Maximum power point tracking based grid connected wind energy system using converters

DISSERTATION-II

Submitted in partial fulfilment of the
Requirement of the award of

Degree of
MASTER OF TECHNOLOGY
IN
ELECTRICAL ENGINEERING
(POWER SYSTEM)

Submitted by
RANDEEP SINGH
Registration No: 11502576

Under the Guidance of
PREETI KHURANA

LOVELY PROFESSIONAL UNIVERSITY

Transforming Education Transforming India

School of Electronics and Electrical Engineering
Lovely Professional University
Punjab

APRIL 2017

CANDIDATE'S DECLARATION

I **Randeep Singh**, student of M.tech (Electrical Engineering) under school of Electronics and Electrical Engineering of Lovely Professional University, Punjab, hereby declare that all the information furnished in this dissertation report is an authentic record of my own work carried out under the supervision of "**Mrs. Preeti Khurana**" Assistant Professor, School of Electronics and Electrical Engineering. The matter presented in this dissertation has not been submitted to Lovely Professional University or to any other university or institute for the award of any degree.

Signature of the Student
Reg. No. 11502576
Date:

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

Signature of the Supervisor

The M.tech Viva-Voce Examination of (Dissertation-II) has been held on __________ and found satisfactory/Not satisfactory.

Signature of the Internal Examiner   Signature of the External Examiner

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my mentor **“Mrs Preeti Khurana”** Assistant Professor for her guidance, encouragement, and support throughout the course of this work. It was an invaluable learning experience for me to be one of her students. From her, I have gained not only extensive knowledge but also a sincere research attitude. I express my gratitude to **Mr. Abishek Sinha** (Assistant Professor), of Electrical Engineering for his invaluable suggestions and constant encouragement all through the research work. My thanks are extended to my friends in “Power Electronics & Power System” who built an academic and friendly research environment that made my study at Lovely Professional University, Phagwara most memorable and fruitful.

I would also like to acknowledge the entire teaching and non-teaching staff of Electrical Department for establishing a working environment and for constructive discussions. Finally, I am always indebted to all my family members especially my parents, for their endless love and blessings.

NAME: RANDEEP SINGH

REG. NO: 11502576

CERTIFICATE

This is to certify that the declaration statement made by this student is correct to the best of my knowledge and belief. He is doing Dissertation-II work under my guidance and supervision. The present work is the result of their original investigation, effort, and study. No part of the work has ever been submitted for any other degree at any University. The Dissertation-II work is fit for the submission and partial fulfilment of the conditions for the award of M.Tech degree in Electronics and Electrical Engineering from Lovely Professional University, Phagwara.

Signature and Name of the Mentor:

Designation:

School of Electronics & Electrical Engineering
Lovely Professional University
Phagwara, Punjab

Date:

ABSTRACT

Wind energy is by far the fastest growing renewable energy due to its free availability and environmental benefits. Maximum power extraction is a way to realize high power efficiency for Wind Energy Conversion System (WECS). This thesis focuses on implementing the Incremental Conductance (INC) method that has been used till now for Maximum Power Point Tracking in photovoltaic (PV) systems.

The proposed system uses Direct Driven Permanent Magnet Synchronous Generator (PMSG) which has no gearbox to reduce the cost and increase the reliability of the wind turbine. Matlab Simulink is used to design boost converter and different MLI, then the most optimal circuitry is chosen to justify the research topic. Although various types of converter are used, the advanced converter with the use of inductor and controlled duty cycle with MPPT is proposed in this work. Thus, the output is being constant under variable voltage condition of the wind turbine by the boost converter. Use of five-level and seven-level MLI to reduce the THD from AC output current and also MLI interrupt the flow of fault signal to the DC link because it is not provide bidirectional power flow. An inverter is controlled by the SPWM technique and obtained desired output across the inverter. **"Maximum power point tracking based grid connected wind energy system using converters"** is done by the use of power electronics devices and their applications have also been emphasized.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBRIVATION

AC	Alternating Current
WT	Wind Turbine
ADCMLI	Active Diode Clamped Multi Level Inverter
IM	Induction Motor
AWEA	American Wind Energy Association
CO2	Carbon Di Oxide
DC	Direct Current
DCPWM	Double Carrier Pulse Width Modulation
DFIG	Doubly Fed Induction Generator
EMF	Electromotive Force
d-q	Direct and Quadrature Axis
HAWT	Horizontal Axis Wind Turbine
IGBT	Insulated-Gate Bipolar Transistor
MATLAB	Matrix Laboratory
MU	Mega Unit
MW	Mega Watt
KWH	Kilo Watt Hour
PMSG	Permanent Magnet Synchronous Generator
PV	Photo Voltaic
PF	Power Factor
PWM	Pulse Width Modulation
SCIG	Squirrel Cage Induction Generator
SEF-DFIG	Single External Feeding of Doubly-Fed Induction Generator
MLI	Multi-Level Inverter
FC-MLI	Flying-capacitor Multi-Level Inverter
DC-MLI	Diode-Clamped Multi-Level Inverter
CMLI	Cascade Multi-Level Inverter
SDCS	Separate DC sources
MPPT	Maximum Power Point Tracking
P & O	Perturb and Observation
INC	Incremental Conductance

SPWM	Sinusoidal Pulse Width Modulation
SVPWM	State Vector Pulse Width Modulation
TEDA	Tami Nadu Power Development Agency
TSR	Tip Speed Ratio
VAWT	Vertical Axis Wind Turbine
VSC	Voltage Source Converter
VSWT	Variable Speed Wind Turbine
WECS	Wind Energy Conversion System
WT	Wind Turbine

CHAPTER-1

INTRODUCTION

1.1 Background

As the demand for electricity increases day by day, to fulfil that demand non-conventional sources are combined with the conventional sources and the reducing of CO_2-emission is one of the challenge faces by us nowadays. It shows the need of renewable energy, hence, the worldwide sector is concentrating on this and did something new for the environment. Their work is not only providing the possibility growth in living standards but also securing that growth for certain sustainability. On addition to the non-renewable sources like fossil fuels oil and gas, the use of renewable sources will give huge contribution to the energy fulfilment. The extraction of oil and gas has also given a positive contribution. It has pushed the technology in most disciplines of engineering. In electrical engineering, the main results are increased power handling of electrical drives to provide power to offshore compressors and pumps, and a significant reliability improvement of many components. As a consequence of this technology advance in oil and gas, high-quality components and systems are developed. These components are also fit for use in other fields - for instance renewable energy. The idea of supplying offshore installations from shore is not only politically driven as a result of global warming. It also requires a certain willingness to make it happen. Oil companies made several attempts during the 80's and 90's, but it was a demanding political process and failed due to the big footprint. The Troll and installation are now fully electrified from shore, being the largest oil platform in the North Sea this saves CO_2-emissions in the range of 100,000 to 150,000 tons per year. Using renewable energy solutions like offshore wind would give a green contribution to the electrification. One idea is to connected offshore wind farms and offshore installations.

From the above discussion, it comes to understand that the generation of energy for the fossil fuels resources are more critical. These types of resources produce lots of amount of CO_2 which is the main cause of global warming. But if we talk about the availability of these sources then these are limited while the demand for energy increases day by day, especially the countries like India and China which are developing and industrializing countries. On account of this reason, nation resembles Europe expanding inclination towards the renewable energy sources. Wind energy is the standout amongst the most prominent wellspring of energy, which is come to as higher rate as hydropower in nation like Denmark and Germany

[BMU 2007]. Denmark has the most elevated share of wind power while Germany has most elevated wind control according to the report [AWEA 2004], [BWE 2006].

In early 1990s, the bulk power supply was done by the largest machine which was built by Charles Steinmetz. But later on its complexity increase as the times passes on. Now in the 21st century, power system is fully standardized to AC systems which includes AC synchronous machines (generators) operating at constant frequency products used and transferred power on distances.

Our understanding of the energy system has on the underlying properties were calculated. But in the 21st century, these properties are no longer universally and understanding of power system concepts is anchored not fixed. The energy system today is expected that a variety of AC and DC systems to integrate into three sectors: generation, transmission, and distribution. Here should be able to handle both synchronous and asynchronous generators, centralized and distributed resources and controllable by nature, and to manage the energy sources inherently intermittent and variable. In India, the capacity of wind power and other renewable energy sources are connected and are provided for the connection to take. This trend will continue due to the growing concern about environmental problems such as carbon emissions and global climate change, energy security in a world that is less than single-ended, and job creation in an environment. Renewable energy is at the crossroads of all complex issues of contention. All the modern sources of renewable energy, wind energy has to have been the most successful, and therefore, the challenge of the immediate integration.

In the present scenario, conventional resources are at the edge of depletion as they are non-renewable plus they are causing damage to our environment. Hence there is a need to see the sources whose availability is easy and at the same time should not affect the environment. Hence we are now focussing on the renewable sources of energy. Advantages of renewable energy sources is that they are replensible as well as environmental friendly. Among these sources, we have wind energy sources. In India, there is a high scope of wind energy especially in the coastal areas as well as the higher altitude places.

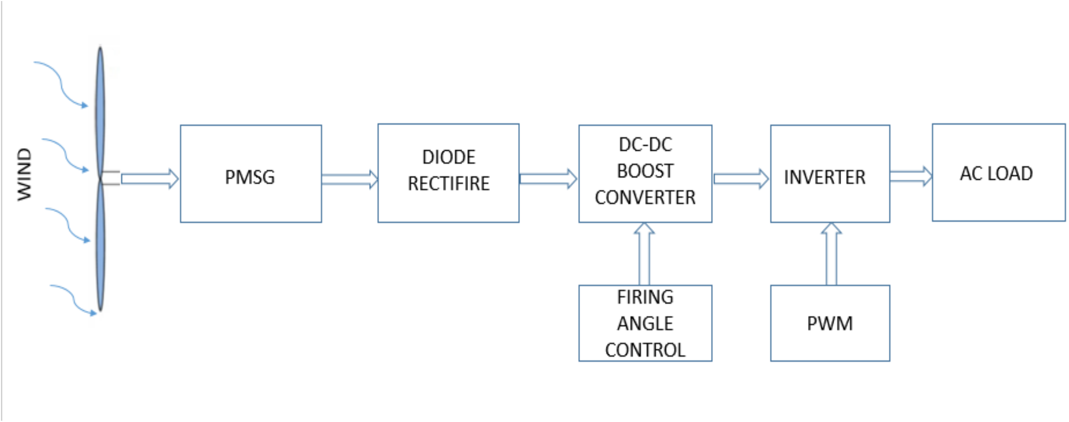

Figure [1.1]: Block Diagram of Wind Energy Conversion

From the above block diagram the whole project process is to be explain as, wind energy will rotate the turbine blade by this rotation the wind power is converted into mechanical power this mechanical power is used to rotate the generator by this generator here mechanical power is further changed into electrical power by the general principle of electromagnetic induction. Now this AC voltage is fed to rectifier, it converts the AC voltage into DC, as we want boost up this voltage level. For this use DC-DC Boost converter. Rectifier converts the 3-phase AC voltage into single phase and that output voltage of rectifier is fed to DC-DC boost converter. Boost converter has a property to increase the voltage level on the output side. Hence this output voltage is fed to inverter which can convert this DC into AC, and hence we use this AC as industrial load or connected it with the grid. But before connected to the grid synchronism is required to check this process is explain in future scope.

1.2 Current status of wind energy in India

The capacity of wind turbine installed across the globe has attained 486.8 GW by the cumulative end of 2016, an increase of 17% compared to the previous year. Worldwide wind power installation increased by 63.633 GW, 51.675 GW and 36.023 GW in 2015, 2014, 2013 respectively. India is at fourth position (28,700 MW) following the lead of China (168,690 MW), US (82,184 MW), Germany (50,018 MW). In India wind energy is getting more attention because of higher reliability and less time required to install wind turbine [40].

Indian-owned company, Suzlon has been global choice in in past decade acquiring 7.7 market share of wind turbine sales worldwide. Suzlon is currently the largest manufacturer of wind turbines for the Indian market to keep about 43 percent market share in India. Suzlon has success in the advanced technology of wind turbines in India in developing countries.

1.3 Monthly Electricity Generation

Wind energy generated power accounts for nearly 8.6% of the overall established capacity of power generated in India. The wind power generated accounts 2.5% of total generation which is approximately 28.700 MW for DEC-2016[40].

