy storage (SMES). Mechanical storage are flywheel energy storage (FES), a pumped hydro energy storage (PHES) or a compressed air energy storage (CAES). In electrochemical application energy storage, we have battery energy storage system (BESS). Lastly thermal storage system (TES), normally used in heat energy storage applications.

2.3.1.1 Superconducting magnetic energy storage (SMES)

This system stores energy in the magnetic field produced by the dc current flowing through a superconducting coil. It comprises of a large superconducting coil maintained at a lower temperature, cryogenic as seen in Figure 2.3. There are also two types of power conversion systems; voltage source converter (VSC) and current source converter (CSC) that connect the system to an AC source, and are used to charge or discharge the coil. The VSC is for ac interface and a dc-dc chopper to charge/discharge the coil whereas the CSC is for ac system interface and charge/discharge the coil. To charge or discharge the SMES coil: a positive or negative voltage is applied across the superconducting coil (Gupta et al., 2011).

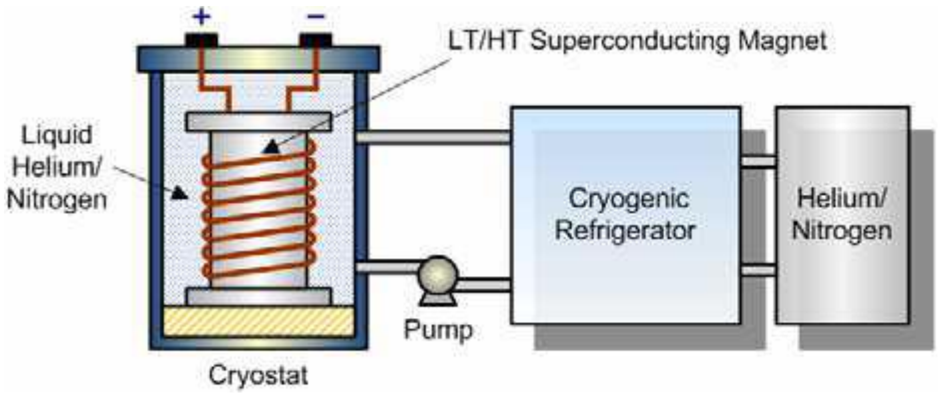

Figure 2.3: SMESS device basic structure (Molina, 2010)

SMES systems are one of the highest efficient energy storage devices with an efficiency rate up to 97% or more. SMESs are capable of storing and then releasing electricity in very short time. SMES systems are also knows as long life storage devices and are suitable for long-term storage. They can store energy capacity up to 100 MW (Jamali et al., 2015). Capital cost is one of the main drawback surrounding SMES systems application in power system (Zakeri and Syri, 2015).

2.3.1.2 Super capacitor energy storage (SCES)

Generally, electric energy is stored by the charges absorbed by its polarities. As shown in figure 2.4, super capacitors are double layer capacitors. They made of porous electrodes, and can store large amount of energy due to their large surface area. Energy is stored in super capacitors when the electrodes are fed with DC source. These capacitors do not experience chemical reactions, unlike the ordinary electrolytic capacitors. Super capacitors have less charging rate with low leakage current. In power system applications, they are not only used as energy storage devices, but can also be used as voltage sags compensators (Ogunniyi and Pienaar, 2017). However, super capacitors have less energy density compared to batteries.

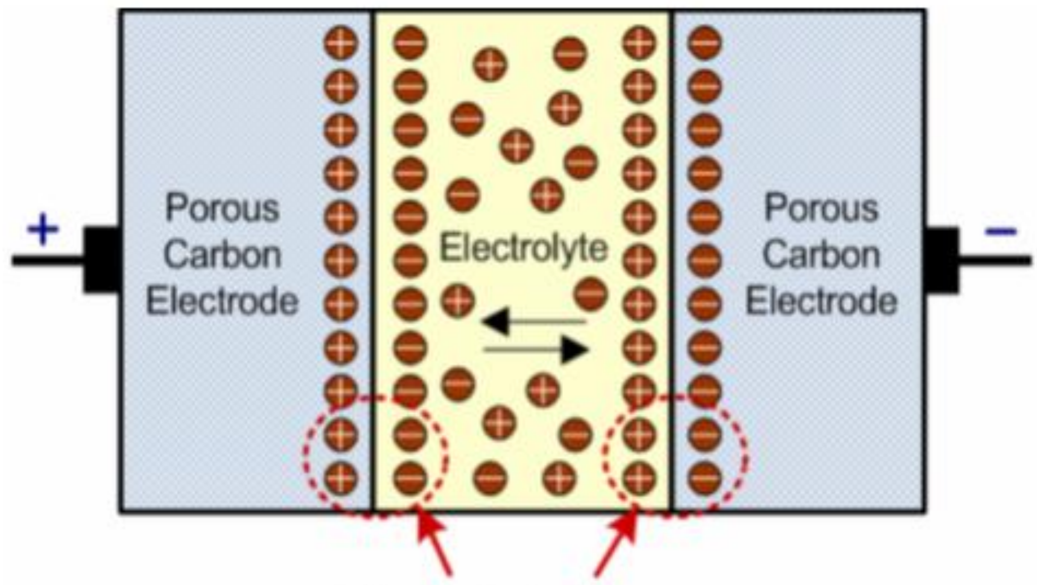

Figure 2.4: Electric double layer capacitor (Molina, 2010)

2.3.1.3 Pumped hydro energy storage system (PHESS)

Pumped hydro storage system involves conversion of electrical energy into potential energy due to gravitational flow of water at different levels (Figure 2.5). The storage components consist of two different dams situated at different height. During off-peak demand, water is pumped from the lower level reservoir to the upper level reservoir. On the other hand, when more power is needed in the utility grid, this stored water is released through the penstock to drive the turbines to generate more power. PHES system has energy conversion rate of 85%, and storage capacity of about 2500 MW. This storage technique is well known for releasing electricity within a shorter time, and can last for more than 50 years. On the contrary, water storage capacity depends on the size of the dams, which can contribute to land degradation (Gupta et al., 2011)

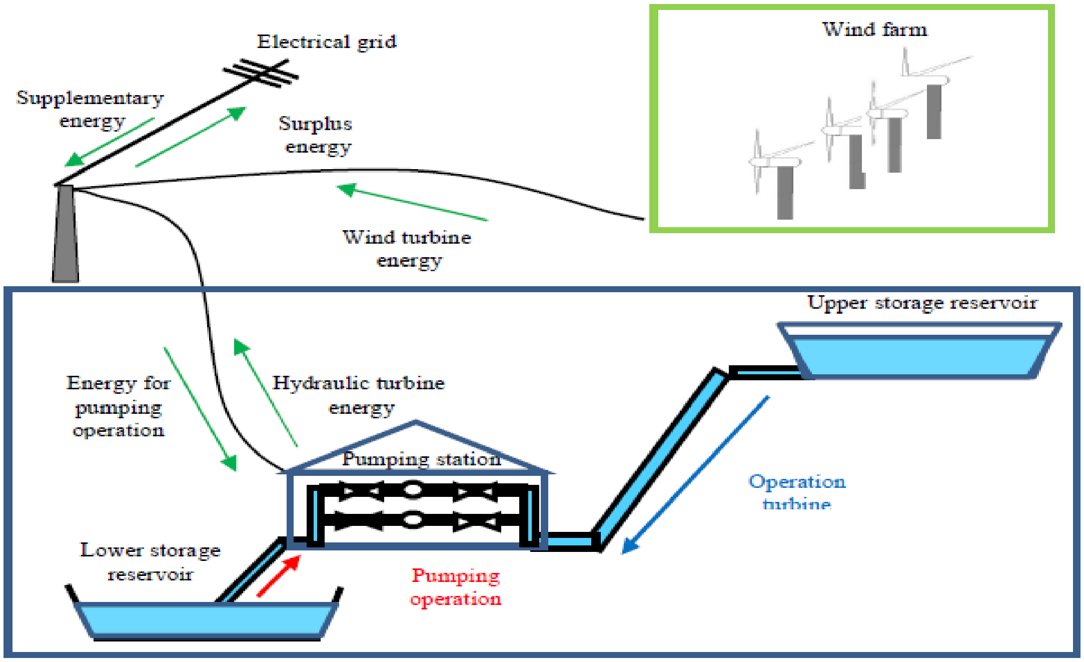

Figure 2.5: Hydro pump energy storage configuration storage (Amrouche et al., 2016)

2.3.1.4 Flywheel energy storage system (FESS)

A flywheel is an electromechanical rotating device, which stores energy in the form of kinetic energy. As seen in Figure 2.6, FES system consists of a motor coupled to the rotor of the flywheel. This motor drives the flywheel and the rotational speed is stored as kinetic energy in the rotor. The stored energy is then released as DC electric energy source by power electronic converter when there is more power demand. Basically, the amount of energy stored depends largely on the square of the angular rotation and the inertia of the rotor. Thus, the kinetic energy (KE) stored is given by;

$$\mathrm{KE} = \frac{1}{2} J \omega^2 \tag{2.1}$$

Where ω is the angular rotation and J is the inertia of the rotor. FESS applications are widely preferred for its ability to handle power quality issues such as frequency variations and voltage sags and swells. It is regarded as a short-term storage system, and can improve upon power quality issues than other storage techniques. However, FES system stores power in modest capacity, therefore, not efficient as a backup technique in large power application (Ogunniyi and Pienaar, 2017).

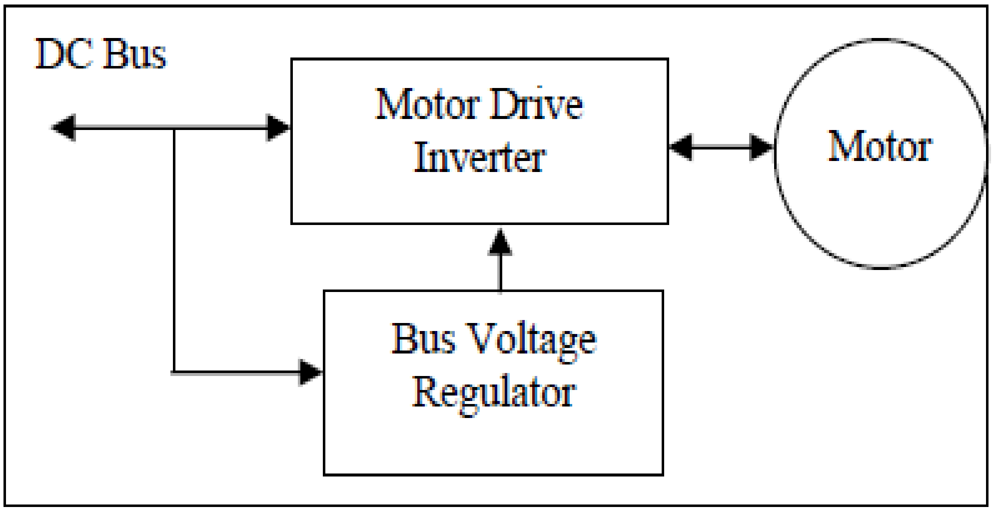

Figure 2.6: Flywheel energy storage schematic

2.3.1.5 Compressed air energy storage system (CAESS)

CAES system stores air compressed at a very high pressure in the form energy. During off-peak period, the available sources, either from the utility or renewable sources is used to run motors to compress air into a storage vessel as seen in Figure 2.7. When more power is needed, the compressed air is combusted together with gas. This hot gas is then released from the combusting chamber under high pressure to drive a gas turbine to produce electricity (Raihan, 2016). CAES system is considered as suitable for storing large amount of energy. This energy storage technique requires less installation cost. The operation is flexible, and therefore, ensures system reliability.

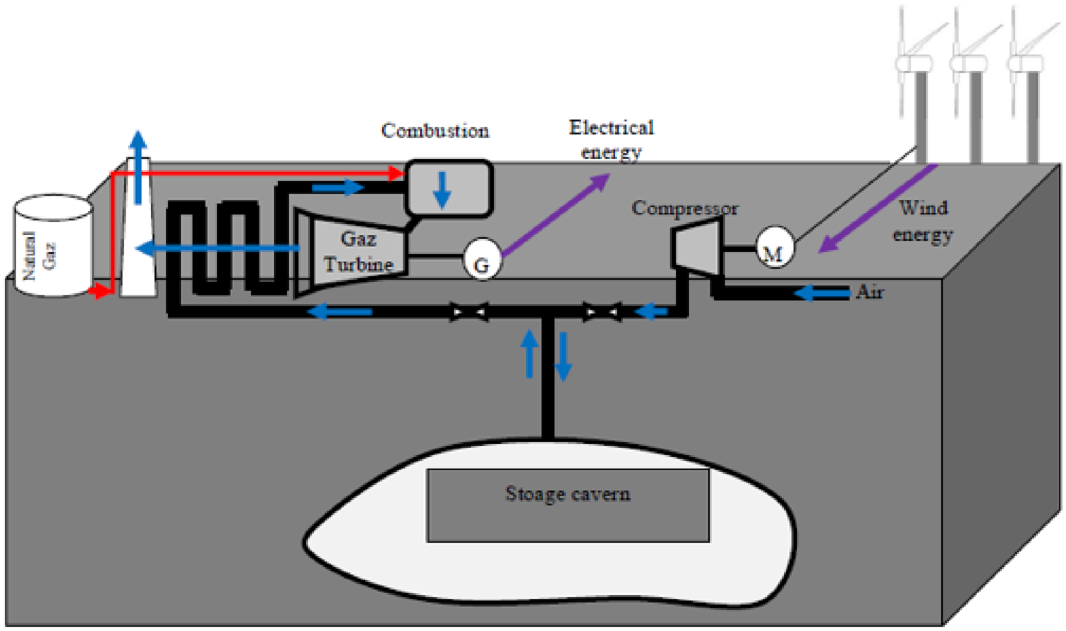

Figure 2.7: Compressed air energy storage (Amrouche et al., 2016)

2.3.1.6 Battery energy storage systems (BESS)

This storage system is otherwise known as electrochemical storage system. Electrochemical cells store electrical energy in the form of chemical energy. In power system applications, BES system involves power conversion unit, which controls the charge/discharge during peak and off-peak. This storage system offers the required flexibility as well as rapid response, and therefore, provides dynamic power response. BESS applications are proven environmental friendly with no emissions. It is cost effective, and improves the quality of delivering power. There are several types of batteries, which can be used for this application. The renowned ones includes lead acid batteries, silver batteries, alkaline secondary batteries, lithium batteries and sodium-sulfur batteries. (Amrouche et al., 2016) For instance, lead acid are widely used for their numerous advantages. They have short construction time, and provide rapid power reserve with abysmal environmental impact.