1.3.1 States wise installed wind power generation India as of 19th October 2016

Table [1]: Power Generation Capacity India

State	Total Capacity (MW)
Tamil Nadu	7,684.31
Gujarat	4,227.31
Andhra Pradesh	1,866.35
Rajasthan	4,123.35
Karnataka	3,082.45
Madhya Pradesh	2,288.08
Andhra Pradesh	1,866.35
Telangna	98.70
Kerala	43.50
Others	4.30

Tamil-Nadu holds the capacity is about 29% of total wind power generation in India. Tamil-Nadu government has come to understand the need and importance of renewable energy, hence, to manage this task Tamil Nadu government has set an organisation in1985 named as Tamil Nadu Energy Development Agency (TEDA). Now, Tamil-Nadu becomes the one of the top leaders in wind power generation in India. According to Indian government under “Make in India” these renewable source sectors like wind and solar have very large scope in power generation so under this segment they are trying to build more and more plants from these sources so it has two advantages:

1) The problem of coal depiction will be solved.

2) The CO_2 emission will be reduced.

In future, consumption of renewable energy must be seeking towards the various aspects of research in wind power. Now days engineers facing challenges intromit the efficiency of energy conversion, safety operation, increase of power capacity etc. In Fig.1.2 shows that as increase in hub height exponentially power capacity also increases with time.

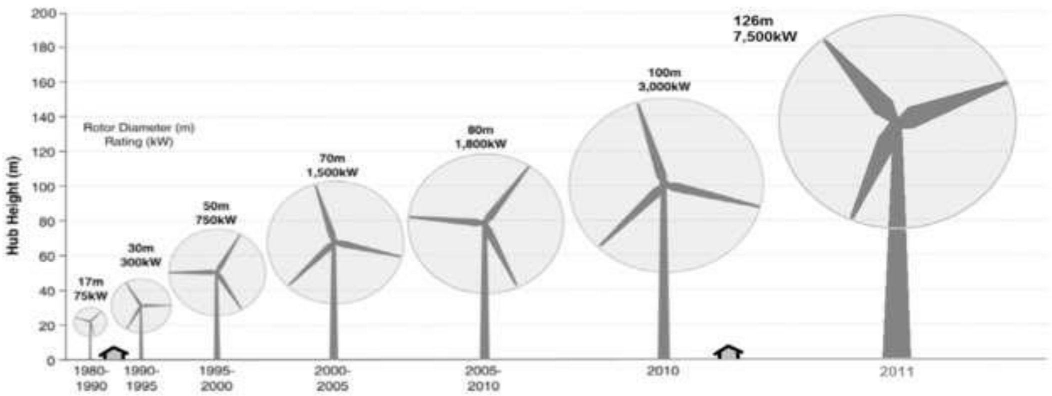

Figure [1.2]: Height of hub and Power evolution with time [1]

1.4 Wind energy conversion system (WECS)

With the WECS electrical energy produces comprises with wind turbine, mechanical connection, generator and integration with grid. Blades of wind turbine are placed in the hub as shown in Fig 1.3. As wind blows, shaft of the turbine starts to rotate. Then gearbox is used to make the rotational speed increase or decrease according to the suitableness of the generator. Now important part integration of grid with wind farm which is done power electronic devices, which makes the voltage and frequency fixed so that power can be supply direct to load or synchronised with grid.

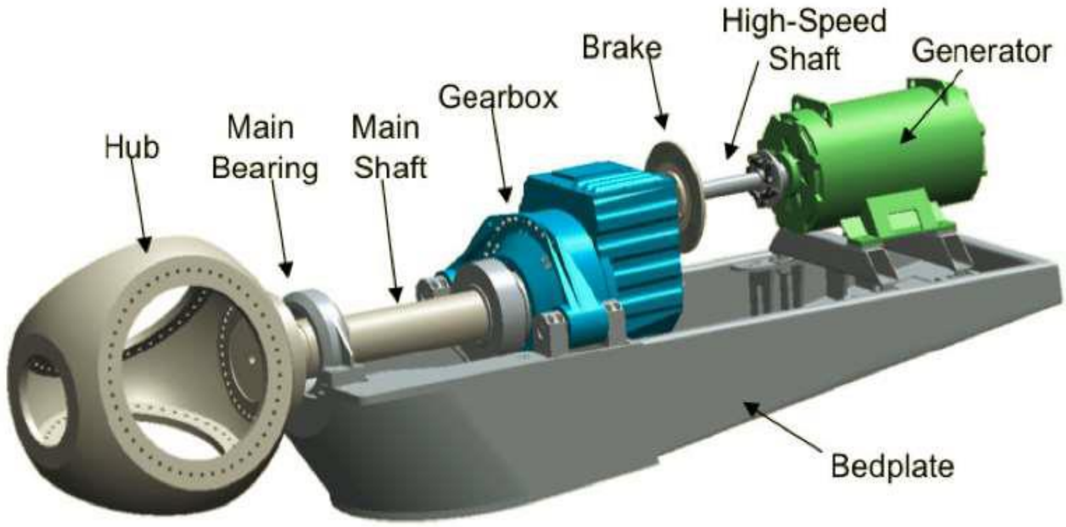

Figure [1.3]: Conventional Configuration Gearbox Drive Train [2]

In present era, two types of generator are widely used in wind farms: Permanent Magnet Synchronous Generator (PMSG) and Doubly Fed Induction Generator (DFIG). Both generator generates high quality of electrical power with controlled grid integration. But superconducting generators brings lots of losses due to AC associated with the stator leads to time varying magnetic field, so this generator is still under research .

1.5 Horizontal Axis Wind Turbine

The Horizontal Axis Wind Turbine (HAWT). In other words, the axis of rotation is parallel to the ground. HAWT rotors are usually classified according to the orientation of the rotor (Facing the wind or downwind of the tower), the hub design (rigid or staggered), the control rotor (pitch vs. stall), the number of blades (usually two or three blades), and how they are aligned with the wind (free or active yaw).

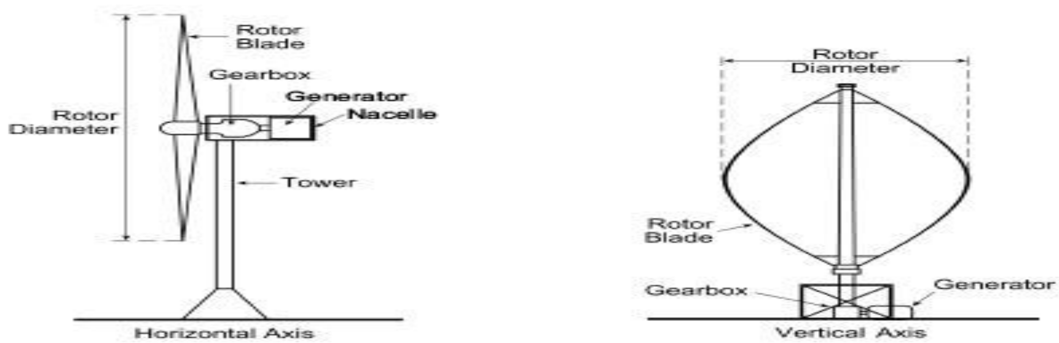

Figure [1.4]: HAWT and VAWT

The major subsystems of a typical horizontal axis wind turbine including:

1) The rotor constituted by the blades and the support hub.
2) The driving mechanism, which has rotating parts of the WT (excluding rotor); it generally has Generator, Shafts, Gearbox, Coupling, and Mechanical Brake.
3) Mainframe, including the nacelle of a wind turbine, bed plate, and yaw mechanism.
4) The tower and foundation.
5) The Controlling of the machine.
6) The balance of the electricity system including, Transformers, Switchgear, Cables, and Electrical power converters.

HAWT Advantages

a) Variable pitch angle gives the best angle of attack.
b) To obtain more efficiency, the blades always rotate perpendicularly to the flow of wind and it receives power from the rotation.

HAWT Disadvantages

a) Transportation is difficult due to 90 meters long blades and tall towers. 20% of equipment costs are occupied by transportation.
b) At high installation of HAWT's are difficult. It requires very large and expensive cranes and skilled person.
c) To support the heavy Blades, Gearbox, and Generators robust tower construction is required.
d) HAWT's require additional yaw control mechanism for the rotating of blades.

1.6 Vertical Axis Wind Turbine

In VAWT's the rotor is mounted on a vertical axis, the arrangement of these types of turbine does not require pointed wind force. So, these can be easily used where the wind speed is variable all the times. In Vertical axis turbine, the tower does not need a large investment to support turbine blades because gearbox and the generator are located near the ground.

VAWT Advantages

a) This tower structure is less frequently used.

b) It doesn't require any fixed pitch rotor designs mechanisms.

c) VAWT's generally they start generating below 10m/s wind speed.

d) Low noise, Low maintenance cost.

VAWT Disadvantages

a) The single blade will work at a time so efficiency is very low.
b) They produce pulsating torque.
c) They have relatively high vibration because the airflow near the ground so, they create high turbulence flow.
d) They create noise pollution.
e) They need an initial push to start, this action use few of its own produce electricity.

1.7 Doubly Fed Induction Generator

IG is electrically and mechanically same as induction motor. Induction motor (IM) work as Induction Generator (IG) when speed of the motor is increased then the synchronous speed or say shaft of the motor rotates quicker than the synchronous frequency. This type of generators are not self- excited. To generate rotating magnetic field, this type of generator need external supply, that is happens by reactive current. So it induces the current inside the rotor and rotor produces a magnetic field also. If rotor starts rotating faster, then it work like generator, which generate power at synchronous frequency.

Doubly Fed Induction Generator depends on multiphase induction generator, which takes the feedback power from the grid. The advantage of the DFIG is at variable speed it permits to maintain the constant value of the frequency and amplitude of the output voltage. In feedback process or loop using a power electronic devices or converters can makes the controllable power factor in between the DFIG and grid [3]. Doubly Fed Induction Generator connected in both way either directed to grid or with feedback loop means with AC-DC, DC-DC, DC-AC converts. This alleviates the induction generator to DFIG, which is shown in Fig 1.5.

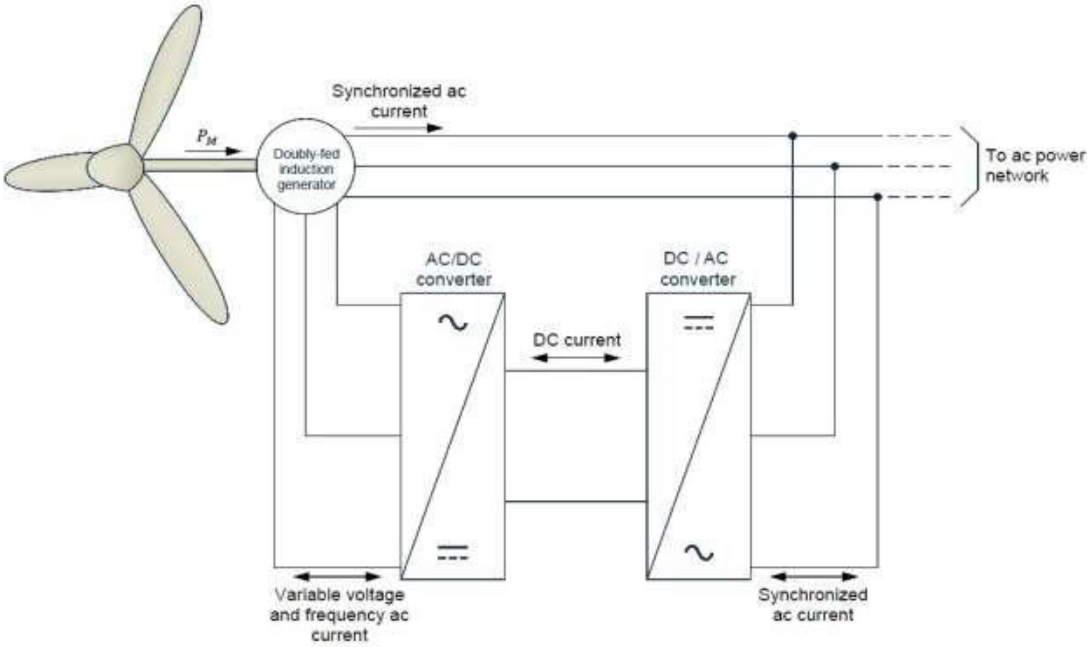

Figure [1.5]: DFIG integrated with grid [3]

1.8 Permanent Magnet Synchronous Generator (PMSG)

PMSG consists permanent magnet inside the rotor which helps to produce magnetic field. Permanent Magnet synchronous Generator having some advantages over IG that are cost and reliability using wound electromagnets. In PMSG based wind turbine design a direct driven because high PMSG power density that permits the generator operates at low speed and thus no need for gearbox as shown in Fig 1.3. Maintenance and repairing of gear box is very expensive, which increase the cost model of the turbine. As compare to other component gearbox failure leads the 2-3 times downtime [4]. By this benefits PMSG has less weigh, need less space and acquire less mechanical losses. In Fig 1.6 grid connected PMSG topology is shown. Permanent Magnet Synchronous Generator cannot sent output power to AC system immediately at variable speed. Integration of grid behaves like a controller that assure the power at grid is synchronized with green energy (wind).