2.3.1.7 Thermal energy storage system (TESS)

As the name implies, thermal energy storage system comprises of chillers and reservoirs, and are used to store energy. They are high-density rate systems with low capital cost. Recently, TES systems come in large size with storage capacity up to 300MW. They are usually considered as main generation and load shifting supply unit. However, they are less efficient with efficiency of about 60% (Koohi-Kamali et al, 2013; Hasan et al., 2013).

The performance of different parameters of different energy storage devices have been summarized in the below Table 2.1.

Table 2.1: Analysis of Energy Storage Devices (Gupta et al., 2011)

Parameters	**SMES**	**SCES**	**PHESS**	**CAESS**	**FESS**	**BESS**	**TESS**
Typical Range	100 MW	1-250 KW	2 GW	20-350 MW	Ranging in kW	100-2 GW	300 MW
Life Time	30yrs	10-20yrs	60yrs	50yrs	10−20yrs	3-6yrs	
Electrical Efficiency	97%	95%	85%	70%	90-95%	88-92%	60%
Losses	17mW	0.004mW			610mW	0.19Mw	
Frequency Support	Yes				yes		
Power Quality	Yes	Yes		Yes	yes	Yes	
Response Time	Milli secs	Milli secs	1−2mins	1−2mins	1-2mins	Seconds	
Emissions	No	No	No	No	No	Very low	Very low

CHAPTER 3
MULTILEVEL INVERTER

3.1 Introduction

Multilevel inverter is a power electronics component, which uses several DC sources as input to produce a required sinusoidal AC output voltage. This DC voltage source is normally received from different renewable energy source as solar cell, fuel cell wind turbine etc. The principles of this structure is to generate a staircase output voltage waveform synonymous to a sinusoidal using several dc voltage source as shown in Figure 3.1.

The concept of multilevel inverters started in the year 1975. This concept was in the form of several inverters connected in series with a diode. Later, new topologies including clamping diodes and neutral point clamped inverters were introduced (Khomfoi and Tolbert, 2011). Conventionally, there was two level inverters that consist of two different level voltages; +V and –V, which when switched from pulse modulation technique, resulted in effective harmonic distortion, EMI and dv/dt stress (Rodriguez et al., 2002). For these reasons, a new multilevel inverter technique working with high number of voltage levels was developed. This multilevel output voltage produced, have provided smooth sinusoidal output waveform, reduced distortions and minimized stress in power electronics switching voltages. As a result, they have gained more popularity in the areas such as; renewable energy systems, static VAR compensation and motor drives applications etc., (Peng et al., 1996).

Multilevel inverters configuration are recognized as attractive amongst the modern day power engineering involving power converters. In recent years, their numerous considerable features have encouraged their penetration in several industrial applications based on the following advantages:

- Multilevel inverters are applicable to both high power and medium power applications.
- Their output voltage levels are generated with very low distortions.
- Common-mode voltage in multilevel inverters are somewhat negligible/reduced.
- Multilevel inverters are suitable for lower voltage rated switches

- They are capable of reducing stresses hence, reduction in EMI capabilities
- Input current in multilevel inverters are drawn with lower distortion.
- They are capable of operating on both high switching PWM and fundamental switching frequency.

However, the use of components such as, clamp diodes and flying capacitors in a large-scale applications, can sometimes effect difficulties in controlling real power flow in individual inverters. Also, the issue of bulky capacitors, the use of numerous power electronic switches (especially in cascaded H-bridges) etc., which is dent on the size of the structure, is a major issue being addressed by electrical power engineers. The few disadvantages of multilevel inverters can be summarized below:

- High number of power semiconductor device switches are required.
- In each switch, a gate driver is needed.
- Multilevel inverter structures are expensive and complex

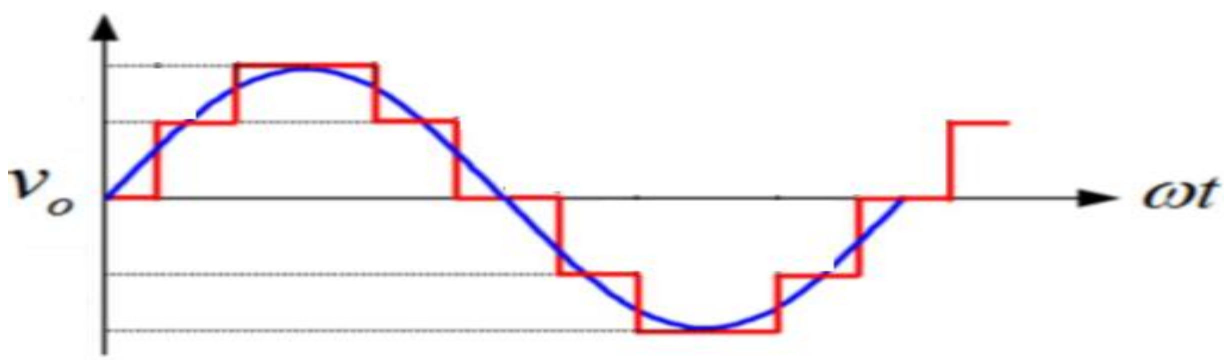

Figure 3.1: Typical staircase multilevel output

3.2 Types of Multilevel Inverters

Over the years, several multilevel inverters, which are capable of generating a staircase output waveform at lower frequency have been introduced. These inverters can be categorized as Diode Clamped Multilevel Inverter (DCMLI), Flying Capacitor Multilevel Inverter (FCMLI) and

Cascaded H-bridge Multilevel Inverter (CHB-MCI). All these inverters use one or more voltage sources.

3.2.1 Diode clamped multilevel inverter (DCMLI)

DCMLI comprises of clamping diodes and capacitors. The capacitors are connected in series and the midpoint is used as the neutral point. Each capacitor provides a voltage level to the system. In addition, m-1 different levels of voltage are used to separate the connections of the clamping diodes (Nordvall, 2011). As shown in the Figure 3.1, the DC-bus voltage is divided into five voltage levels by four series capacitors. It is clear from Table 3.1 that by controlling the input voltages, five different output voltage levels can be generated, $\frac{\pm V_{dc}}{2}$, $\frac{\pm V_{dc}}{4}$ and 0.

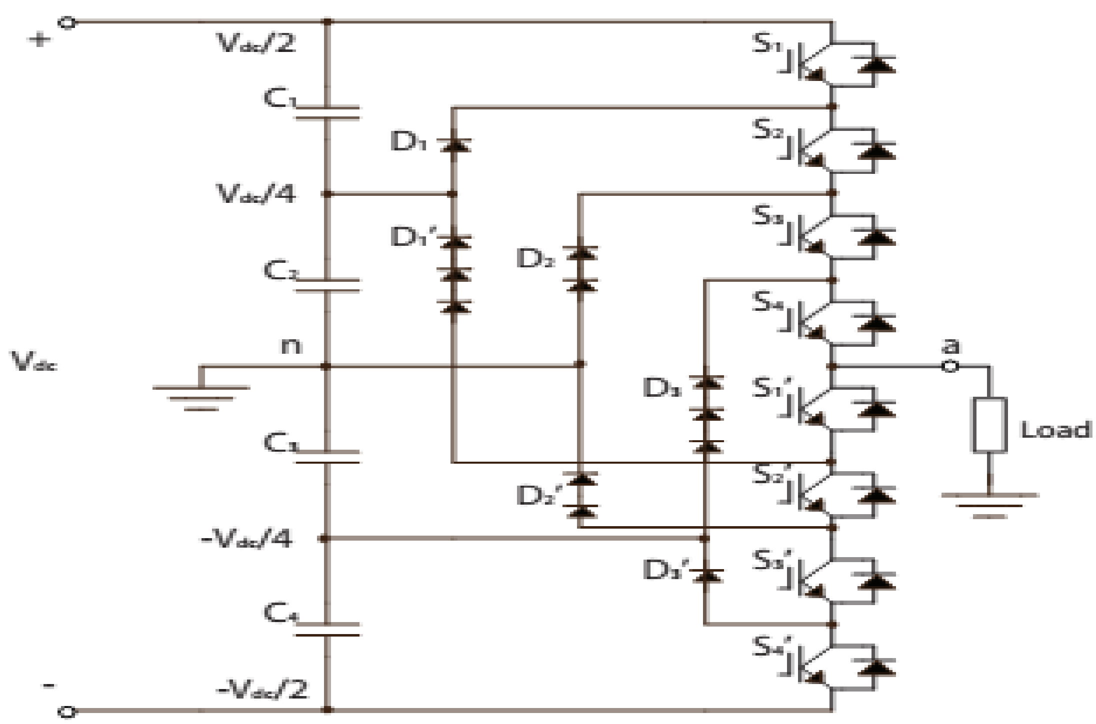

Figure 3.2: Five-level Diode-clamped multilevel inverter circuit

For a different output voltages, upper and lower switches must be turned ON and OFF complementarily as shown in the table 3 below. Each switching devices is expected to block a certain $\frac{V_{dc}}{(m-1)}$ voltage level: because of the different voltage levels at each capacitor terminal to limit the voltage stress on each device. Four complementary switch pairs (S_1 $S_1^{'}$, S_2 $S_2^{'}$, S_3 $S_3^{'}$ and S_4 $S_4^{'}$) create corresponding switching states. Each one is switched ON once per cycle. To generate a staircase output voltage, the neutral point is taken as the output phase voltage reference. For example, to generate $+V_{dc}/2$, turn ON two upper switches S_1 through S_4 as explained in the Table 3 below.

Table 3.1: Switch states for a five-level diode clamped multilevel inverter

Switching State	S_1	S_2	S_3	S_4	$S_1^{'}$	$S_2^{'}$	$S_3^{'}$	$S_4^{'}$	Output Voltage
1	1	1	1	1	0	0	0	0	$+V_{dc}/2$
2	0	1	1	1	1	0	0	0	$+V_{dc}/4$
3	0	0	1	1	1	1	0	0	0
4	0	0	0	1	1	1	1	0	$-V_{dc}/2$
5	0	0	0	0	1	1	1	1	$-V_{dc}/4$

3.2.1.1 Advantages

1. High number of output voltage levels results to reduction of total harmonic content hence no need of filtering components.

2. Fundamental switching frequency technique is suitable for this structure, and therefore, has high working efficiency

3. Power system parameters such as reactive power flow is easily controlled by this type of multilevel.

4. Back-to-back applications are easy to be controlled in this topology.

3.2.1.2 Disadvantages

1. For a higher output levels, higher number of clamping diodes are required.

2. Real power flow control is somewhat difficult to achieve.

3.2.2 Flying capacitor multilevel inverter (FCMLI)

Unlike DCMLI, FCMLI thrives on clamping capacitors instead of clamping diodes to hold the voltages at a required value. During each switching state, one or more of this clamping capacitors voltage is synched with the DC-bus voltage. The DC bus voltage is divided into five levels by using four series capacitors as shown in Figure 3.3 (Nordvall, 2011). The middle point of the four divisions is defined as the neutral point. Also, capacitors permit the flow of reverse voltages, so several switching are needed to generate the same output voltage levels as in DCMLI. This will create inner voltage redundancy.

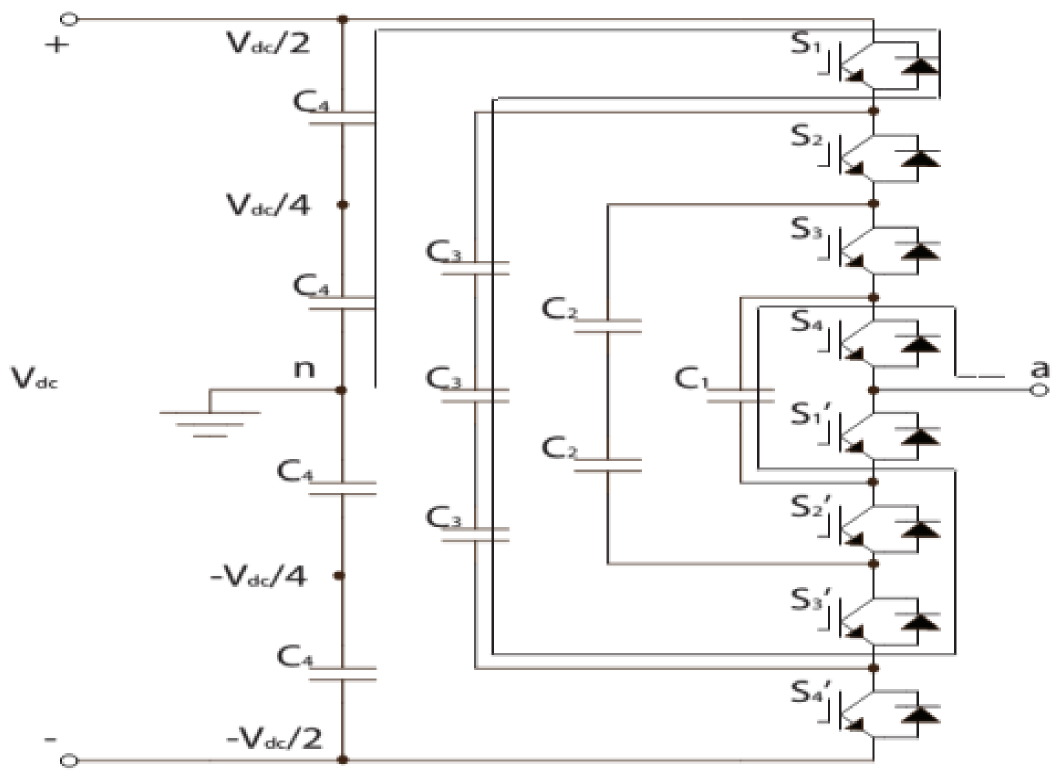

Figure 3.3: Capacitor clamped five level multilevel inverter circuit

To produce same output voltage levels, different capacitors involving charging or discharging of individual capacitors are combined. This makes synthesized voltage level of FCMLI more flexible and efficient. Also, this property with proper selection of switching combinations makes FCMLI more applicable to real power conversions. By controlling the phase leg voltage (by alternating the switching states in table 3.2 below) in combination with neutral point, the following five output voltage levels can be generated; $\frac{\pm V_{dc}}{2}$, $\frac{\pm V_{dc}}{4}$ and 0.The switches are complementarily turned ON and OFF at least once during each cycle of a particular output voltage level. For $+V_{dc}/4$ upper switches S_1 through S_3 and one lower switch S_4' are simultaneously turned ON as explained in table 3.2. These switching states further charge the capacitors during negative sign (-v) mode and discharge the capacitors during positive sign (+v) mode.