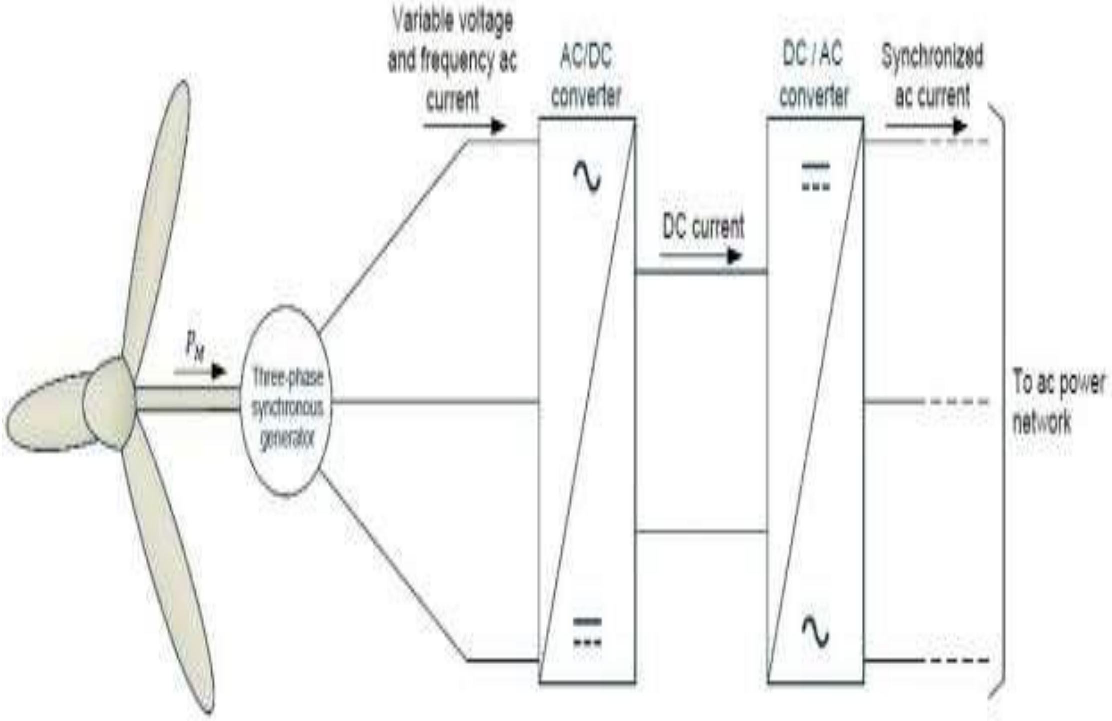

Figure [1.6]: Integration of grid PMSG based wind turbine [3]

19 Maximum power extraction of wind

Wind speed is not constant it varies all the time. Output power of wind energy conversion system affect with change in speed. In fig 1.6 shows that power varies as speed varies. So WECS use some controllers or make some adjustment to get maximum power at any time. Maximum power can be extracted by track the speed at different wind speed like as shown in fig 1.7. Let’s take example at wind speed is 6m/s, the maximum power is extracted at 1pu. To get maximum efficiency from wind turbine maximum wind power extraction topology should be applied in the control mechanism of wind energy conversion system.

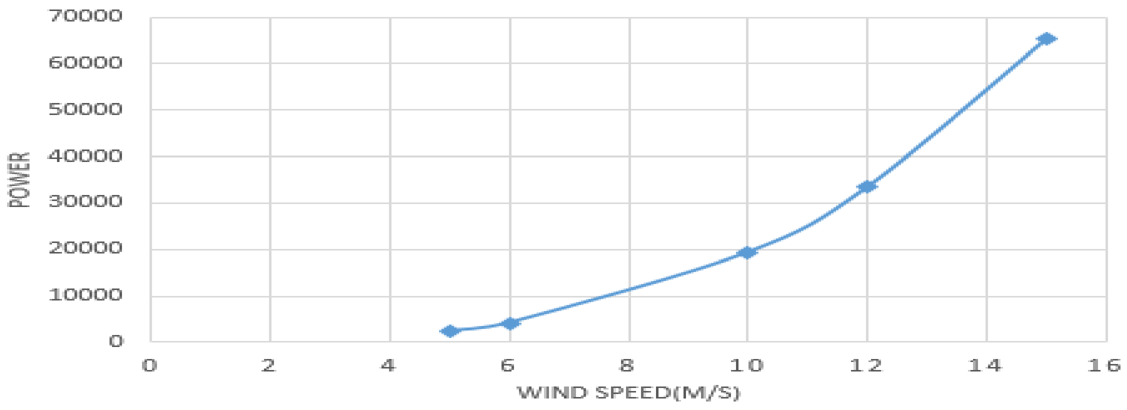

Figure [1.7] wind speed versus power

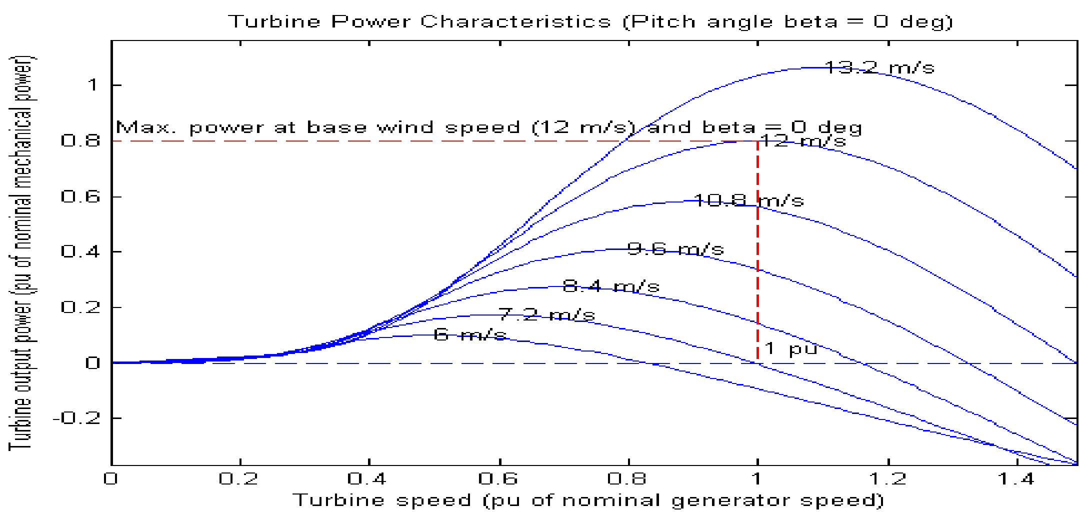

Fig [1.8]: Characteristics of wind turbine

CHAPTER-2

LITERATURE REVIEW

Ajami, Ali, RanaAlizadeh, and Mahdi Elmi et al. (2016) proposed a six switch converter which is basically based on the PMSG having MPPT capability. It works as rectifier to incorporate two variables wind turbine which is rely upon PMSG (permanent magnet synchronous generator). Maximum power point tracking (MPPT) is used in order to achieve higher efficiency. In low power applications, this approach is efficient in terms of cost. Also this proposed technique enhances its reliability, reduces its weight and also its size. MATLAB /SIMULIMK are used for its performance and results. [5]

Raju Krishnama, S., and G. N. Pillaiet al. (2016) This paper talks about Type-2 Fuzzy Logic Controller for DFIG-Based Wind Energy Systems in Distribution System. DFIG based system is capable to tackle issues like faults, load changes and wind speed. The performance is checked by connecting the wind turbine to IEEE 34-bus test system. The real time simulations are carried out using real time digital simulator (RTDS) connected to hardware in loop (HIL) configuration to affirm the implementation of the controller. [6]

Lee, Jinsik, Eduard Muljadi, Poul Sorensen et al. (2016) in this study, Releasable Kinetic Energy-Based Inertial Control of a DFIG Wind Power Plant has been proposed. In the wind power plant, wind turbine generators having several levels of releasable kinetic energy. This kinetic energy is due to wake effects. The change in frequency along with droop loops are implanted in doubly fed induction generator controller. The paper conclude about improvement in frequency. [7]

Nguyen, Danvu, and Goro Fujita. et al (2015) In this study , Analysis of sensor less MPPT algorithm has been proposed .This strategy comprises of wind turbine, doubly fed induction generator and photovoltaic system .this strategy is then compared with the separate system with MPPT system. [8]

Fateh, Fariba, Warren N. White, and Don Gruenbacher. et al. (2015) Suggested a MPPT technique based on wind turbines for doubly fed induction generator (DFIG). But in the conventional method, torque is directly related to the square of rotor speed and three control laws are used to adjust its proportionality coefficient. The first and second control law calculated the electrical torque and estimate real time values for power respectively. The third law provides the speed to rotor. [9]

Nayanar, V., N. Kumaresan, and N. AmmasaiGounden et al.(2015) proposed a Maximum Power Point Tracking having single sensor. The algorithm for MPPT which is proposed here is not depending on any machine and wind turbine and MPPT method is available for application of mircogrid. [10]

M. F. Elmorshedy et al. (2015) This paper portrays controlling procedure for a off grid WECS using a permanent magnet synchronous generator (PMSG). In this initially DC link voltage is controlled by duty cycle. Therefore, to convert the voltage of the DC link to the amplitude and to the required frequency of the charging voltage, a sinusoidal pulse-width modulation (SPWM) for controlling the inverter.
The presented control strategy aims to regulate the load voltage in terms of magnitude and frequency in different operating conditions, including wind speed. Wind generation system under consideration he uses PMSG with a wind turbine, AC-DC, DC-DC and DC-AC converter. The control strategy is presented based in part on control of the duty cycle, Converter to convert the input variable to DC voltage, because to different operating conditions, at a suitable constant DC voltage. Therefore, a modulated sinusoidal pulse width (SPWM) UPS is used to adjust the amplitude and frequency by controlling the modulation index. A sample simulation results are obtained and analysed here. [11]

Xiaoyan Du and Huajie Yin(2015) This paper proposed DFIG-based wind turbines have become the predominant wind turbines for high stability and its develop control innovation. And MPPT controlling topology of Doubly Fed Induction Generator based wind turbines is very important to enhance the wind power conversion efficiency. This paper builds up the mathematical models of DFIG, wind turbine and rotor side converter, outlines the MPPT control procedure controller and the rotor side converter controller, and employs the double steps hill climb searching method. Results demonstrate that double steps hill climb exploring algorithm is a good method to accomplish the MPPT of Doubly Fed Induction Generator based wind turbines. [12]

Ms. Srushti R. Chafle*, A. Gadekar *et al.* (2015) This paper talks about control algorithm for MPPT used in cuk converter. The MPPT helps in deriving maximum power from photovoltaic and send it load by means of cuk converter boost up the magnitude of the voltage. The objective is to extract the maximum possible power from the photovoltaic module for this MPPT locates the point at which maximum power of module is available. The generalized algorithms are applied for MPPT which are easy to code and easy to use in model. [13]

G. Hima Bindu and Dr. P. Nagaraju Mandadi (2014) Paper presents the comparison of wind systems based on various IG. Here three induction machines studied for the comparison are DFIG and SCIG and using a DFIG in single-sided grid connection. Then the performances of all three machines are compared. The controlling of rotor of SEF-DFIG by means of inverter **[**14]

Dalala, Zakariya M, Zaka Ullah Zahid et al. (2013) presented a small scale wind power system with a MPPT algorithm and it utilizes the dc current as concerning variable. The proposed algorithm identifies the sudden variation in the wind speed. The presented algorithm indicates the improved stability and less variation in the speed of wind condition and is implemented using a $1.5*10^3$ Watt model hardware setup. [15]

Jlassi, Imed, Jorge O. Estima, El Khil, SejirKhojet, NajibaMrabetBellaaj (2013) et al. presented Multiple Open-Circuit Faults Diagnosis in Back-to-Back Converters of PMSG Drives for Wind Turbine Systems. In this study different simulations and results using PMSG drives has been analyzed. [16]

A.Bharathi Sankar, Dr.R.Seyezhai (2013) The paper projects the simulation for power electronic converter applied in WECS for the the Permanent Magnet Synchronous Generator (PMSG). This simulation uses Double Carrier Pulse Width Modulation (DCPWM) with Active Diode-Clamped Multilevel Inverter (ADCMLI) to calculate the parameter for PMSG Execution parameters are assessed for the proposed converter and the outcomes are confirmed. [17]

G. Estay et al. (2012) WECS are currently focusing on the higher power rating like 10MW. As in first generation turbines, they using SCIG which are directly connected to the grid, which is limited to fixed speed operation if you want to obtain more power than the second generation turbine are used which is DFIG here the rotor current are controlled by reduced capacity of back-to-back VSC. The most modern turbine is PMSG here two full bridge rectifier are connected to the boost converter. [18]

Joanne Hui *et al.* (2012) The modelling and controlling of a wind energy system having a single-switch three phase boost converter and an adaptive maximum power point tracking (MPPT) method has been presented in this paper. The benefit of single-switch three phase boost converter is to accomplish for the generator's power factor correction of output current, and is able to modify the controlling of the MPPT in WES applications. The MPPT controller is able to extract maximum power for different wind velocity without using a wind speed sensor. The control of the MPPT relies on feed forwarding both the input voltage and current of the boost converter to permit the momentary power information to the MPPT controller. In this paper the modelling and stability analysis of every segment in this WES will be talked about in this paper. [19]

Rajaei, Amir Hossein et al. (2011) In this work, novel wind conversion system using PMSG has been presented. This proposed system uses Vienna rectifier. The performance of proposed wind conversion system has been compared with already existing system such as wind conversion system using back to back converter. It is found from the comparison that proposed system provides improved efficiency. [20]

Xin Wang *et al.* (2010) for varying speed in wind turbine generator systems Permanent magnet synchronous generators (PMSGs) are ordinarily utilized. The paper portrays Buck-boost converter capable of following MPPT for enhance the output for wide range of wind velocity. WECS is compelled by a PWM following closed loop to drain maximum power by altering output voltage phase angle. The control scheme promises effective performances of WECS at maximum efficiency. [21]

Peng Xiao *et al.* (2009) high-power adjustable-speed motor drives, such as those used in electric ship propulsion systems, active filters provide a viable solution to mitigating harmonic related issues caused by diode or thyristors rectifier front-ends. To handle the large compensation currents and provide better thermal management, two or more paralleled semiconductor switching devices can be used. In this paper, a novel topology is proposed where two active filter inverters are connected with tapped reactors to share the compensation currents. The proposed active filter topology can also produce seven voltage levels, which significantly reduces the switching current ripple and the size of passive components. Based on the joint redundant state selection strategy, a current balancing algorithm is proposed to keep the reactor magnetizing current to a minimum. It is shown through simulation that the proposed active filter can achieve high overall system performance. The system is also implemented on a real-time digital simulator to further verify its effectiveness.[22]

Xiong Xin and Liang Hui (2005) the paper discuss about the work on conversion of AC-DC-AC WECS with 1.2 MW as rated output with constant speed and variable speed. The high level power is delivered to grid from PMSG via AC-DC-AC. The simulation result justify the feasibility for multiple boost converter in wind energy system, controlled by DSP. [23]

CHAPTER-3

RESEARCH OBJECTIVE

Lots of researches are going, on renewable sources because after the depletion of the sources like coal and oil, off the track sources like wind and solar attract everybody towards it. It is also important because firstly it is free source and lots of new things can be done in this field. The research is going on, how the 16/27 ratio increases because till now we are able to get only 59.3% means wind turbine will convert only 70% of wind power means initially we lost 30% wind power. The basic objectives of this paper are:

a) Improved the power quality wind Energy conversion system with integrated grid.

b) Designing of the Boost Converter in MATLAB SIMULINK

c) Designing of Multi-Level Inverter in MATLAB SIMULINK

d) Using MPPT algorithm tries the optimum power point of the wind turbine as perfect as possible in MATLAB SIMULINK.

CHAPTER-4

BASIC PRINCIPLES OF PMSG WITH WIND TURBINE

4.1 Wind Speed Model

For simulation of distributed wind speed and their dynamic behaviour, a model of variable wind speed is needed. During simulation of wind model ramp, Gust and random noise must be considered. Variable wind speed model has four components- ramp v_r, random v_g , gust v_g , constant v_b [24]. Wind speed is taken as the sum of all these four component.

The base wind speed of the turbine itself says that it is the constant value v_b of wind.

Ramp signal v_r shows linear change in wind speed with respect to time. Fig 4.1 shows ramp component of wind speed.

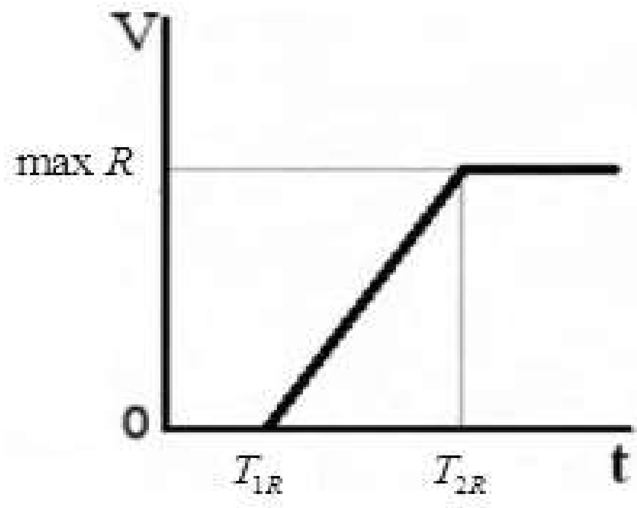

Figure [4.1]: Ramp component of wind speed

$$v_r = \begin{cases} 0 & ; \quad t < T_{1R} \\ \max R\left[1-(t-T_{2R})/(T_{1R}-T_{2R})\right] & ; \quad T_{1R} \le t < T_{2R} \\ \max R & ; \quad T_{2R} \le t < T_{2R}+T_R \\ 0 & ; \quad t \ge T_{2R}+T_R \end{cases}$$

where,

max R : maximum value of ramp, m/s

T_{1R} : rise time of ramp, s

T_{2R} : settling time of ramp, s

T_R : the duration in which ramp has maximum value, i.e. max R, s

V_g is component of wind speed that simulate rapid change in wind speed. Its operation is shown in Fig 4.2

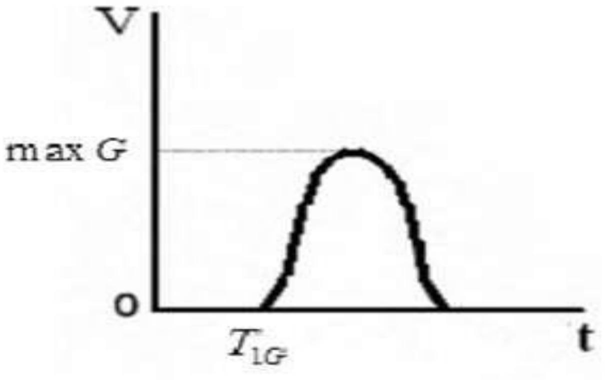

Figure [4.2]: Gust

$$v_g = \begin{cases} 0 & ; \quad t < T_{1G} \\ (\max G/2) * \{1-\cos[2\pi * (t/T_G) - (T_{1G}/T_G)]\} & ; \quad T_{1G} \le t < T_{1G}+T_G \\ 0 & ; \quad t \ge T_{1G}+T_G \end{cases}$$

where,

max G : gust’s maximum value, m/s

T_G : gust period, s

T_{1G} : time taken by the gust to starts

v_n is Gaussian distributed random noise. It comes due to friction of blades and ground and it is shown in Fig 4.3

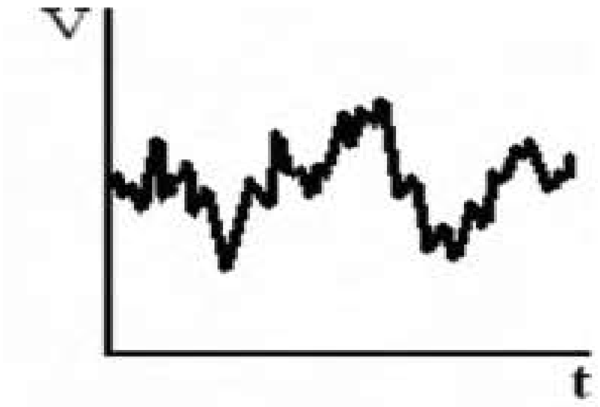

Figure [4.3]: Gaussian distributed random Noise

$$v_n = 2\sum_{i=1}^{N} \cos(\omega_i + \varphi_i)\sqrt{S_v(\omega_i)\Delta\omega}$$

$$\omega_i = (i - 0.5)\Delta\omega$$

$$S_v(\omega_i) = \frac{2K_N F^2|\omega_i|}{\pi^2\left[1 + (F\omega_i / \mu\pi)^2\right]^{4/3}}$$

Hence, model of variable wind speed can be termed as:

$$V_w(t) = v_b(t) + v_r(t) + v_g(t) + v_n(t)$$

4.2 Model of wind turbine

It depends upon the design and manufacturer, that some may design like if the wind speed is less than the desired speed than maybe they rotate but can't generate or build any power, or may happen they didn't rotate.

If the wind speed is too high, for the protection of wind turbine, we have to engage our protection mechanism and cannot allow the wind turbine to rotate because stress is so high and may wind turbine brake so at this time wind turbine stop.

Yaw control: It is essentially the means of orienting the wind turbine, as it turns in the direction of the wind. If we use Yaw as control mechanism then we have to make it all the time move.

There are two types of Wind Flow

a) **Down Stream wind Flow:** In this, downstream wind turbine there is no need of Yaw control, because it automatically turns, but here disadvantage is a tower, as the maximum wind will be wasted due to the tower.

b) **Up Stream wind Flow:** In this, there is a need to control the Yaw control.

The mechanical power is extracted using wind turbine is dependent upon air density (ρ), swept area (A), speed of the wind (v). Conversion of kinetic energy into mechanical energy is done by the use of wind turbine [25]. Kinetic energy (KE) is expressed as:

$$KE = 1/2mv^2$$

where,

m is mass of air, kg

v is speed of wind, m/s

Since power is defined as the rate of change of energy, therefore,

P = dE/dt

$$P= \frac{1}{2} v^2 \frac{dm}{dt} \text{ .... } (3.1)$$

Since mass flow rate is,

$$\frac{dm}{dt} = \rho A \frac{dx}{dt}$$

$$\frac{dm}{dt} = \rho A v$$

Where, v = $\frac{dx}{dt}$

From equation (3.1)

$$P = = \frac{1}{2}\ \rho A v^3$$

P = air density, kg/m^3

A = swept area of turbine blades, m^2

It can be seen from above equation that mechanical power of wind turbine directly proportional cube of wind speed. Every wind turbine have their betz limit (approximately 59%) which ensure that how much energy can be extracted from wind. Turbine can never extract whole kinetic energy present in wind and if it can then there will be no downwind behind the rotor. Fig 4.4 shows the area covered by upwind and downwind are different. Therefore, upwind speed will be higher in comparison to the downwind wind speed.

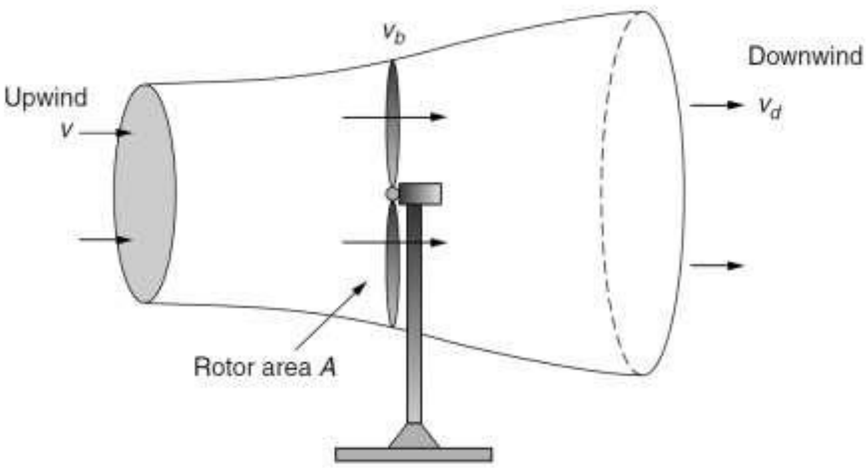

Figure [4.4]: Steam of wind turbine [24]

$$\frac{1}{2}\ \rho A v_b^2 - \frac{1}{2}\ \rho A v_b v_d^2 = \frac{1}{2}\ \rho A \left(\frac{v + v_d}{2}\right)(v^2 - v_d^2)$$

Where,

Pm = mechanical power produced by wind turbine, watt

v_d = downwind speed, m/s

v= upwind speed, m/s

4.2.1 Solidity

Solidity is defined as the ratio of the projected blade area to the area of the wind intercepted. The projected blade area is equal to the area projected in the direction of the wind. With torque and speed solidity has a direct relationship. High solidity rotors are suitable for pumping water because it has high torque and low speed. Low solidity rotors are suitable for electrical power generation because it has high-speed and low torque.