Table 3.2: Switch states for five level capacitor clamped multilevel inverter

Switching State	**S_1**	**S_2**	**S_3**	**S_4**	**S_1'**	**S_2'**	**S_3'**	**S_4'**	**Output**
1	1	1	1	1	0	0	0	0	$+V_{dc}/4$
2	1	1	1	0	0	0	0	1	$+V_{dc}/2$
3	1	1	0	0	0	0	1	1	0
4	1	0	0	0	0	1	1	1	$-V_{dc}/2$
5	0	0	0	0	1	1	1	1	$-V_{dc}/4$

3.2.2.1 Advantages

1. There is a possible to achieve extra ride through capabilities to safeguard power outages due to large number of storage capacitors.

2. Control method to achieve balanced different voltage levels result to switching combination redundancy.

3. High value of output levels lead to less total harmonic content hence, no need of filtering components.

4. Both reactive and real power flow are easily controlled.

3.2.2.2 Disadvantage

1. This inverter type can be expensive due to high number of storage capacitors that are needed when a higher outputs are required.
2. Very complex in inverter control.
3. It has high switching frequency and high switching losses in power applications.

3.2.3 Cascaded h-bridges multilevel inverter (CHB-MLI)

CHB-MLI is a simplified type of inverter other than FCMLI and DCMLI. It consists of two or more H-bridge inverters put together as one circuit. This inverter has neither clamping diodes nor clamping capacitors. The output voltages levels is generated by separate input DC sources, mostly from renewables such as photovoltaic, wind energy, biomass, etc. These input sources can be symmetric (CHB inverters with equal input sources) or asymmetric (CHB inverters with unequal input sources) depending on the application.

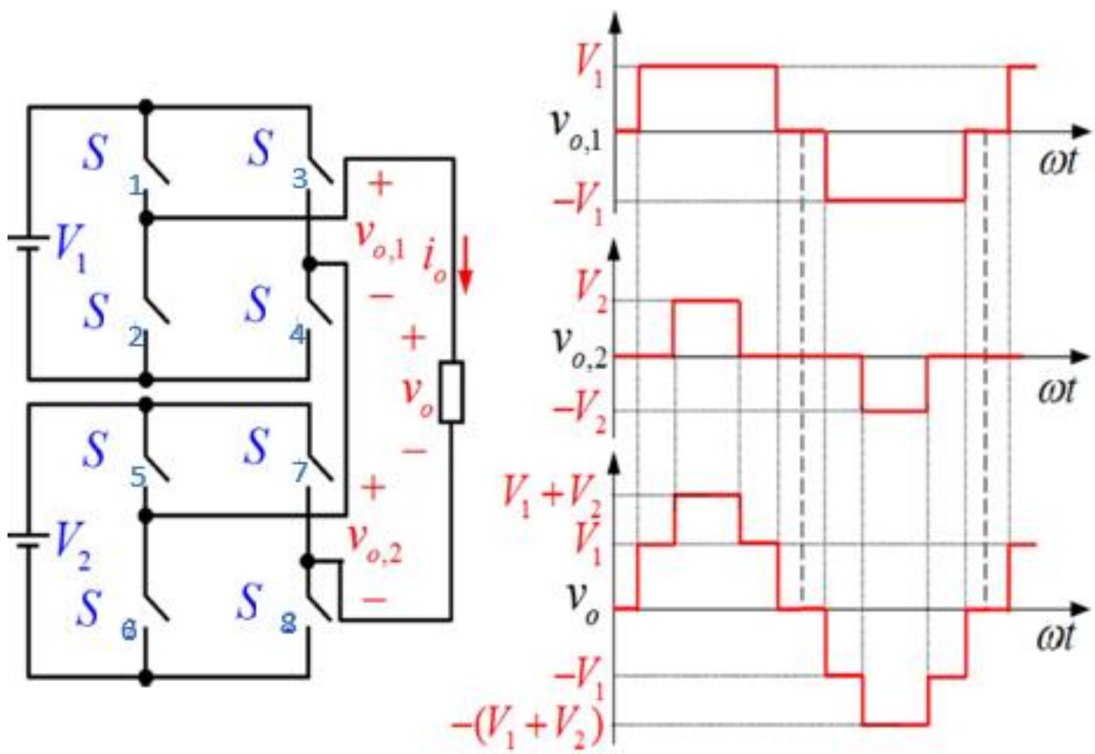

Figure 3.4: Five level cascaded h-bridge multilevel inverter

Unlike FCMLI and DCMLI, which are capable of exhibiting only half of the total DC-bus voltage, CHB-MLI can exhibit the total cascaded voltage in both positive and negative direction of magnitude. However, because of the cascaded concept, this type of inverter has one unique disadvantage over the other two types: as high number of power, electronic switches are required. As shown in Figure 3.4 is a five level symmetric source CHB-MLI. Each H-bridge inverter can generate the different outputs, V_o, $-V_o$ and 0. In total, the output voltages from the two H-bridges inverters when synthesized, yields five level outputs, $\pm 2V_o$, $\pm V_o$, and 0.

The switching combinations to generate an output at each switching state down to the total five level output are fully explained in the Table 3.3. To obtain $+V_o$, S_1 and S_4 switches or S_5 and S_8 switches are turned on, whereas $-V_o$ can be generated when S_2 and S_3 or S_6 and S_7 switches are turned on. In addition, zero output voltage can be obtained by turning on S_1-S_3 or S_5-S_7 (Muhammad, 2004). As mention early on, the DC sources this type of inverter are classified into two namely; Symmetric and Asymmetric configurations. Symmetric DC source is when the separate H-bridge inverters are fed with equal values of sources whilst asymmetric is when the separate inverters are fed with different (Binary and Trinary) values of DC sources. The details to implement these methods are clearly explained in the Table 3.4.

Table.3.3: Switching states for five level cascaded H-bridge multilevel inverter

Switching State	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**	**S_6**	**S_7**	**S_8**	**Output Voltage**
1	1	0	0	1	1	0	0	1	$+2V_o$
2	1	0	0	1	1	0	1	0	$+V_o$
3	1	0	1	0	1	0	1	0	0
4	0	1	1	0	0	1	1	0	$-V_o$
5	0	1	1	0	0	1	1	0	$-2V_o$

3.2.3.1 Advantages:

1. Regardless of output voltage needed, least components are needed as compare to other multilevel inverters.
2. This inverter type is easy to implement as well as less bulky: as clamping diodes and voltage balancing capacitors are not needed
3. To avoid switching losses and other stresses on the device, Soft-switching method is required in this structure.

3.2.3.2 Disadvantage:

1. Separate dc voltage sources are required for each inverter. This leads to limit its applications in power conversions.

Table 3.4: Illustration of symmetric and asymmetric voltage source configuration (Babaei et al., 2007)

Parameters	Symmetric	Asymmetric	
		Binary	**Trinary**
N_{step}	$2n + 1$	$2^{n+1} - 1$	3^n
V_n	V_{dc}	$2^{n-1} V_{dc}$	$3^{n-1} V_{dc}$
$V_{o,max}$	nV_{dc}	$(2^n - 1)V_{dc}$	$\left(\frac{3^n - 1}{2}\right) V_{dc}$
V_{stand}	$4nV_{dc}$	$4(2^n - 1)V_{dc}$	$2(3^n - 1)V_{dc}$

Where:

N_{step} Number of output levels

V_n DC voltage sources applied to each H-bridge inverter

$V_{o,max}$ Maximum voltage generated by the complete cascaded inverter

V_{stand} Total maximum voltage the power electronic switches can withstand

3.3 Multilevel Inverter Switching Technique

Pulse Width Modulation (PWM) technique, which is applicable to ordinary inverters can be applied in multilevel inverters when modified. This modified PWM technique is grouped into two: fundamental switching and high switching frequency as illustrated in Figure 3.5. The high switching frequency technique is further modulated with some PWM in achieving a staircase output voltage levels. Consequently, in both switching techniques, a staircase output levels are achieved (Khomfoi and Tolbert, 2011).

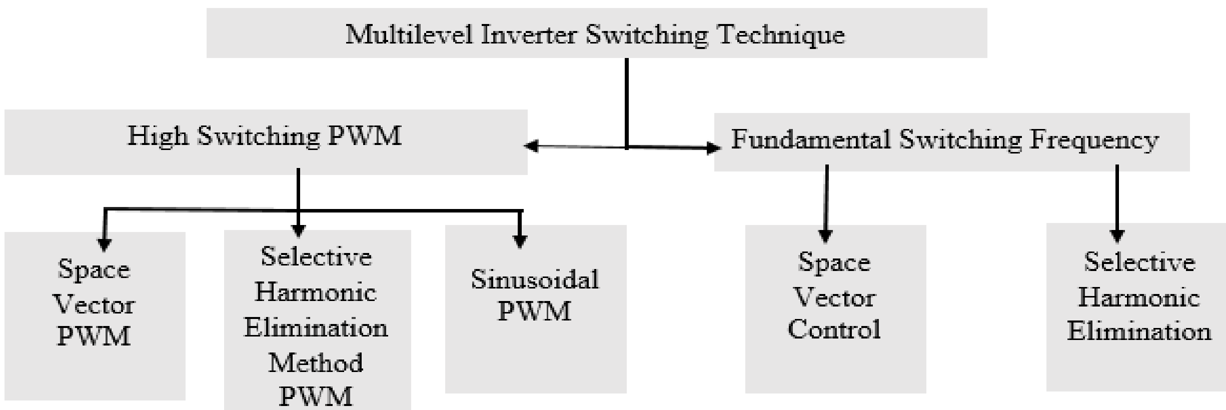

Figure 3.5: Multilevel inverter switching technique

Table 3.5 Comparison of component requirements for a single-phase multilevel inverter types

Inverter type	Diode clamp	Flying capacitor	Cascaded H-bridge
DC bus capacitors	$k-1$	$k-1$	$\frac{k-1}{2}$
Main diodes	$2(k-1)$	$2(k-1)$	$2(k-1)$
Clamping diodes	$(k-1)2(k-2)$	0	0
Clamping capacitors	0	$\frac{(k-1)(k-2)}{2}$	0
Transformers	0	0	0
Main switches	$2(k-1)$	$2(k-1)$	$2(k-1)$

Where k shows the number of voltage level

CHAPTER 4

DESIGN AND SIMULATION RESULTS

4.1 Methodology

This project presents the study of multilevel inverters for the integration of different kinds of renewable energy sources and storage techniques into utility grid. The introductory sections provide the concepts and the fundamental requirements of the proposed topic. The following sections explain renewable energy principles, energy storage systems in addition to the benefits and setbacks of grid integration. The proposed topology consists DC/AC cascaded H-bridge multilevel inverter fed with trinary asymmetric DC sources, boost converter and DC/DC buck boost converter for energy storage units. In this project, the boost converter will control and stabilize the DC sources representing energy from renewable sources. The cascaded H-bridge multilevel inverter and the DC/DC bidirectional shall manage the power between the renewables, the energy storage units, and the utility grid. When there is more available energy from the renewable sources, buck-boost converters will charge the energy storage units for future use. On the other hand, the stored energy in the storage units must be supplied to the utility grid through the buck-boost converters and the multilevel inverter. This means the DC/DC buck boost converter must be able to conduct in both directions in order to charge and discharge the energy storage units. The final simulation is developed using PSCAD/EMDTC model to demonstrate the feasibility results of the proposed subject. This software (PSCAD/EMTDC) is a simulation device for Power System Computer Aided Design and Electromagnetic transients with DC.

4.2 Proposed Topology

The proposed topology for the study of this concept consists of six converters. It composed of two boost converters for the input sources, two buck-boost converters for the charge/discharge of energy storage units and two H-bridge inverters connected in cascade for the DC/AC power conversion into the network. Figure 4.1 illustrates the schematic of the proposed topology that contains all the mythological components used in the following sections.

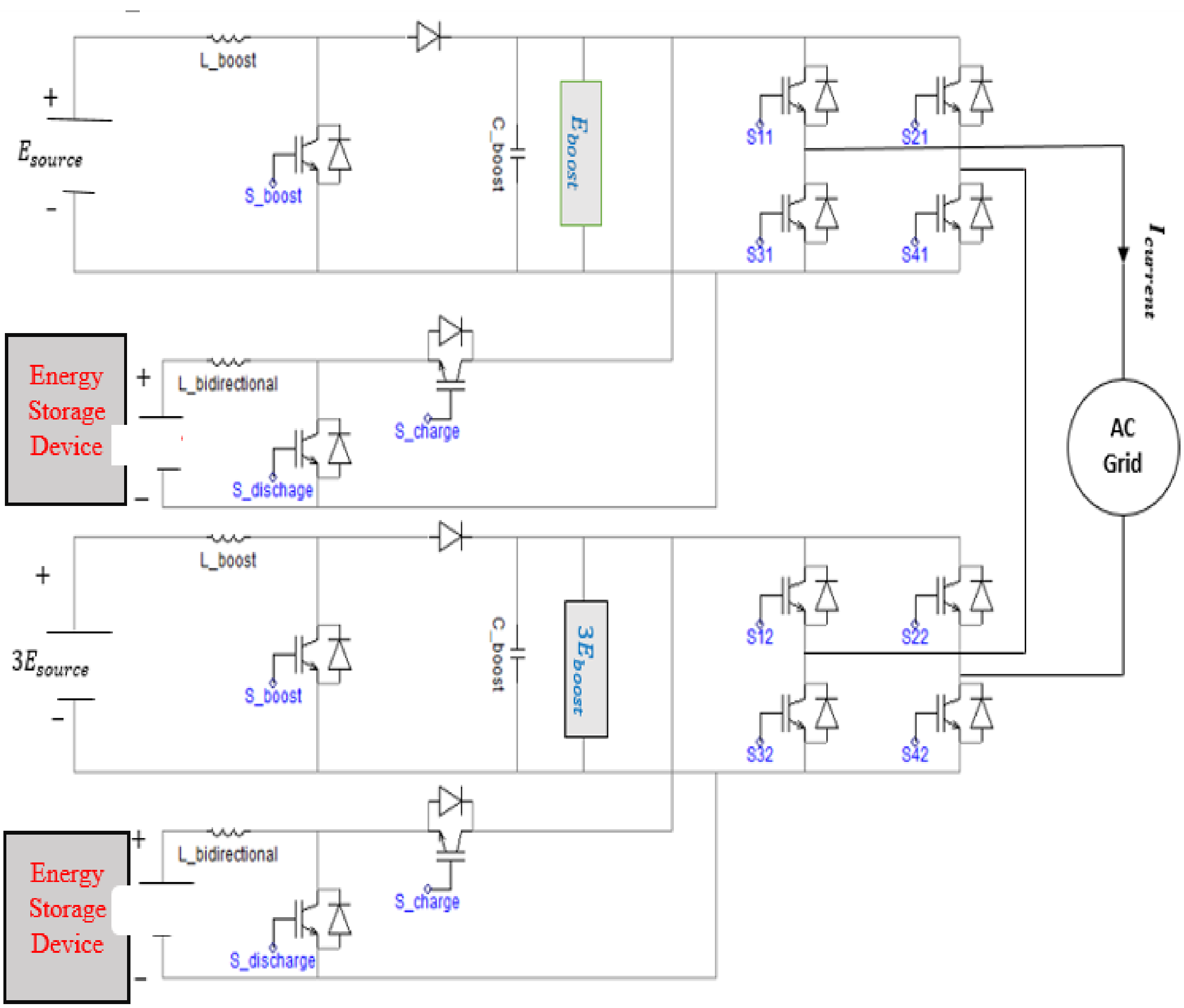

Figure 4.1: Schematic of proposed topology

4.2.1 Proposed boost converter

In this topology, a DC source output is connected to a DC-DC boost converter at the initial stage. This converter stepped up the DC input, and further supplied the boosted output to the main H-bridge inverter and the energy storage bidirectional converter respectively.

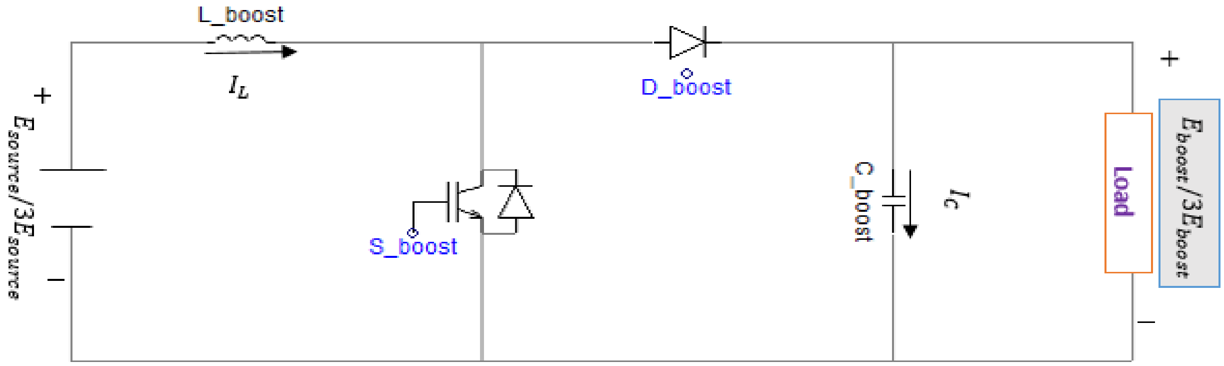

Figure 4.2: proposed boost converter

The converter consists of the following parameters: input voltage (E_{source}), output voltage (E_{boost}), input power (P_{in}), inductor (L_{boost}), capacitor (C_{boost}), switching frequency (f_{sw}), switching period (T_{sw}) and duty cycle (D). The values of these parameters were calculated on the below assumptions/analogies:

The input current of the boost converter is given by:

$$I_{input} = \frac{P_{input}}{E_{source}} \tag{4.1}$$

Boost converter ripple current is given by:

$$I_{ripple} = \frac{DE_{source}}{L_{boost}f_{sw}} \tag{4.2}$$

Where D is the duty cycle in continuous conduction mode and is given by:

$$D = 1 - \frac{E_{source}}{E_{boost}} \tag{4.3}$$

This ripple current can also be given by

$$I_{ripple} = \frac{I_{max} - I_{min}}{2} \tag{4.4}$$

where $I_{max} = I_{input} + \frac{0.2I_{input}}{2}$ and $I_{min} = I_{input} - \frac{0.2I_{input}}{2}$

This implies that;

$$L_{boost} = \frac{E_{boost}}{4 f_{sw} I_{max(ripple)}} \tag{4.5}$$

This means the inductor should be capable to handle maximum switching current without saturation.

Again, the boost converter capacitor (C_{boost}) was calculated using 1.2% of the boost converter output voltage (E_{boost}).

$$C_{boost} = \frac{D I_{out} T_{sw}}{V_{pp}} \tag{4.6}$$

where V_{pp} is the peak-peak voltage ripple of boost converter output and T_{sw} is the switching period, which is denoted as (Rafiq and Hasan, 2011).

$$T_{sw} = \frac{1}{f_{sw}} \tag{4.7}$$

4.2.2 DC-DC energy storage bidirectional converter

The incorporation of storage units in the proposed topology needs a DC-DC bidirectional converter. This buck-boost converter regulates the power/energy flow between the storage units and the main cascaded H-bridge multilevel inverter. This converter has three operational stages: charging stage, discharging stage and standby stage. In charging stage, component S_{charge} and

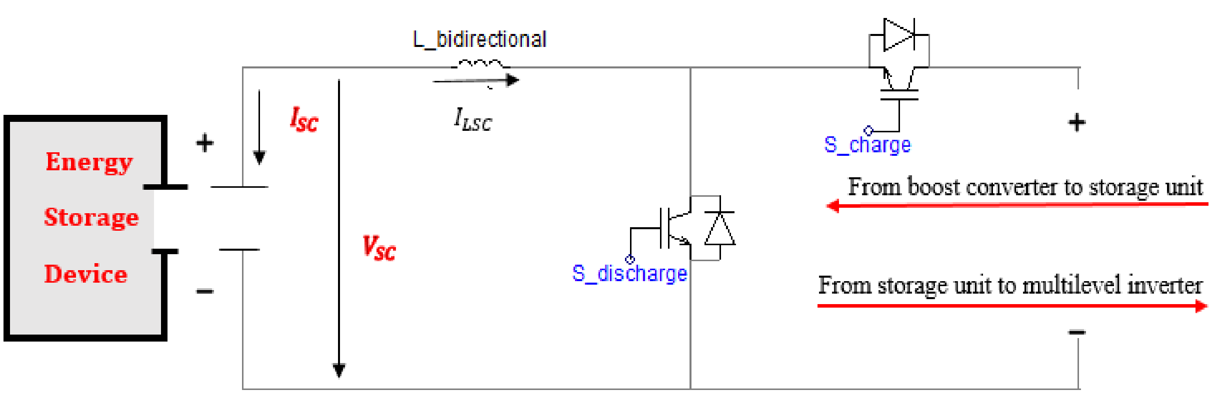

Figure 4.3: Bidirectional energy storage converter

$L_{bidirectional}$ conduct and the device works as a buck converter. During discharging stage, $S_{discharge}$ and $L_{bidirecttional}$ conduct, and the device works as boost converter. In either case, current flows through $L_{bidirectional}$ all the time to keep the converter in a continuous current mode operation.

4.2.3 Cascaded H-bridge inverter

In this project, a cascaded H-bridge multilevel inverter is proposed. The proposed inverter composed of two separate H-bridge inverters connected in series to achieve a nine level output. The inverters are supplied with asymmetric trinary input sources which first boosted by the boost converter. The figure 4.5 below shows the configuration of the proposed inverter. The inputs of the inverters are provided with E_{boost} and $3E_{boost}$. The switching states associated with the proposed inverter are explained in Table 4.1. By controlling the switches, a nine-staircase output level is produced.

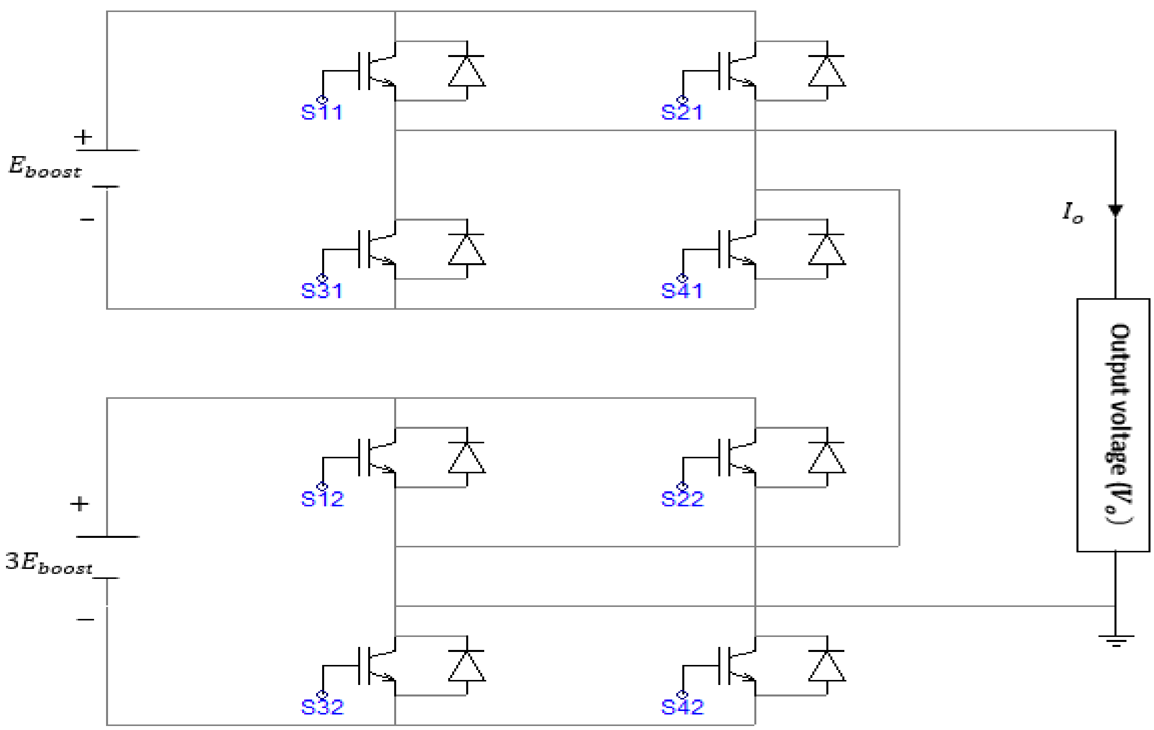

Figure 4.4: Cascaded H-bridge multilevel inverter

Table 4.1: Switches states of the proposed nine level cascaded h-bridge inverter

Switches states	$S_{1,1}$	$S_{2,1}$	$S_{3,1}$	$S_{4,1}$	$S_{1,2}$	$S_{2,2}$	$S_{3,2}$	$S_{4,2}$	Output (Vo)
1	1	0	0	1	1	0	0	1	$+4E_{boost}$
2	1	1	0	0	1	0	0	1	$+3E_{boost}$
3	0	1	1	0	1	0	0	1	$+2E_{boost}$
4	1	0	0	1	1	1	0	0	$+E_{boost}$
	1	1	0	0	1	1	0	0	
	1	1	0	0	0	0	1	1	
5	0	0	1	1	1	1	0	0	0
	0	0	1	1	0	0	1	1	
6	0	1	1	0	1	1	0	0	$-E_{boost}$
7	1	0	0	1	0	1	1	0	$-2E_{boost}$
8	1	1	0	0	0	1	1	0	$-3E_{boost}$
9	0	1	1	0	0	1	1	0	$-4E_{boost}$

For example, to generate an output voltage of $\pm 3E_{boost}$, switches $S_{1,1}$, $S_{2,1}$, $S_{1,2}$ and $S_{4,2}$ are turned ON whiles the rest of the switches are kept off. Similarly, to obtain $-2E_{boost}$, switches $S_{1,1}$, $S_{4,1}$, $S_{2,2}$ and $S_{3,2}$ are switched on whiles the rest of the switches are kept off. This process is repeated to generate all the required outputs. The PSCAD implementation of this switching technique is depicted in Figure 4.9. In total, the output voltages from the two H-bridge bridges inverters when cascaded, yields nine level outputs: $\pm 4E_{boost}$, $\pm 3E_{boost}$, $\pm 2E_{boost}$, $\pm E_{boost}$ and 0.

4.3 Proposed Control Method

The proposed topology is divided into three sections, namely; boost side, energy storage side and the main inverter side as shown in figure 4.5 below.

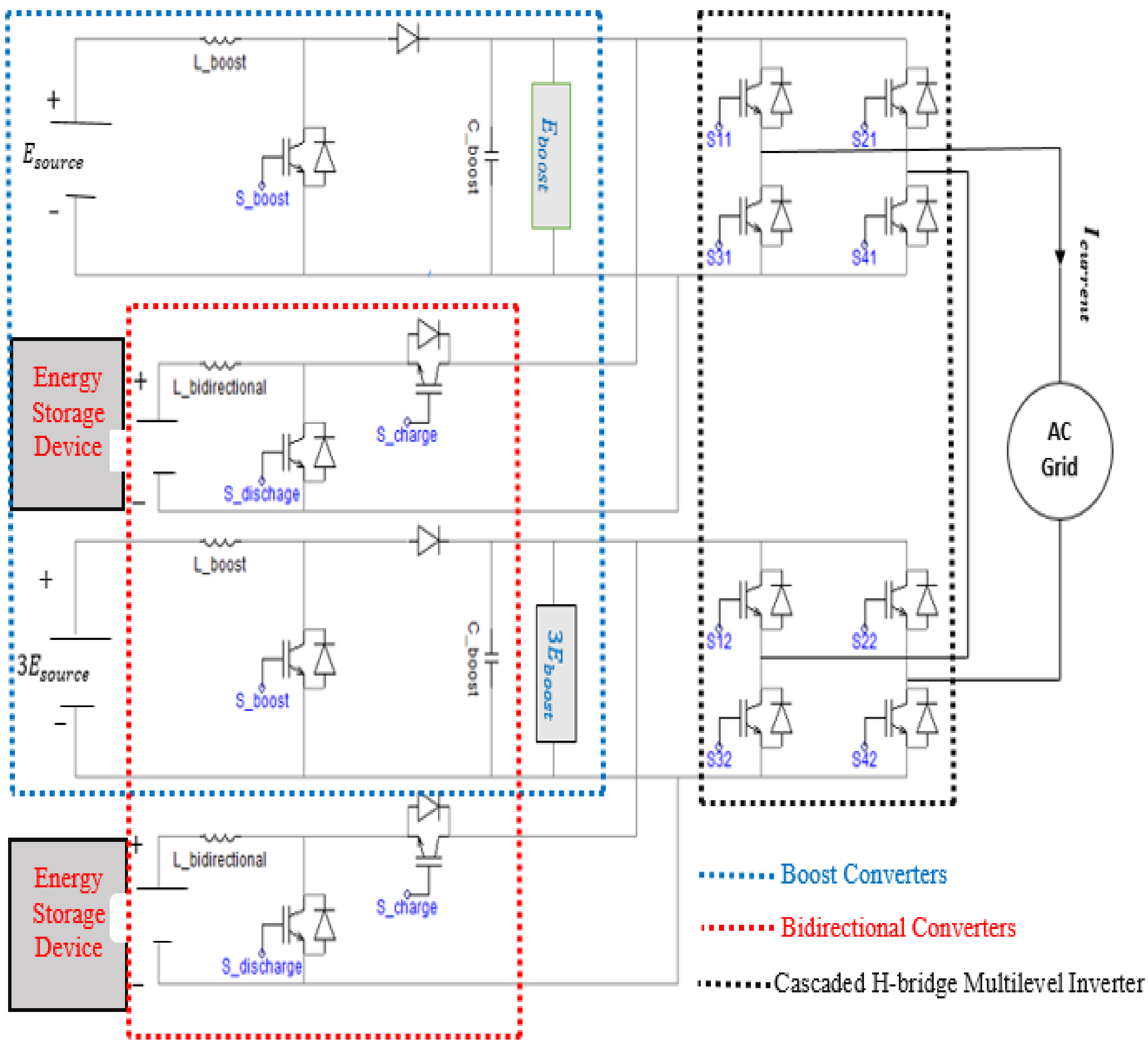

Figure 4.5: Schematic of control circuitry

4.3.1 Boost converter side control

In Figure 4.6, a closed loop control is employed to obtain a constant output. This is ensured by the duty cycle and the switching frequency of the converter. The output voltage is compared with a reference voltage and the difference is used to regulate the duty cycle. The proposed boost converter is controlled based on the below equation:

$$E_{boost} = \frac{E_{source}}{1-D} \tag{4.8}$$

This means that, the output is strictly dependent of switching frequency and the duty cycle (D). In this project, the switching frequency is set at 3 kHz and the duty cycle of 0.5 (50%), and the output voltage was doubled. The output results was very fast and the stability was somewhat good. One-quarter wave decay (decay ratio) method is used to achieve the exact $\frac{1}{4}$ decay ratio of the output response. As shown in Table 4.2, the constants values were recorded as control parameters (proportional gain and integral time constant). From Figure 4.7, the one-quarter decay ratio was achieved by:

$$\text{One-quarter } \left(\frac{1}{4}\right) \text{ wave decay} = \frac{\mathbf{B}}{\mathbf{A}} \tag{4.9}$$

$$= \frac{115-95}{80}$$

$$= \frac{1}{4}$$

Table 4.2: Proposed boost converter control parameters

Parameters	Values
Proportional gain (k_p)	1.0
Integral time constant (T_i)	0.01 s
Switching frequency (f_{sw})	3 kHz

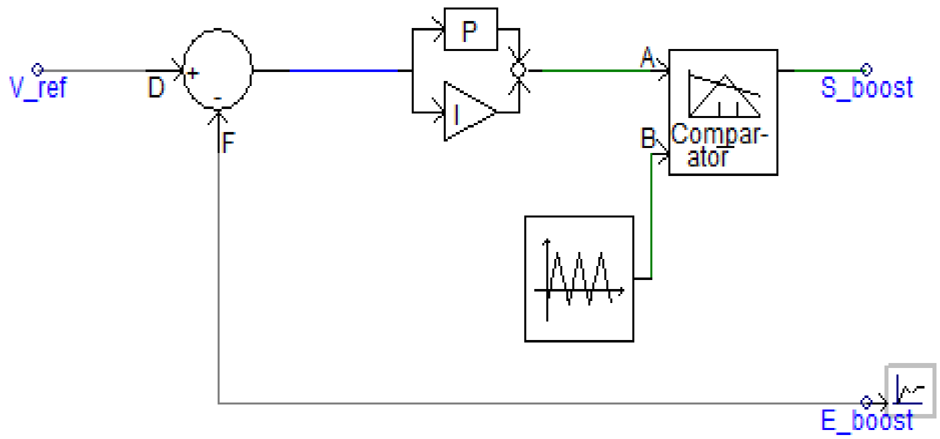

Figure 4.6: Proposed boost controller with input source

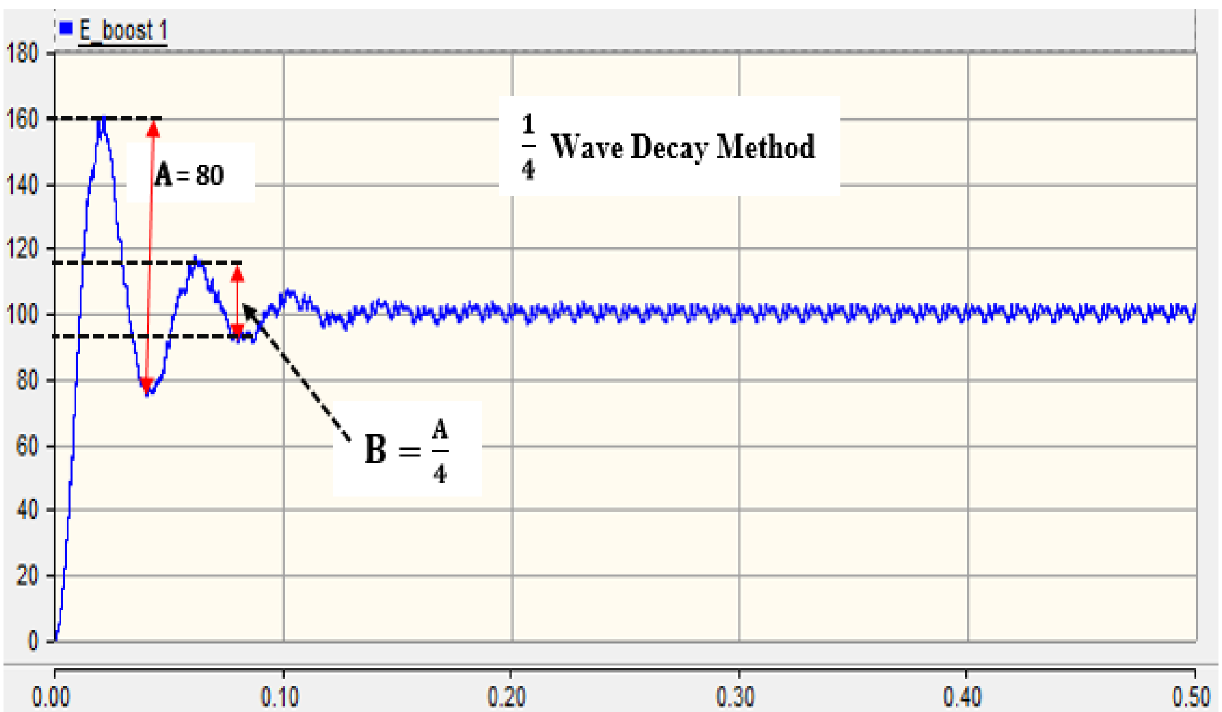

Figure 4.7: Graphical representation of one-quarter decay ratio in boost converter output response

4.3.2 Energy storage bidirectional converter control

This consists of DC-DC bidirectional converter for energy storage system. The system is designed to store energy during off-peak demand and deliver energy during demand. In charge mode, switch S_{charge} is set to charge: in this case, the converter act as buck converter. Thus, the upper IGBT is turned on and the lower IGBT is kept off. On the other hand, during discharge mode $S_{discharge}$ is set to discharge: in this manner, the converter act as boost converter. Thus, the lower IGBT is turned on and the upper IGBT is kept off. The energy released from the storage system is regulated by the Duty cycle of the boost converter. The nature of output DC voltage required for charging the storage unit is shown in Figure 4.1. The voltage is regulated due the voltage of the storage unit pack by the duty cycle and the switching frequency of the buck converter.

4.3.3 Cascaded h-bridge inverter control technique

This is responsible for providing signals for the main eight switches of the cascaded H-bridge inverter. Fundamental switching frequency control method is used to generate a nine-output level. This technique has low harmonic content and low switching losses. Figure 4.8 below represents the building block of fundamental control.

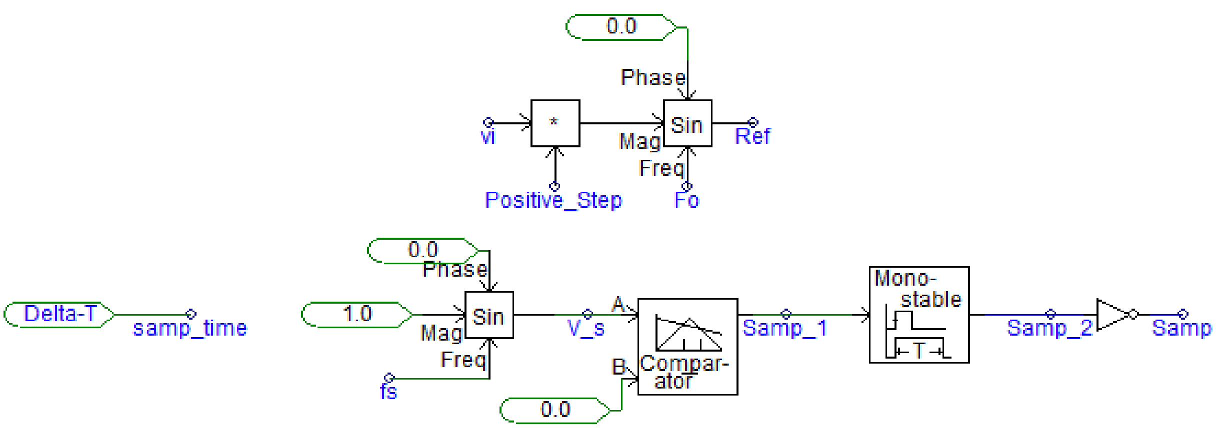

Figure 4.8: PSCAD implementation of fundamental control building technique

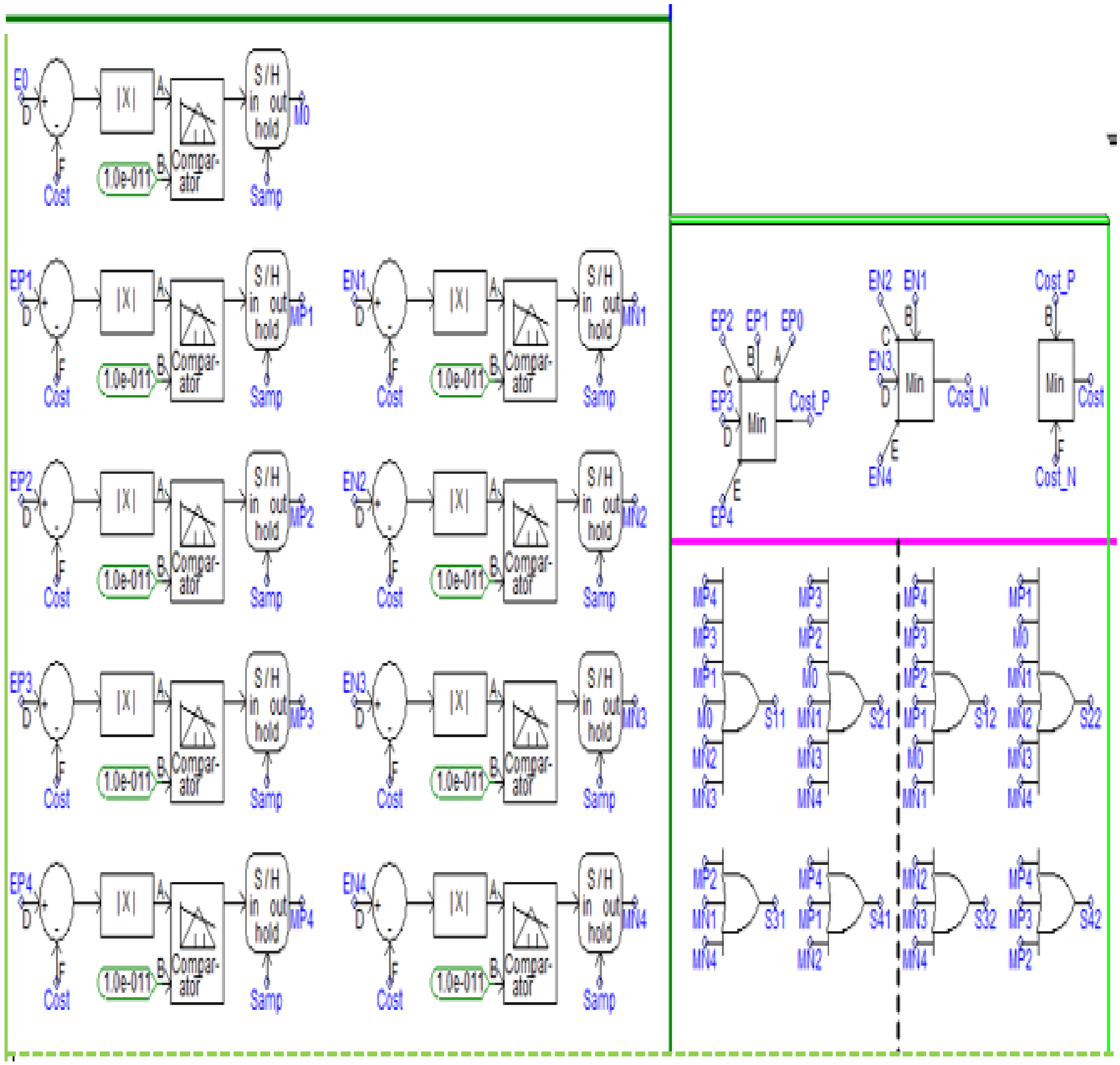

Figure 4.9: PSCAD implementation of switching technique for nine level output

4.4 Simulation Results and Discussion

The simulation results are shown for the proposed topic. Simulations were analyzed for three different scenarios; 1) stand-alone operation, thus when the system operates without incorporation of energy storage units (when the bidirectional converters are isolated). 2) When the energy storage units are set to charge mode (when the bidirectional converters are ON to supply charging voltage to the storage units). 3) When the storage units are set to discharge mode. Thus, when the storage systems are switched to ON state to discharge the stored energy into the power network between the DC-DC bidirectional converter and the cascaded H-bridge inverter. The simulations were carried out in the PSCAD/ETMDC software with the parameters in Table 4.3 below

Table 4.3: PSCAD topology design parameters

Parameters	**Value**
Input power (P)	2.5kW
DC source voltage (E_{source})	40V, 120V
Boost converter inductor (L_{boost})	$20mH$
Boost converter capacitor (C_{boost})	$500uF$
Bidirectional inductor ($L_{bidirectional}$)	$100mH$
RL load	70ohms, 600 $600mH$
Switching frequency	2kHz
Fundamental frequency	50Hz

The simulation results are shown between figure 4.9 and 4.16. The results include instantaneous output ac voltage, RMS value of the output ac voltage, instantaneous output ac current, DC voltage for storage units, Fourier frequency spectrum and total harmonic distortion (THD). The first six THD of output voltage and current values including the fundamental were calculated and the results are presented in Table 4.3. The power factor was calculated after finding the real power and the reactive power of the system.