4.2.2 Tip Speed Ratio

TSR of a wind turbine can be express that

$$\lambda = WT\ R/Vw$$

λ= Non-dimensional
WT= Rotational Speed of turbine
R= Radius of turbine
VW= Wind Speed (m/s)

4.3 Modelling of Permanent Magnet Synchronous Generator

Modelling of PMSG is done by the use of Park's Transformation. In park's transformation three phase rotating frame (abc) is converted into two phase rotating frame (dq). Using this voltage and current of three phase rotating frame can be converted into dq reference frame [26]. Simulink block of Permanent Magnet synchronous generator is shown in Fig.4.5.

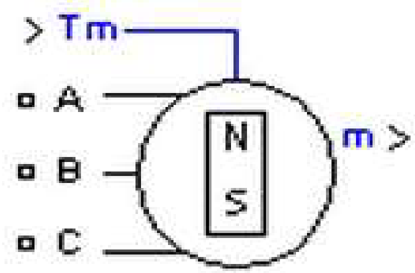

Figure [4.5]: Simulink block of PMSG

Phasor representation of Park' Transformation is shown in Fig.4.6

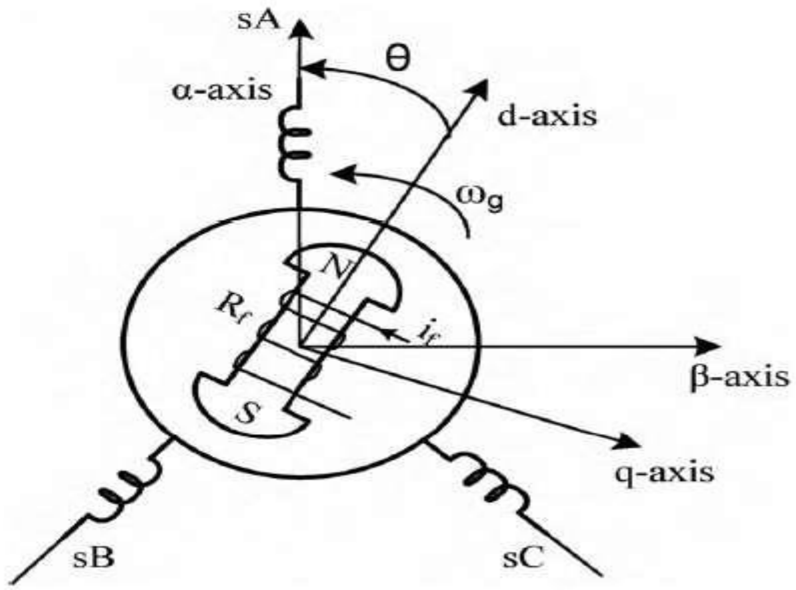

Figure [4.6]: Phasor representation of Park's Transformation

$$V_{\alpha\beta} = C_{abc-\alpha\beta} V_{abc}$$

$V_{\alpha\beta}$ has a 2*1 matrix. V_{abc} has 3*1 matrix

$$C_{abc} - {}_{\alpha\beta} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

$$V_{dq} = C_{\alpha\beta-dq} V_{\alpha\beta}$$

V_{dq} has 2*1 marix.

$$C_{\alpha\beta-dq} = \begin{bmatrix} cos\omega_g t & cos\omega_g t \\ -sin\omega_g t & cos\omega_g t \end{bmatrix}$$

Voltage and current can be modelled in dq frame as:

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_d + \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda p \omega_r}{L_q}$$

$$T_e = 1.5p\,[\lambda i_q + (L_d - L_q) i_d i_q$$

Where,

L_d , L_q = inductance of d and q axis, mH

i_d , i_q = current of d and q axis, A

R = stator winding resistance, **Ω**

v_d , v_q = voltage of d and q axis, V

λ = amplitude of induced flux in stator phases by rotor, W_b

T_e = electromagnetic torque of PMSG, N*m

ω_r = angular velocity of rotor, rad/s

p = no. of pole pairs

Now,

$$\omega_e = p\omega_r$$

ω_e = electrical rotating speed of the generator

From above equation rotational speed of rotor also calculated, because no. of pole par known and with the help of measured electrical signal ω_e can be found.

4.4 Maximum Power Point Tracking Techniques for WECS

Wind energy is one of the source which attract huge attraction as a renewable energy source. This is also because due to depletion of fossil fuels. Wind energy is abundant source and varies continuously as wind speed changes mean to say it is not constant all times so to make it effective we need to extract variable speed as power conversion. The amount of power we get from this conversion system depends upon the accuracy with which the peak power at the time can be tracked by the new and ongoing technique (MPPT), maximum power point tracking controller of the WECS irrespective of the type of generator used for this process.

A proficient tracker iteration is required for the MPPT to acquire the maximum power from the wind turbine. A tracker algorithm tries to trace the optimum power point of the wind turbine as perfect as possible, i.e. as reliable and fast as possible.

Throughout the years, many tracker algorithms have been established, each with his own benefits and drawbacks. MPPT has many algorithms to track the maximum power from input namely, Tip Speed ratio, Power signal Feedback, Hill Climbing Algorithms, Fuzzy Logic Control, The Current Sweep method and the direct method,

in this chapter, we will discuss the Hill climb method. The goal of the chapter is to perform a literature review of the Hill climb method and its type's algorithms in order to be able to evaluate them and choose the most suitable one for our application.
The equation (A) has defined the efficiency of the algorithms, where Pact is the product of current and voltage at the output of the wind turbine when the simulation is carried out under desired operating conditions. The power obtain is maximum obtained from wind turbine theoretically which is Pmax.

$$\eta = \frac{Pact}{Pmax} * 100\% \qquad \text{(A)}$$

4.4.1 Tip Speed Ratio (TSR)

This method aim is to keeps the TSR value at an optimum value by tracing the change in kinetic energy of wind. It is a simple method but it needs the data, which is collected or sensing by sensor to measures angular speed and wind speed of the wind turbine. In Fig.4.7 shows the block diagram of TSR method.

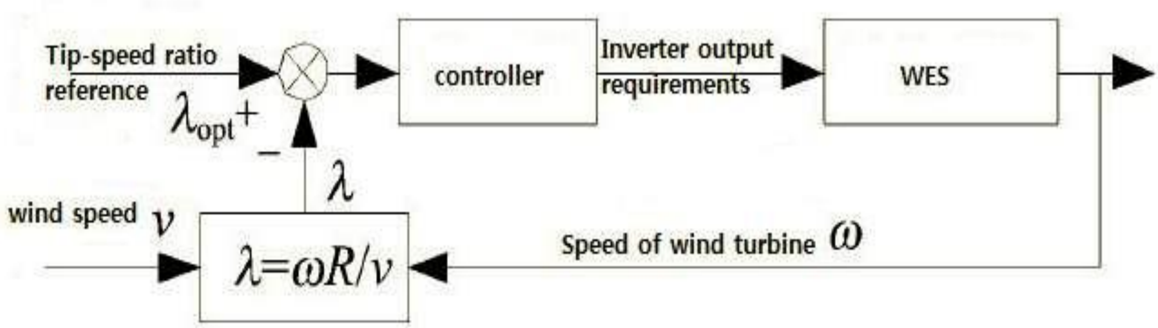

Figure [4.7]: Block Diagram Tip Speed Ratio Method

4.4.2 Power Signal Feedback

In this method estimation process is involves so that without flux sensor and wind speed sensor only controller can take action. Sometimes control fuzzy logic algorithm is used. The aim of this method is that at load side controls the reactive and active power. In Fig. 4.8 shows that on the basis of electrical signal how converter at generator side is regulated without evaluating the wind speed. Estimated reference compared with voltage and current but first voltage and current are transformed into dq frame. The estimation is performed in the basis of output power of rotational speed ω, it is taken as a reference value.

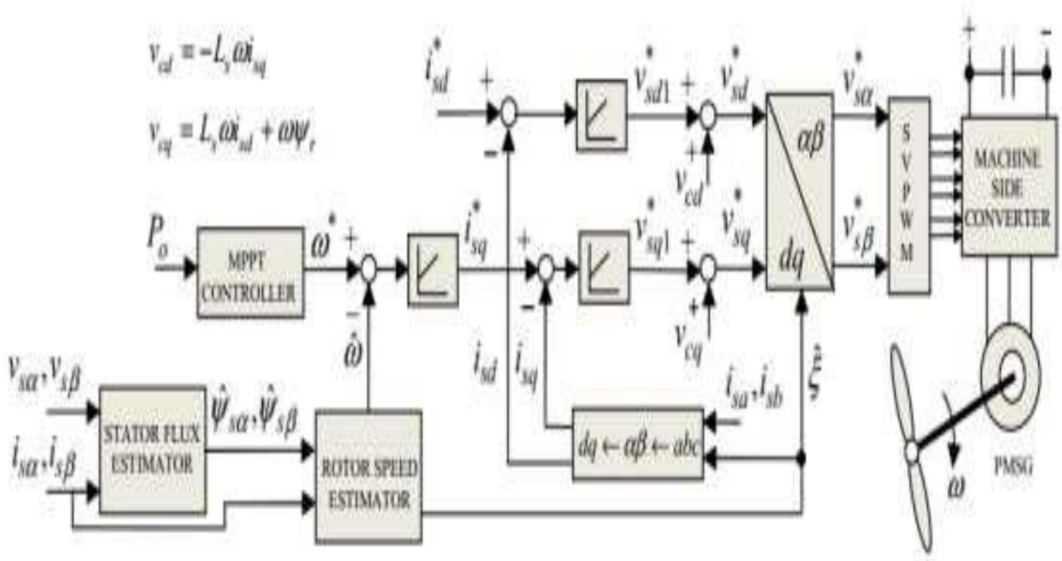

Fig. [4.8]: Block diagram Power Signal Feedback [26]

4.4.3 Hill Climbing Algorithm

This method is the most common. Hill Climbing means that the iteration run in step over p-v characteristic to locate the MPP. Hill Climbing can be classified in following algorithms which are Perturb & Observe (P & O), dP/dV Feedback Control and Incremental Conductance(IC).

In P & O the operating voltage is taken in consideration by sampling it. The algorithm is designed in such manner that it changes the operating voltage in the direction desired. For any positive value of voltage obtain algorithm changes the value in the direction of MPP until negative is obtain. This process is carried up to the point MPPT is obtain and frequency of perturb value chosen carefully according to respond of WECS speed. This method is limited to the high variation in wind velocity. The operating point oscillates around the maximum point. This method is most common employing less number of sensor [28] and [29].