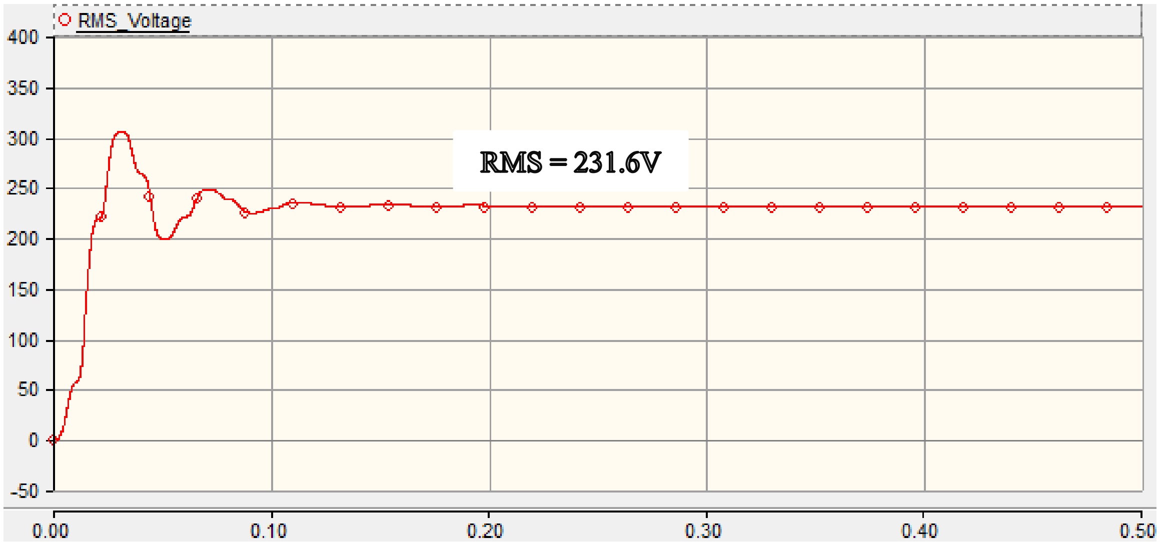

Figure 4.10: Output rms voltage

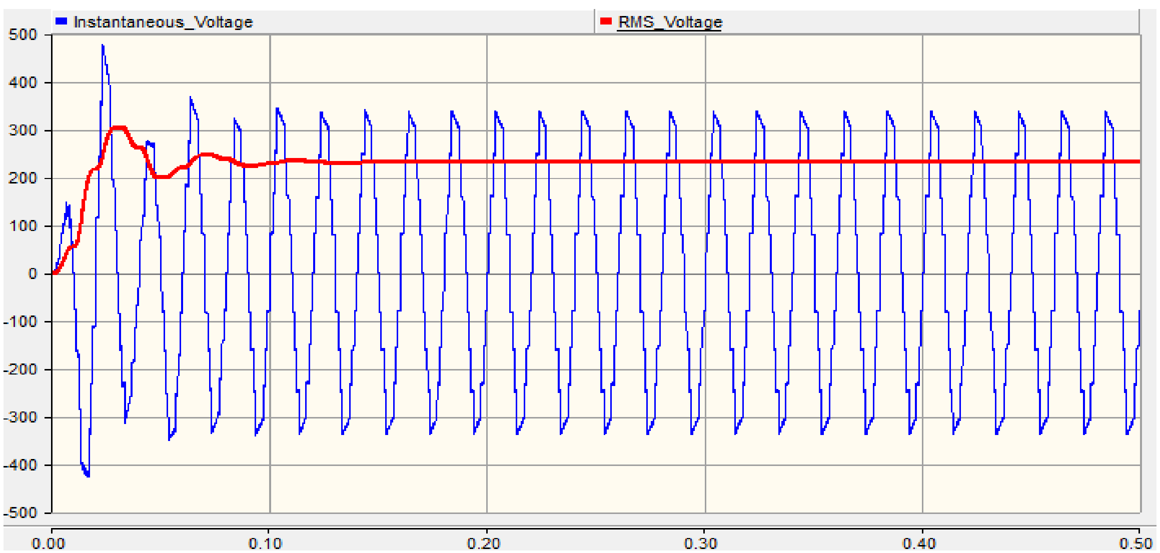

Figure 4.11: Output instantaneous voltage and rms value

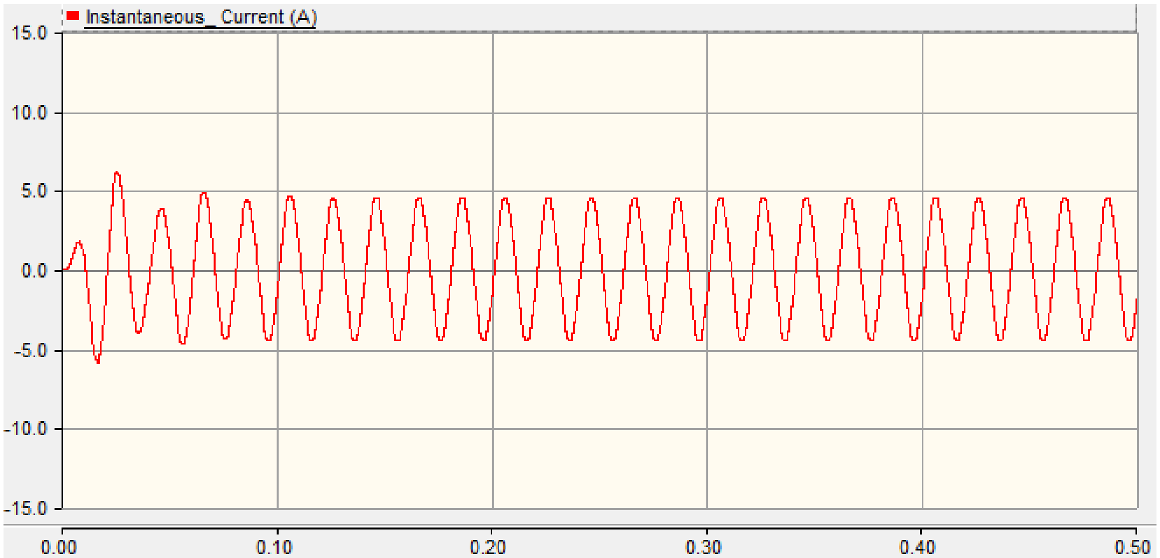

Figure 4.12: Output instantaneous ac current

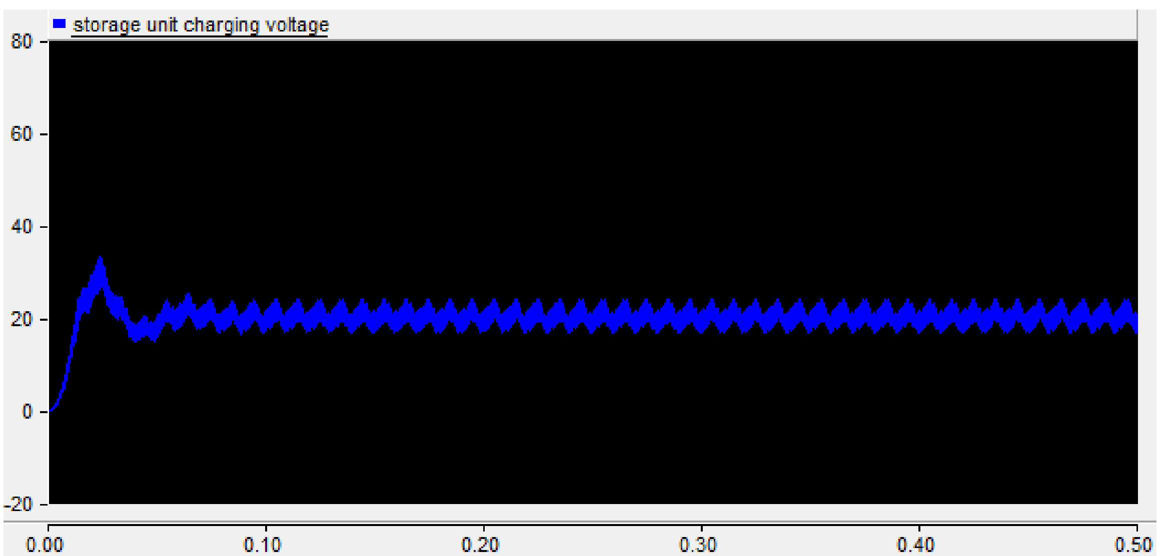

Figure 4.13: DC voltage for storage unit

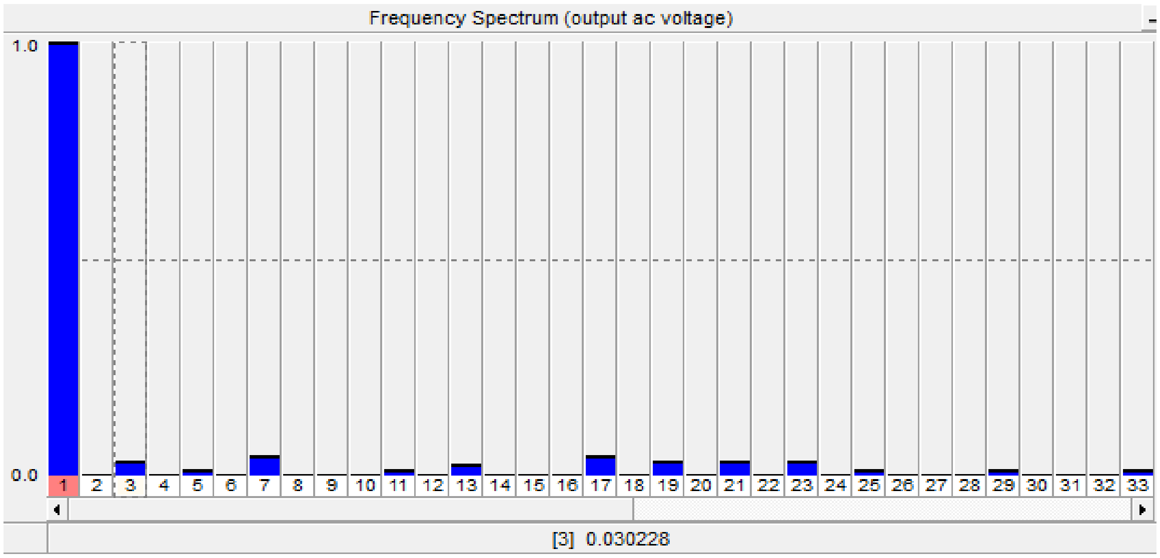

Figure 4.14: Output voltage frequency spectrum

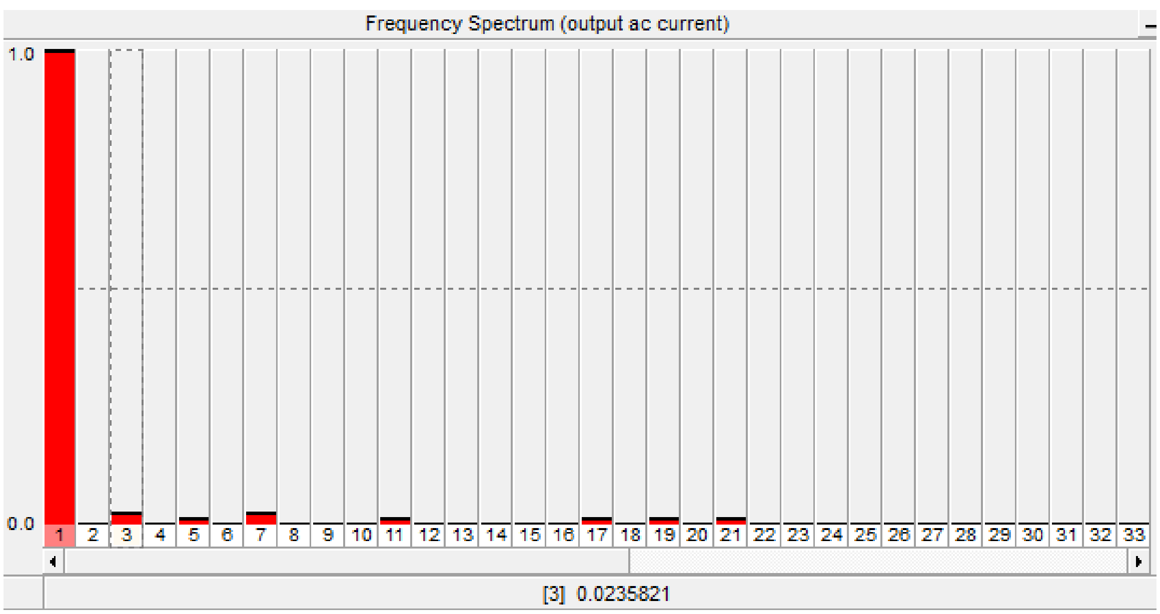

Figure 4.15: Output current frequency spectrum

Table 4.4: Percentage harmonics of the output at unity power factor

N^{th} Harmonic	Current percentage (%) harmonic	Voltage percentage (%) harmonic
Fundamental	1.0	1.0
3^{rd}	0.0244	0.0289
5^{th}	0.0060	0.0115
7^{th}	0.0169	0.0406
9^{th}	0.0021	0.0009
11^{th}	0.0053	0.0140

Table 4.5: Total harmonic distortion (THD) values at unity power factor

Parameter	Total harmonic distortion
Voltage	9.6%
Current	3.2%

In addition, Simulation was performed to determine the power factor of the system. As seen in figure 4.16, the system injected reasonable active power (P) to the grid, but the reactive power (Q) was zero. Therefore, the total power factor of the system is unity.

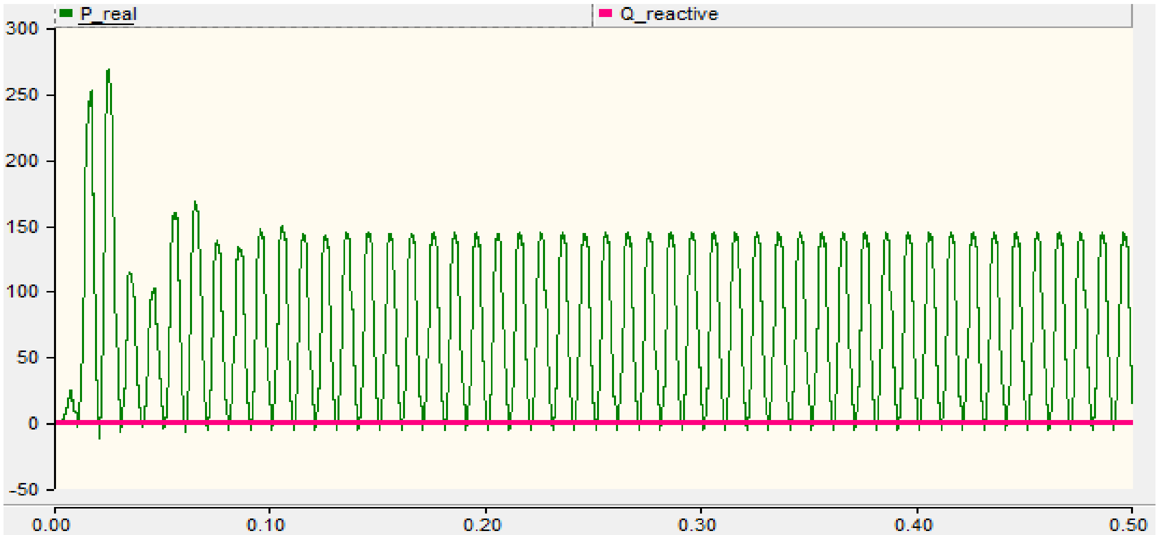

Figure 4.16: Active power and reactive power at unity power factor

From the results, it can be seen that the system gives a fast response, and takes shortest time to attain its steady state output. The system provides a stable instantaneous outputs (voltage and current) output in shortest time with less intermittency. Which, invariably, results effective RMS value. It has ability to control real and reactive power. In this topology, real power is injected into the grid whiles reactive power is maintained at zero hence, unity power.

4.4.1 Simulation results for injected reactive power

In addition, simulation was performed at injected reactive power. Thus, at non-unity power factor. In this scenario, reactive power (Q) as shown if Figure 17, is injected from the system into the network at increased real power (P). The higher the inductor, the increase in total harmonics (THD). Thus, harmonics content increases when more reactive is introduced in the system. The results in this scenario are shown between Table 4.6 and 4.7. The results include active and reactive, the current and voltage THD as well as the first six THD of output voltage and current values including the fundamental were calculated and the results are presented.

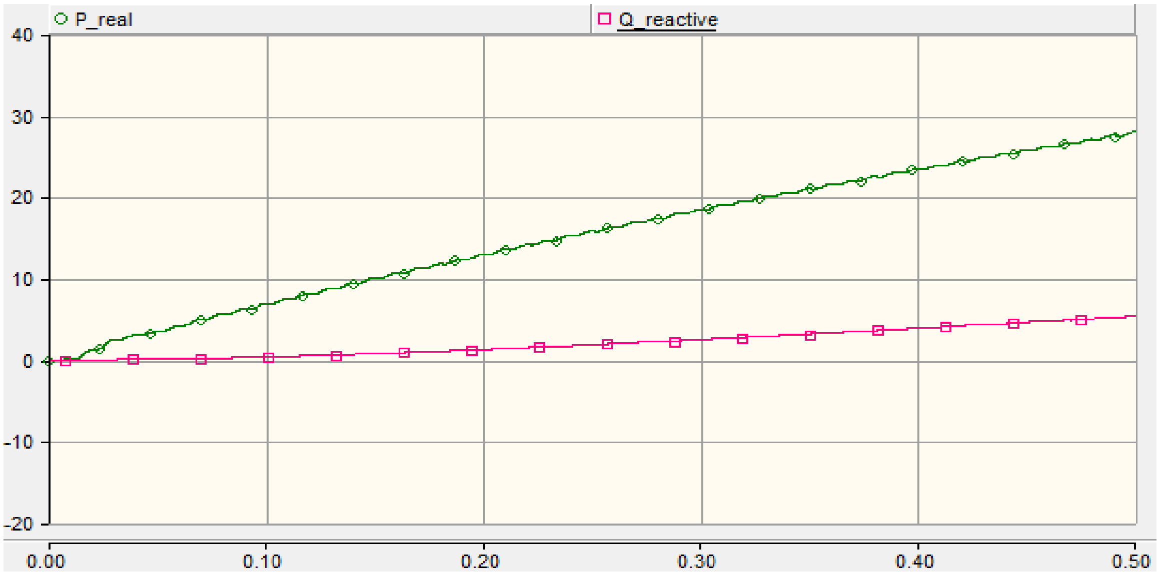

Figure 4.17: Active power and reactive power at 98% power factor

Table 4.6: Percentage harmonics of current and voltage at 98% power factor

N^{th} Harmonic	**Current percentage (%) harmonic**	**Voltage percentage (%) harmonic**
Fundamental	1.0	1.0
3^{rd}	0.0235	0.0302
5^{th}	0.0059	0.0112
7^{th}	0.0181	0.0430
9^{th}	0.0017	0.0004
11^{th}	0.0055	0.0147

Table 4.7: Total harmonic distortion (THD) values at 98% power factor

Parameters	Total harmonic distortion
Voltage	9.7%
Current	3.3%

4.4.2 Summary of results

In summary, it can be compared between Tables 4.5 and 4.7 that, both current and voltage harmonic values are lower at unity power factor than at injected reactive power. Similarly, there is a little difference in THD values in both scenarios. Above all, simulation results depict that, fundamental frequency technique in multilevel inverter applications, especially cascaded H-bridge multilevel inverter yields efficient results. Hence, power factor corrections and harmonics mitigation can be assured. More importantly, the results show that parameters such as real power and reactive power can be controlled with this topology. Output voltage and current were generated with less distortion. Hence, ability of this technique to achieve power quality when used in renewable energy integration.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORKS

5.1 Conclusion

A topology of renewables with energy storage unit integration is presented in this project. There are several forms of renewable energy sources. Each source has its advantages and its short falls. This project explains renewables benefits regarding to why they are gaining global prominence as far power generation is concerned. The development of recent renewables integration has briefly been discussed. Systematically contributions of renewables integrations are presented in this project. Dynamic factors affecting integration were not left out.

Furthermore, power from renewables is dynamic as a result of fickle nature of the weather conditions such as wind turbulence and solar irradiation. In view of this, various types of energy storage systems that tend to correct these power fluctuations were illustrated. These systems are able to provide power stability and reliability.

In addition, renewables integration is enhanced by power electronic applications. Voltage from renewable energy sources is normally DC source, and power electronic system is required to convert this voltage from DC to AC for onward integration into the power network. This project discusses topologies of power electronic inverters such as multilevel inverters needed for renewables applications. The discussion includes applicable control method to achieve harmonic mitigations.

More importantly, a new topology is designed in accordance with the existence once. In this topology, a trinary asymmetric input cascaded h-bride multilevel inverter is designed. The designed includes hybrid storage units to store large amount of energy during off-peak hour for future usage and also, to improve upon power quality and reliability issues.

Finally, asymmetric source cascaded H-bridge multilevel inverter topology has been used to present renewable integration in this project. The final simulation was executed using PSCAD/EMTDC, and following observations were made:

- Multilevel inverters possesses viable factors such as high power and medium power applications in addition to ability to generate an output voltage with less distortion. Therefore, they can be classified as ideal inverters for renewables integration.
- Power factor and harmonic distortions are unwarranted issues in power system, especially in renewables integration. Harmonic mitigation and power factor correction can be overcome with cascaded H-bridge multilevel inverter, especially when fundamental switching frequency control technique is used. Hence, power quality is improved
- Harmonic mitigation can be achieved when energy storage unit is incorporated in renewables integration (power system network).

5.2 Future Work Recommendations

After carefully analysis, the following were arrived for future research works:

- Multilevel inverters have different control techniques, and one of them other than fundamental frequency method can be applied to achieve more harmonic mitigation.
- Multilevel inverters such as capacity clamp type is very complex to control, yet it is very useful in application that require more real power and power reactive. Therefore, researchers are encouraged to enhance on control methods validation.
- Energy storage units are well known for their ability to improve power quality issues. For this reason, more different energy storage methods can be used in similar applications to improve upon power quality.

REFERENCES

Amamra, S. A., Meghriche, K., Cherifi, A., & Francois, B. (2017). Multilevel Inverter Topology for Renewable Energy Grid Integration. *IEEE Transactions on Industrial Electronics, 64*(11), 8855-8866

Amrouche, S. O., Rekioua, D., Rekioua, T., & Bacha, S. (2016). Overview of energy storage in renewable energy systems. *International Journal of Hydrogen Energy, 41*(45), 20914-20927

Arif, S., & Aziz, T. (2017, February). Impact of battery energy storage system on post-fault frequency fluctuation in renewable integrated microgrid. In *Electrical, Computer and Communication Engineering (ECCE), International Conference on* (pp. 594-598). IEEE.

Babaei, E., Hosseini, S. H., Gharehpetian, G. B., Haque, M. T., & Sabahi, M. (2007). Reduction of dc voltage sources and switches in asymmetrical multilevel converters using a novel topology. *Electric Power Systems Research*, *77*(8), 1073-1085.

Bhoyar, R. R., & Bharatkar, S. S. (2013, December). Renewable energy integration in to microgrid: Powering rural Maharashtra State of India. In *India Conference (INDICON), 2013 Annual IEEE* (pp. 1-6). IEEE

Blaabjerg, F., Iov, F., Teodorescu, R., & Chen, Z. (2006, August). Power electronics in renewable energy systems. In *Power Electronics and Motion Control Conference, 2006. EPE-PEMC 2006. 12th International* (pp. 1-17). IEEE

Converse, A. O. (2012). Seasonal energy storage in a renewable energy system. *Proceedings of the IEEE*, *100*(2), 401-409.

Guinane, A., Shafiullah, G. M., Oo, A. M., & Harvey, B. E. (2012, July). Voltage fluctuations in PV penetration on SWER networks—A case study for regional Australia. In *Power and Energy Society General Meeting, 2012 IEEE* (pp. 1-6). IEEE.

Gupta, R., Nigam, N., & Gupta, A. (2011). Application of energy storage devices in power systems. *International Journal of Engineering, Science and Technology*, *3*(1), 289-297

Hasan, N. S., Hassan, M. Y., Majid, M. S., & Rahman, H. A. (2013). Review of storage schemes for wind energy systems. *Renewable and Sustainable Energy Reviews*, *21*, 237-247

Jamali, A. A., Nor, N. M., & Ibrahim, T. (2015, October). Energy storage systems and their sizing techniques in power system—A review. In *Energy Conversion (CENCON), 2015 IEEE Conference on* (pp. 215-220). IEEE.

Khomfoi, S., & Tolbert, L. M. (2011). Multilevel power converters. In *Power Electronics Handbook (Third Edition)* (pp. 455-486).

Koohi-Kamali, S., Tyagi, V. V., Rahim, N. A., Panwar, N. L., & Mokhlis, H. (2013). Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review. *Renewable and Sustainable Energy Reviews*, *25*, 135-165.

Kumar, D., Zare, F., & Ghosh, A. (2017). DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects. *Ieee Access*, *5*, 12230-12256.

Liang, X. (2017). Emerging power quality challenges due to integration of renewable energy sources. *IEEE Transactions on Industry Applications*, *53*(2), 855-866.

Miñambres-Marcos, V. M., Guerrero-Martínez, M. Á., Barrero-González, F., & Milanés-Montero, M. I. (2017). A Grid Connected Photovoltaic Inverter with Battery Super capacitor Hybrid Energy Storage. *Sensors*, *17*(8), 1856.

Mizutani, M., Monden, Y., Sato, J., Kono, T., & Nakajima, R. (2016, June). Energy management for hydrogen energy storage system. In *CIRED Workshop 2016* (pp. 1-4). IET.

Muhammad, H. R. (2004). Power Electronics-Circuits, Devices, and Applications. *Upper Saddle River, NJ, Pearson Prentice Hall.*

Ogunniyi, E. O., & Pienaar, H. (2017, April). Overview of battery energy storage system advancement for renewable (photovoltaic) energy applications. In *Domestic Use of Energy (DUE), 2017 International Conference on* (pp. 233-239). IEEE

Paulino, H. D., Menegáz, P. J. M., & Simonetti, D. S. L. (2011, September). A review of the main inverter topologies applied on the integration of renewable energy resources to the grid. In *Power Electronics Conference (COBEP), 2011 Brazilian* (pp. 963-969). IEEE

Peng, F. Z., Lai, J. S., McKeever, J. W., & Van Coevering, J. (1996). A multilevel voltage-source inverter with separate DC sources for static var generation. *IEEE Transactions on Industry Applications*, *32*(5), 1130-1138

Peralta, C. O., & Salles, M. B. C. (2017, June). Advanced energy storage systems to increase the penetration of renewable energies in Fernando de Noronha Island. In *Clean Electrical Power (ICCEP), 2017 6th International Conference on* (pp. 392-396). IEEE

Rahman, M. S., Hassan, A., Mahmud, N., Iftekhar, A. T., & Mazumder, M. D. H. (2014). Power Management and Control of Grid Connected Photovoltaic System with Plug in Hybrid Vehicle Load. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, *3*(1).

Raihan, M. I. A. (2016, December). Impact of energy storage devices on reliability of distribution system. In *Electrical, Computer & Telecommunication Engineering (ICECTE), International Conference on* (pp. 1-4). IEEE.

Renewable energy sources presentation, (2008) Retrieved November, 14th 2017. From: https://www.slideshare.net/trilby/renewable-energy-sources-presentation

Rodriguez, J., Lai, J. S., & Peng, F. Z. (2002). Multilevel inverters: a survey of topologies, controls, and applications. *IEEE Transactions on industrial electronics*, *49*(4), 724-738.

Romlie, M. F., Rashed, M., Klumpner, C., & Asher, G. M. (2014, April). An analysis of efficiency improvement with the installation of energy storage in power systems. In *Power Electronics, Machines and Drives (PEMD 2014), 7th IET International Conference on* (pp. 1-6). IET.

Sekar, R., Suresh, D. S., & Naganagouda, H. (2017, December). A review on power electronic converters suitable for renewable energy sources. In *Electrical, Electronics, Communication, Computer, and Optimization Techniques (ICEECCOT), 2017 International Conference on* (pp. 501-506). IEEE.

Shafiullah, G. M. (2016, January). Impacts of renewable energy integration into the high voltage (HV) networks. In *Development in the in Renewable Energy Technology (ICDRET), 2016 4th International Conference on the* (pp. 1-7). IEEE

Swain, P., Jagadish, S., & Mahesh, K. U. (2017, July). Integration of renewable sources of energy into power grid. In *IEEE Region 10 Symposium (TENSYMP), 2017* (pp. 1-5). IEEE.

Tannous, C., Ahlam, D., & Rosa, M. (2016, July). Renewable energy integration into existing plants: Application: Deir Ammar thermal plant-North Lebanon. In *Renewable Energies for Developing Countries (REDEC), 2016 3rd International Conference on* (pp. 1-9). IEEE.