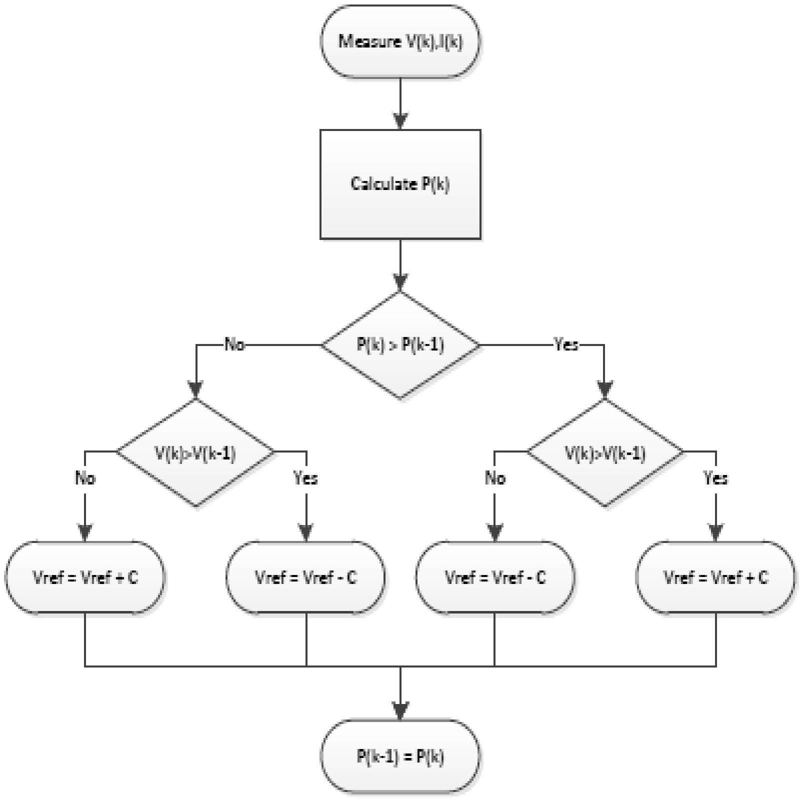

Figure [4.9]: Flowchart of the P&O algorithm

The $\frac{dP}{dV}$ algorithm is based on the rate of change of power with respect to rate of change of voltage. The power and derivative ($\frac{dP}{dV}$) is calculated after measuring of both the current and the voltage and It also stored the sign of derivative algorithm for the past few cycles. The duty ratio can be varied based on these signs to attain the Maximum power point. The algorithm tells the fact that the derivative should be equals to zero at the MPP.

Incremental conductance overcome the limitation of perturb and observe method or say it is modified version P & O method.

Figure.10 shows that how the power increase with change in speed like when speed is v_{w1} wind turbine working at "a" point. Then speed of the wind is change v_{w2}, the working point wind turbine shifts at "b" same as at v_{w3} point shifts at "c". In Fig.4.10 power is follow the dash line.

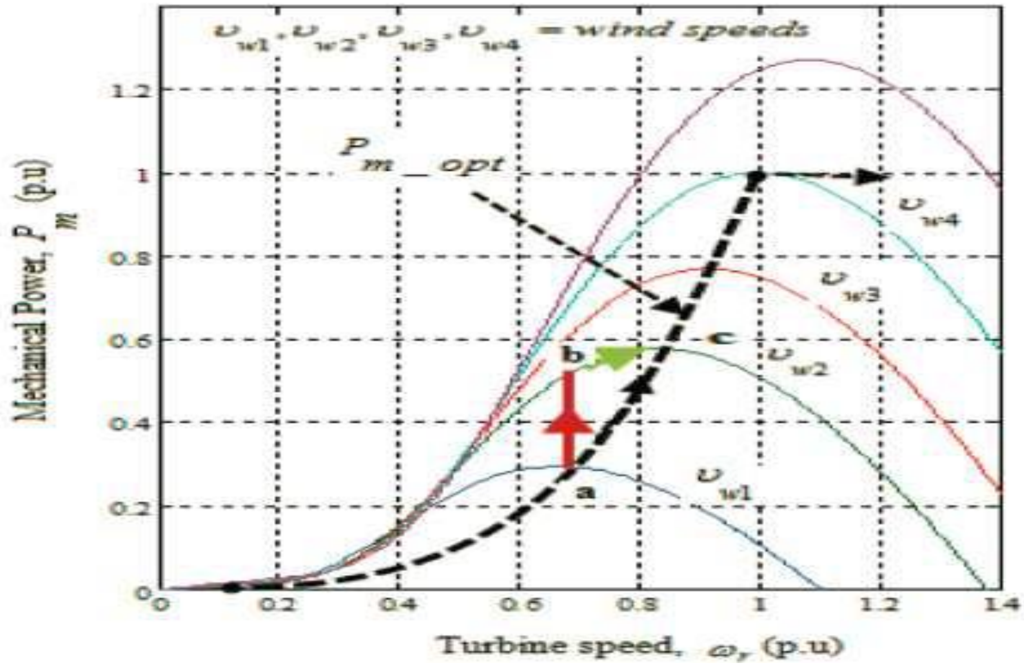

Fig. [4.10]: Speed v/s output power of wind turbine [29]

4.4.4 Summary of MPPT techniques

Generally TSR is not adopted because complexity of network communication and sensor cost also high [19]. In Power Signal Feedback controller circuit takes the input from electrical signals and wind speed sensor is not required in this method. To make estimation it requires exact acknowledge of Wind Energy Conversion Method. Controller installation increases the cost also because every time a new model for every new network has to be built. Hill climb method doesn't need any mathematics model of Wind Energy Conversion Method and wind speed sensor.

In this thesis incremental conductance method is studied, which is one of the Hill climb system method. For various Wind Energy Conversion Method IC technique is simpler and easy to use then others.

CHAPTER-5

GRID INTEGRATION OF WECS

5.1 Wind Turbine

The Wind is a free source of power and it is available everywhere. Always the wind flows from a higher atmospheric pressure region to the lower atmospheric pressure region due to the non-uniform heat by the sun and due to the rotation of the earth. In other words, we can say that the wind is a form of solar energy available in the form of that kinetic energy of air.

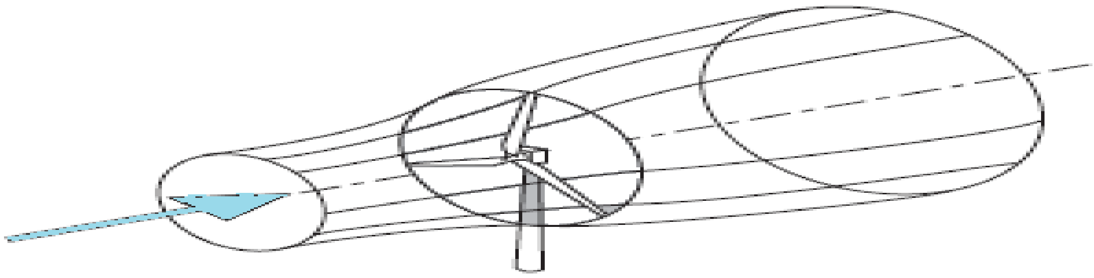

Figure [5.1]: Wind Flow through Turbine

Wind energy can be transformed into many forms of energy, such as the wind is used to generate electricity, windmills are also used to lift water pump turbines and propelling vessels. The Wind have a good amount of energy in it and whatever amount of power obtained from the wind is much greater than the power available from other sources which are used by humans. An alternative source of fossil fuels is wind power, it is broadly expanded neat & clean renewable and the most important one greenhouse gases are not going to be produced during its operation.

The day after Day, the development of the wind energy is improving and if it is used properly then it is capable of fulfilling the growing demand of the consume. To fulfill the growing demand of the consumer, the turbine should be developed with two blades or three blades which have the higher efficiency to collect more wind power.

Higher speed and more efficient turbines were necessary electricity generation .With the help of wind power, wind turbine generator electricity by driving an electrical generator. By using the power of the wind, wind turbines produce electricity by drive an electrical generator. The Wind produces a driving force to the blades while passing over it which drive the generator. A shaft connected to blades and shaft will rotate when blades are rotating and gear box is connected to the shaft. The gearbox helps to adjust the rotational speed which is favorable or suitable for the generator at the speed where the appropriate output is obtained. The obtained power from the wind generator is transferred to the transformer which steps up generated voltage up to 33KV. Which is the desirable voltage of power system? From the swept area of the blades, a wind turbine extracts kinetic energy. Wind energy can be defined as the kinetic energy of the air mass flowing per unit time. The power available and the power transformed is different by the factor of power coefficient. So the power generated aerodynamically because of wind turbine is given by

$$P_0 = 0.5(\rho A Vw^3) * C_p$$

The Wind turbine is moreover dependent on the velocity of the wind. According to Indian geographical conditions nobody can expect constant wind flow.

During soft start fluctuations occurred, and due to change in the direction of the flow of wind, the revolution speed also changes. Due to the fluctuation occur in the flow of air, the output voltage is also distributed so to attain desired output, we have to boost the voltage and get constant output.

These are two constraints related to wind power, everyone knows that the wind is a very abounded source, and it is very large power as it can destroy anything, So being engineered our moto is to use this power source smartly till now lots of inventions are done in the field of wind sector. But lots of can be about to happen there are related to the voltage stability as due to the revolution of the generator or motor flux will be produced and due to this, the electricity is generated.

Basically, a). If wind power is so less than it is useless.

b). If wind power is so large then it can damage the equipment like a turbine.

Basically, what is the wind, The Wind is moving air (something with considerable force) from an area of high pressure to an area of low pressure.

5.1.1 Operation

If the wind is too high, so from that the wind turbine has to be protected, if it is too high wind speed and we are extracting the full amount than the gearbox, the generator will be overloaded and may be burned. Strategy to control the wind turbine is clear. For that, we have to make a plan,

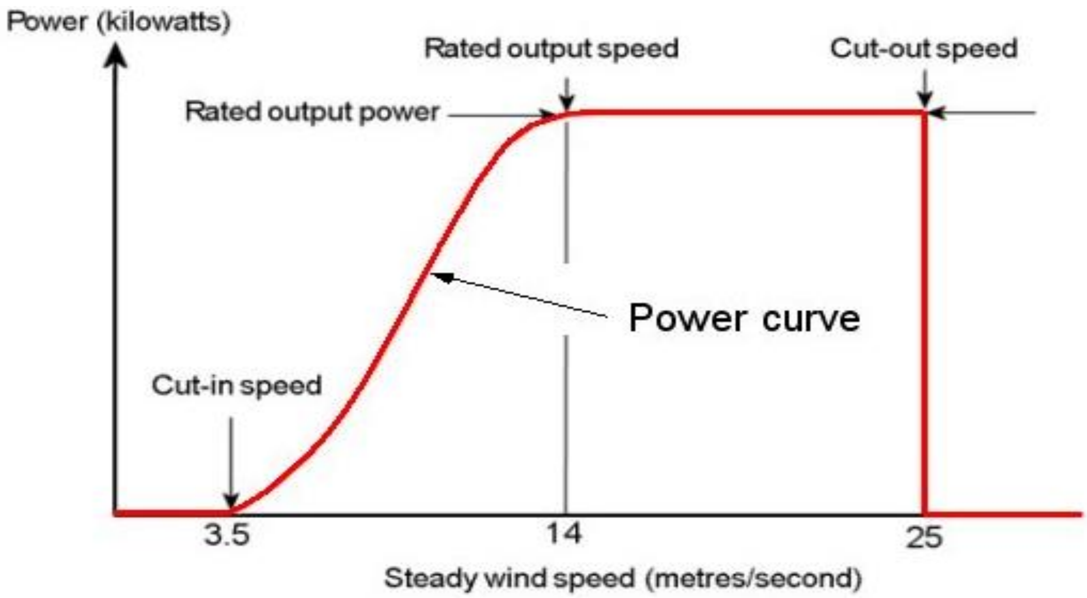

Figure [5.2]: Wind Turbine Graph for Cut in Speed

From this graph, it is shown that at very low wind speed, it could not able to generate any power so it should start from a cut in speed. Below this cut, in speed, the turbine is not started or rotated.

5.2 Introduction about grid integration of WECS

Power electronic devices are used to integrate the grid with WECS that able to transform the power into useful form. To make synchronism between WECS with grid then constant frequency, constant voltage and high power factor (PF). Power electronic components are AC-DC rectifier, DC-AC inverter and DC-DC converter are can be integrate or combined for different intentions to satisfy the conversion of power requirement of the load or grid.

5.2.1 Basic Switching Devices

SCR was first introduced in 1957 as power semiconductor devices. A great variety of solid state devices is available in the market. Some of the most commonly used devices are as follows:

a) Diodes: These are uncontrolled rectifying devices.
b) Thyristors: These are controlled by turning ON and OFF by the gate signal.
c) Controllable Switches: These turn ON and OFF by controlling signals.

For a specific application, the choice depends on the power, voltage, current and the condition of the system frequency. A common feature to these devices is that all devices are three-terminal as shown in their circuits symbols generally used.

Triac and RCT possess bi-directional current controlling capability whereas the devices like SCR, GTO, BJT, IGBT and MOSFET are unidirectional current controlling devices.

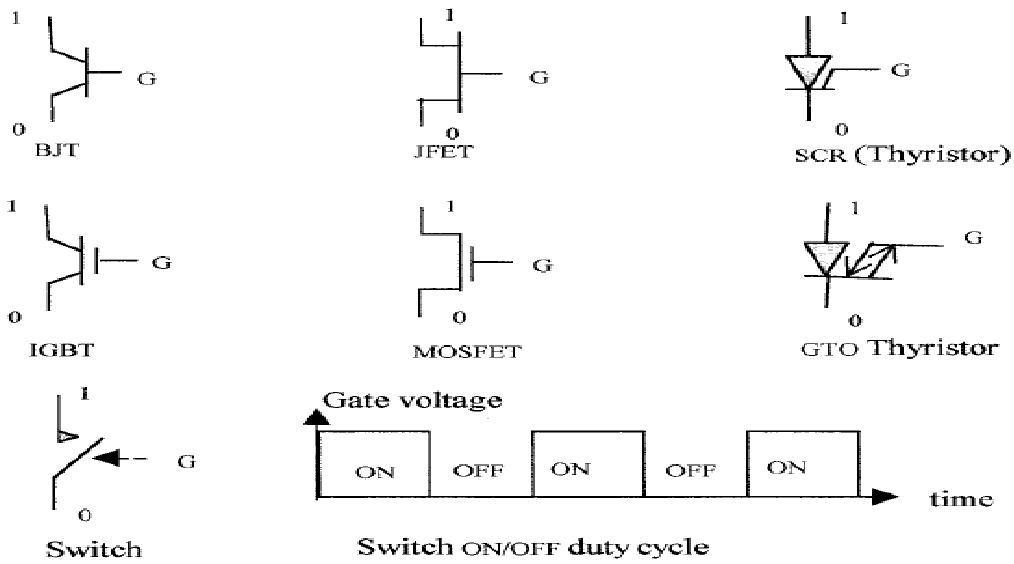

Figure [5.3]: Power Electronics Devices

5.3 AC to DC Rectifier

The circuit diagram of the three-phase AC to DC rectifier showed. The power switch usually used in the rectifier is the silicon controlled rectifier. In WECS rectifier is direct joined or connected with generator. The average DC output voltage of this circuit is given by the following:

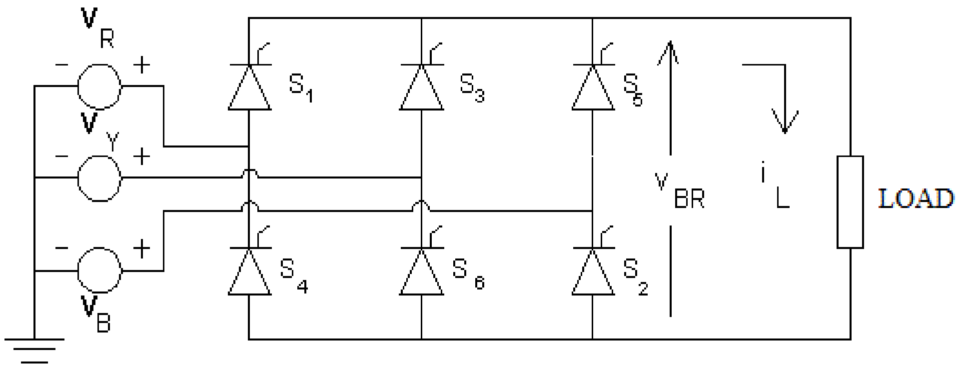

Figure [5.4]: Three-Phase Full Bridge AC to DC

$$V_{DC}=3\left(\frac{3\sqrt{2}}{\pi}\right)*VL*cos\alpha$$

Where,

VL= line-to-line voltage on three-phase AC side of the rectifier

α= angle of firing delay in the switching.

5.4 Boost Converter

DC-DC Converter is a device that accepts a DC input voltage and generates a desired DC output voltage. The output obtained is at a different voltage level than the input. There are three types of DC-DC converters that are a buck, boost, and buck-boost Converter and here in this Boost converter is used to step up the output. Also, DC-DC converters are used to provide noise isolation and power bus regulation.

In general, the transformer is used to step up the voltage, but there are some losses in the transformer. To overcome these problems DC-DC converter is used to get the desired output. It consists of an inductor, capacitor diode, and an IGBT as a high-frequency switch. Due to this type of arrangement power supply to the load at a greater voltage. According to the duty cycle of the switch the output voltage change.

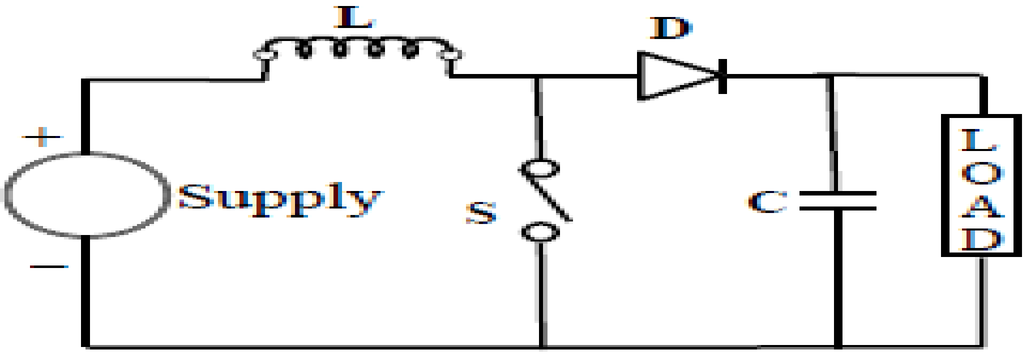

Figure [5.5]: Circuit Diagram of Boost Converter

5.4.1 Modes of Operation

There are two operating modes for the DC-DC converter, and the mode of operation depends on the short-circuiting and opening of the high-frequency switch. When the switch is closed, the inductor will charge. This is mode-1 operation and is known as a charging mode similarly, in the second mode, the switch is open and the inductor start discharging which is known as the discharging mode.

5.4.1.1 First Mode Operation

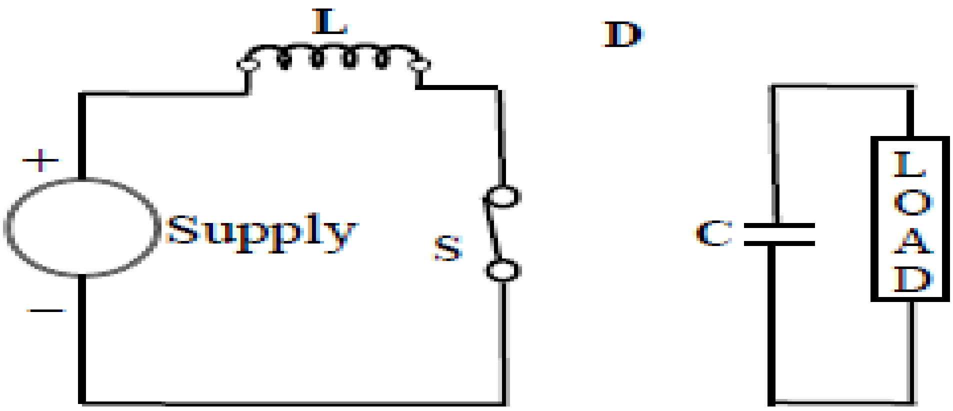

Figure [5.6]: First Mode of Operation of Boost Converter

In the first mode, the IGBT is closed and the inductor starts charging due to the supply trough the switch. The diode used in this circuit to restricts the current flow to the load and the output voltage rises by the discharging of the capacitor.

5.4.1.2 Second Mode Operation

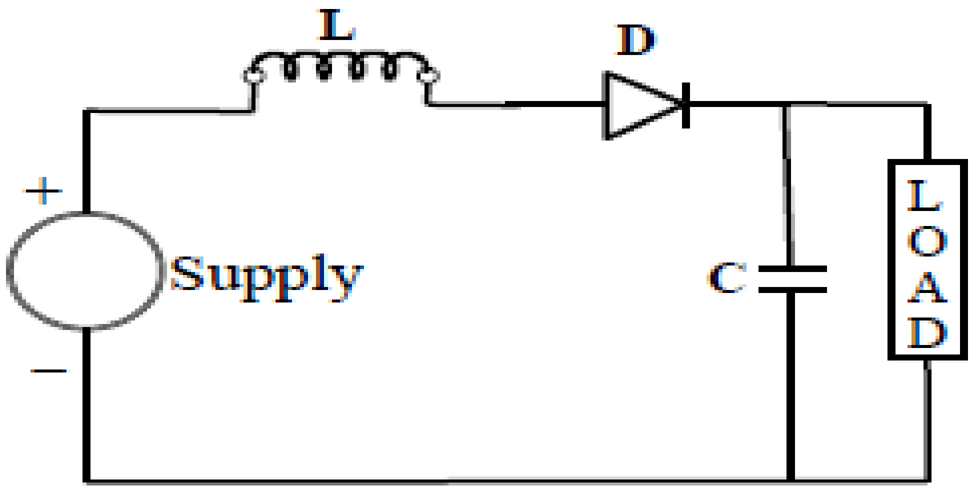

Figure [5.7]: Second Mode of Operation

In the second method of operation, the IGBT is utilized as a high-frequency switch is open so the diode turns out to be short circuits. From the first method, there is some energy kept in the inductor now that is discharged via the capacitor. The load current variation is assumed constant throughout the operation because it is very small in many cases.

5.4.2 Waveforms

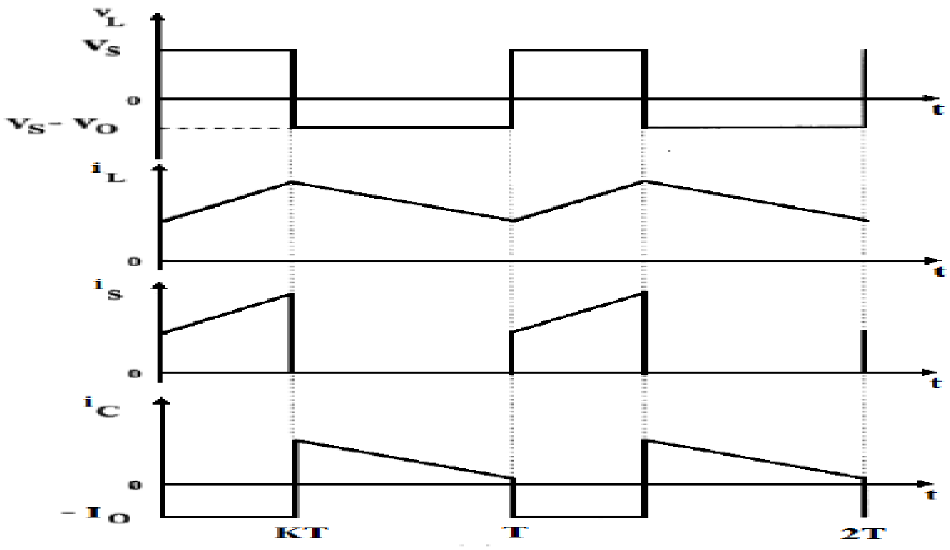

Figure [5.8]: Waveform of Boost Converter

5.5 Multi-Level Inverter

MLI have attracted many utilities and power industries because of their use and advantages. It is well suited for reactive power compensation. It can work with high voltage and high power application with the use of IGBTs. It produce voltage waveform in shape of staircase. Level of voltage is dependent on the number of DC voltage sources are used. Harmonic content present in the voltage waveform decreases with the increase in DC voltage sources [39]. The upcoming topologies of MLI must have these things which are given below:

a) Less switching devices as much as possible.
b) Lower switching frequency.
c) Capable to withstand with very high power and voltage application.