Zakeri, B., & Syri, S. (2015). Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and Sustainable Energy Reviews*, *42*, 569-596.

Zhang, N., Sutanto, D., & Muttaqi, K. M. (2016, November). A novel topology for integration of solar PV and energy storage system. In *Power and Energy (PECon), 2016 IEEE International Conference on* (pp. 401-406). IEEE.

Zhang, X., Wang, R., Bao, J., & Skyllas-Kazacos, M. (2016, November). Control of distributed energy storage systems in residential microgrids. In *Control Conference (AuCC), 2016 Australian* (pp. 270-275). IEEE.

APPENDICES

APPENDIX (1)

The Overall Proposed Circuit Diagram

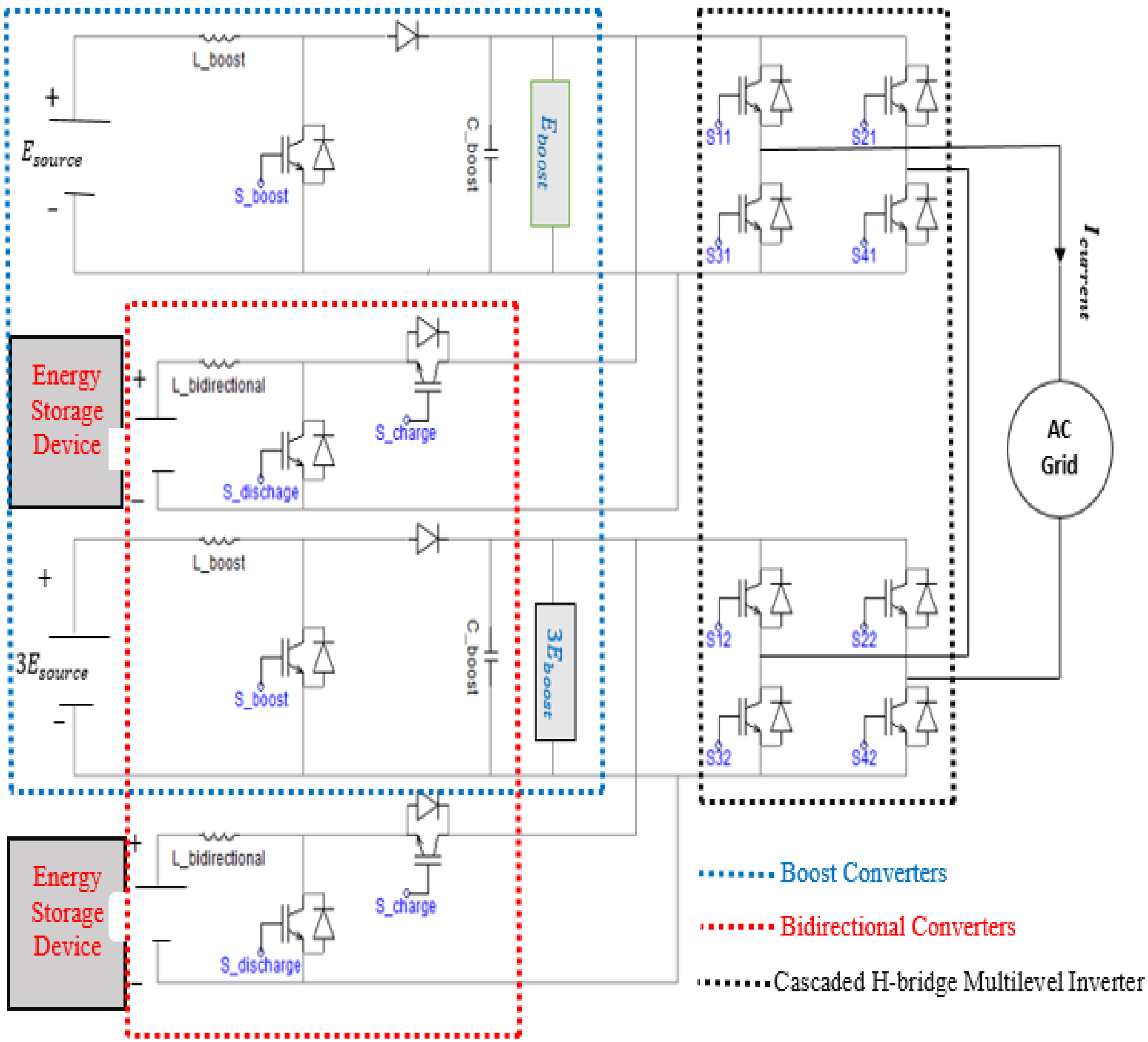

Figure A: PSCAD implementation of proposed circuit diagram

APPENDIX (2)

PSCAD Implementation of Fundamental Switching Technique

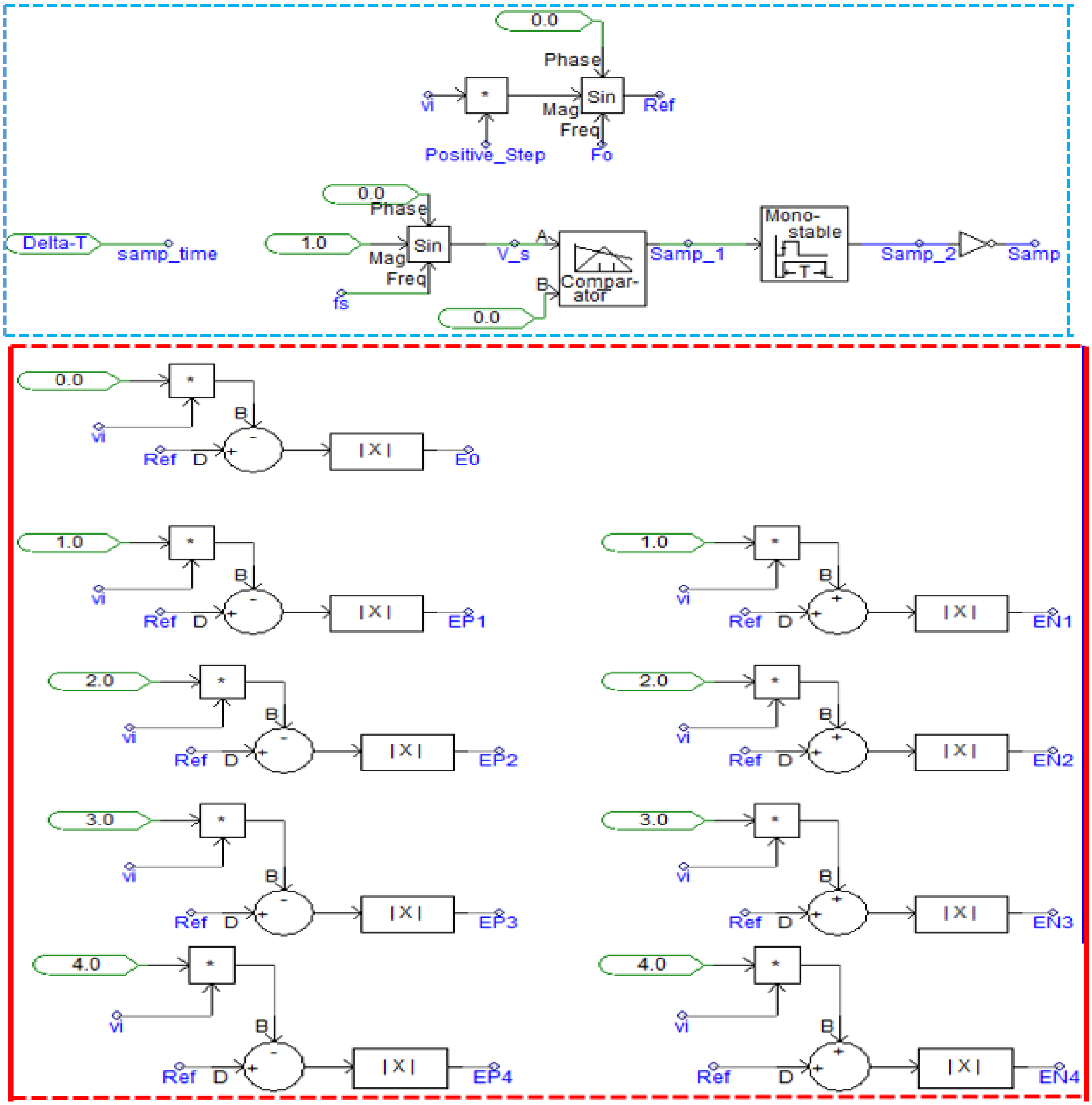

Figure B: PSCAD fundamental frequency switching control building block

APPENDIX (3)

PSCAD Cascaded Multilevel Inverter Switching Technique

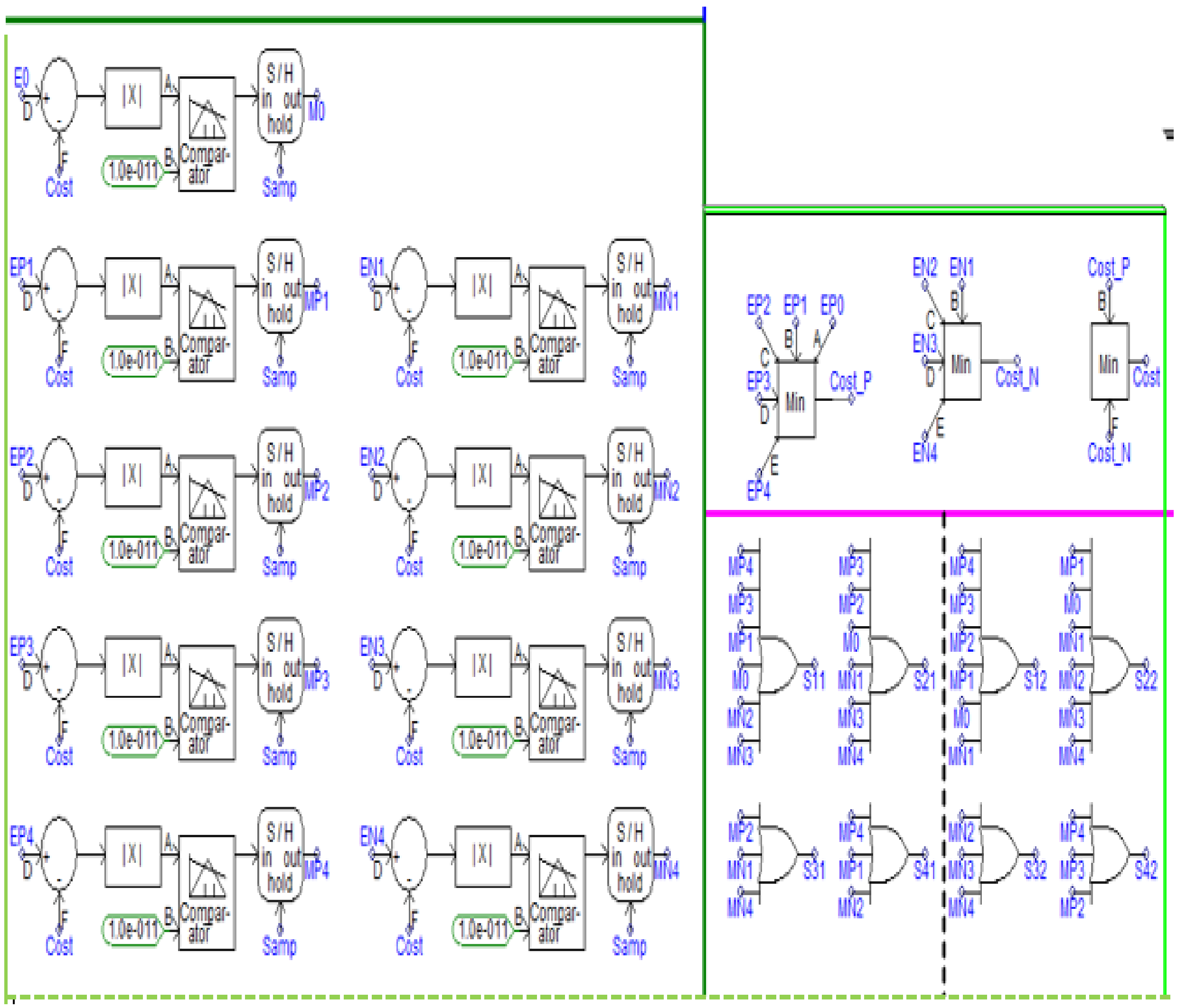

Figure C: PSCAD cascaded multilevel inverter switching technique for nine level output

APPENDIX (4)

Table 1: charge balance control method switching states

Switches states	$S_{1,1}$	$S_{2,1}$	$S_{3,1}$	$S_{4,1}$	$S_{1,2}$	$S_{2,2}$	$S_{3,2}$	$S_{4,2}$	**Output (Vo)**
1	1	0	0	1	1	0	0	1	$+4E_{boost}$
2	1	1	0	0	1	0	0	1	$+3E_{boost}$
3	0	1	1	0	1	0	0	1	$+2E_{boost}$
4	1	0	0	1	1	1	0	0	$+E_{boost}$
5	1	1	0	0	1	1	0	0	0
	1	1	0	0	0	0	1	1	
	0	0	1	1	1	1	0	0	
	0	0	1	1	0	0	1	1	
6	0	1	1	0	1	1	0	0	$-E_{boost}$
7	1	0	0	1	0	1	1	0	$-2E_{boost}$
8	1	1	0	0	0	1	1	0	$-3E_{boost}$
9	0	1	1	0	0	1	1	0	$-4E_{boost}$

Table 2: PSCAD implementation switching states

Error	$S_{1,1}$	$S_{2,1}$	$S_{3,1}$	$S_{4,1}$	$S_{1,2}$	$S_{2,2}$	$S_{3,2}$	$S_{4,2}$	**Output (Vo)**
MP4	1	0	0	1	1	0	0	1	$+4E_{boost}$
MP3	1	1	0	0	1	0	0	1	$+3E_{boost}$
MP2	0	1	1	0	1	0	0	1	$+2E_{boost}$
MP1	1	0	0	1	1	1	0	0	$+E_{boost}$
M0	1	1	0	0	1	1	0	0	0
	1	1	0	0	0	0	1	1	
	0	0	1	1	1	1	0	0	
	0	0	1	1	0	0	1	1	
MN1	0	1	1	0	1	1	0	0	$-E_{boost}$
MN2	1	0	0	1	0	1	1	0	$-2E_{boost}$
MN3	1	1	0	0	0	1	1	0	$-3E_{boost}$
MN4	0	1	1	0	0	1	1	0	$-4E_{boost}$