5.5.1 Types of MLI

1) Diode-clamped MLI (DCMLI)
2) Flying-capacitor MLI (FCMLI)
3) Cascade MLI (CMLI)

5.5.1.1 Diode-clamped MLI (DCMLI) - In 1981 neutral point DCMLI is proposed by Nabae, Takahashi and Akagi. It was a three level inverter. Then in 1990s, four, five and six-level DCMLI have been proposed by many researchers. From past some decades, they have been used for connection of high voltage system, reactive power compensation, controlling of frequency and variable speed motor drives. The name of this MLI is given as DCMLI because diode is used to clamping the voltage [36]. Three level DCMLI is shown below:

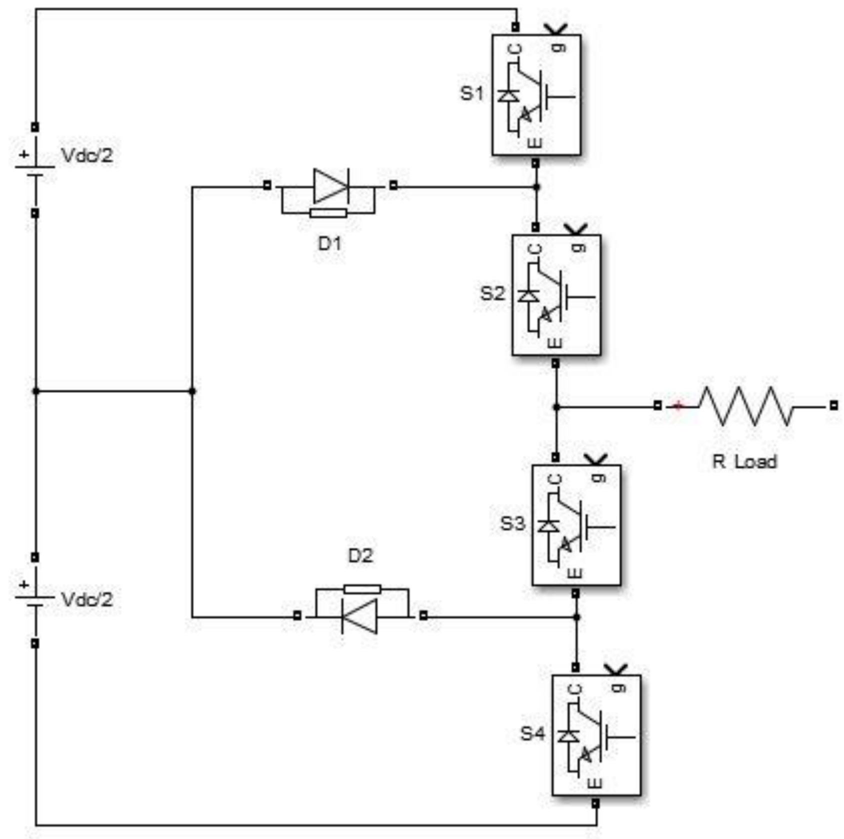

Fig. [5.9]: Single leg 3-Level DCMLI connected with R load.

An m-level DCMLI has (m-1) DC voltage sources on DC bus, (m-1) (m-2) clamping diodes and 2(m-1) switching devices. Above figure is of three-level DCMLI which has two DC sources having capacity of $V_{dc}/2$. At any particular time, two switches will be on [36].

Advantages:

1) Harmonic content is decreased with the increase in voltage level which reduces the need of filters.
2) All IGBTs switched on at fundamental frequency due to this efficiency of inverter is increased.
3) Simple controlling method.
4) Since DCMLI has common DC link due to this, it reduces the capacitance requirements.
5) Before using capacitor can be charged and then use.

Disadvantages:

1) Requirement of clamping diode is higher when number of level is increases.
2) Control of real power is difficult for a single inverter because without monitoring and control DC level gets discharge and overcharge.

5.5.1.2 Flying-capacitor MLI (FCMLI) – In 1992 flying capacitor based MLI is proposed by Foch and Meynard. Design structure of FCMLI is same as the DCMLI but it uses capacitor instead of diode. DC side capacitors are arranged in ladder structure in this topology with different voltages as sown in fig.4.2. Level of the voltage is dependent upon the number of capacitors used. One increment in level is determined by the voltage increment in two adjacent capacitors. One main advantages of this MLI that for inner voltage level it has redundancies. It means there may be another combination of switches and capacitors for getting the same level of output voltage [37-39]. FCMLI has more redundancies in comparison to the DCMLI. These redundancies helps to reduce the overcharging and discharging of particular capacitor. Because of this it helps to maintain appropriate voltage level across capacitors and further gives the quality to control real power. An m-level FCMLI needs (m-1)*(m-2)/2 dc link capacitors per phase [36].

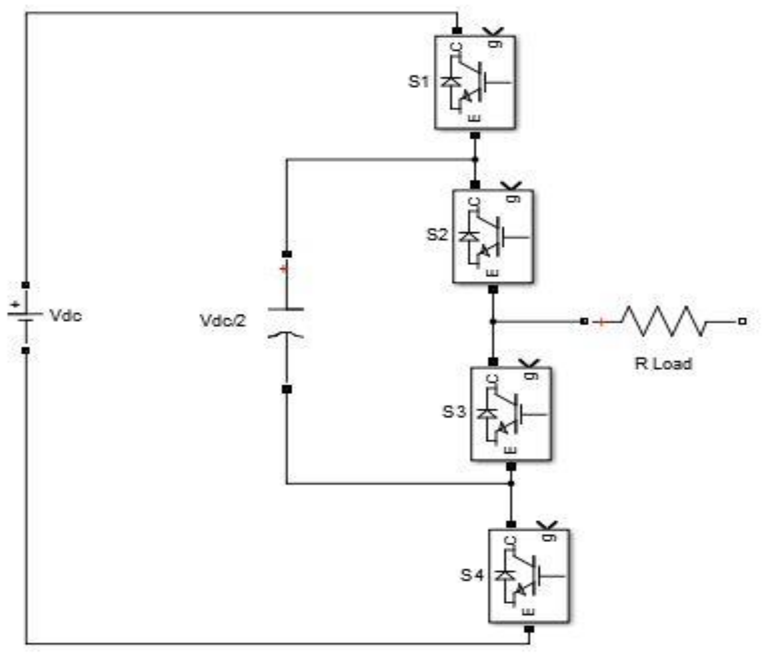

Fig. [5.10]: Single leg 3-Level FCMLI connected with R load

Advantages:

1) Voltage levels across each capacitors is maintained due to phase redundancies.
2) Controlling of active and reactive power is possible.
3) FCMLI gives capabilities to inverter, to ride through voltage sag and outages of short duration due to large number of capacitors.
4) Like DCMLI it helps to reduce the need of filters to increase the level of output voltages.

Disadvantages:

1) Requirement of capacitors are increased with the increase in level of output voltages.
2) For high power applications, switching frequency and losses will be high.
3) Controlling of inverters becomes complex.
4) Due to large number of capacitors FCMLI is more expensive and bulky in comparison to DCMLI.

5.5.1.3 Cascade MLI – Cascade MLI contains single phase full bridge inverter which is also known as H-bridge inverter. Single H-bridge has only three-level of output voltage from peak to peak. Number of H-bridge increase with the increase in level of output voltage and they are connected in series. Every H-bridge contains one separate DC sources (SDCS) which can be taken from fuel cell, solar cell or batteries [36]. The ac terminal of each H-bridge is connected in series. Cascade H-bridge does not require any clamping diodes for clamping or capacitors for voltage balancing. An m-level of cascade MLI is shown below, which has (m-1) SDCS and H-bridge. It also can be used for reactive power compensation [37-39].

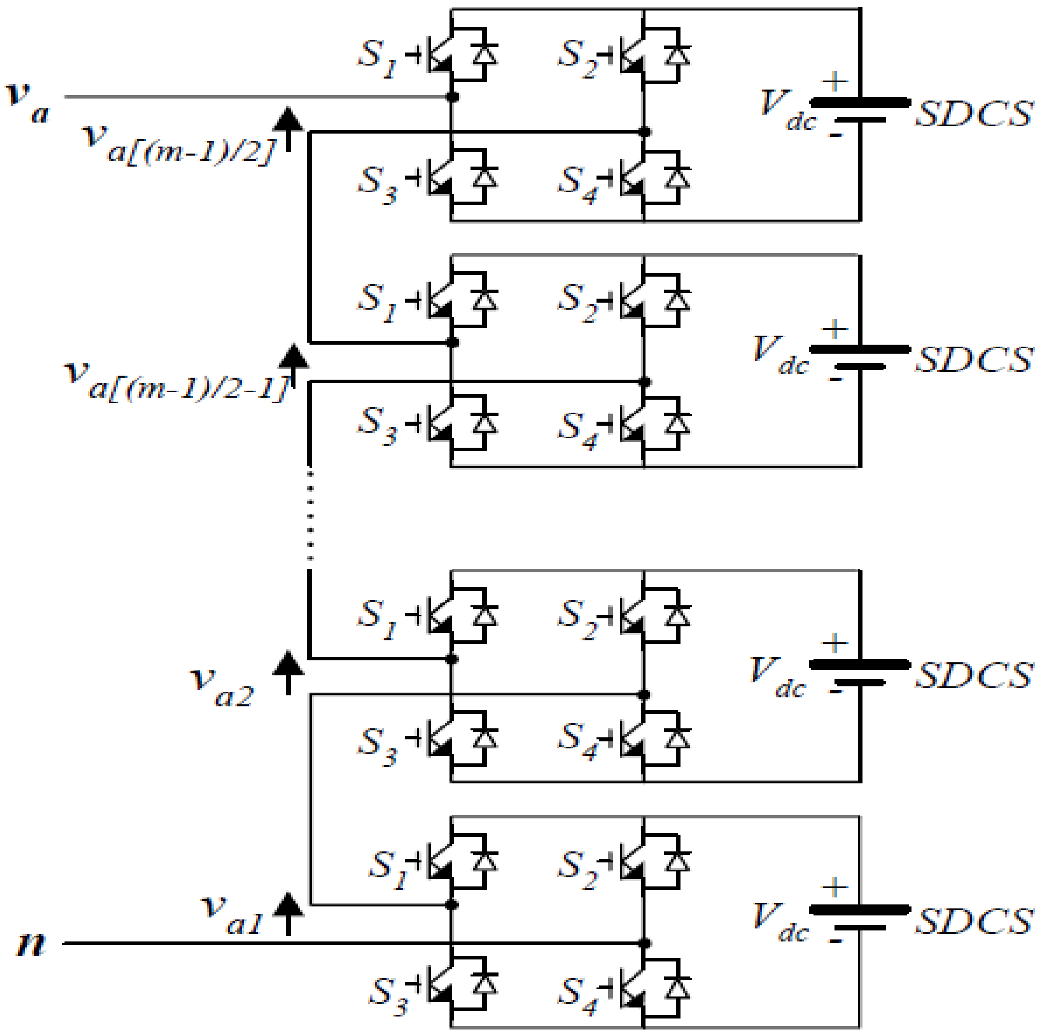

Fig. [5.11]: M-level cascade MLI

Advantages:

1) Level of output voltage is twice the number of SDCS ($m=2N_s+1$, where N_s is the number of bridges).
2) It is cheaply and less complex in comparison to DCMLI and FCMLI.
3) To reduce the switching losses and stresses on device, soft switching can be done.

Disadvantages:

1) For active power conversion, SDCS is required.

5.6 Grid Connection of PMSG

For connection of PMSG with grid has four topologies [31]. First one is back to back converter topology which is studied commonly, shown in Fig. 5.12. In this topology rectifier is connected at generator side and inverter is connected at grid side, both are controlled. DC link between the inverter and rectifier helps to stabilise the DC voltage.

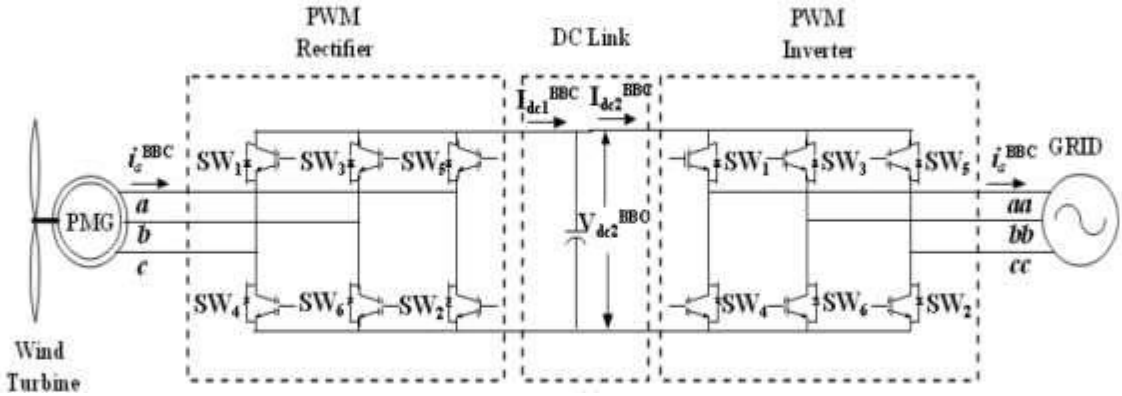

Figure [5.12]: Back to Back Converter

Second topology with uncontrolled rectifier is shown in Fig.5.13. Using a buck-boost converter and three phase inverter.

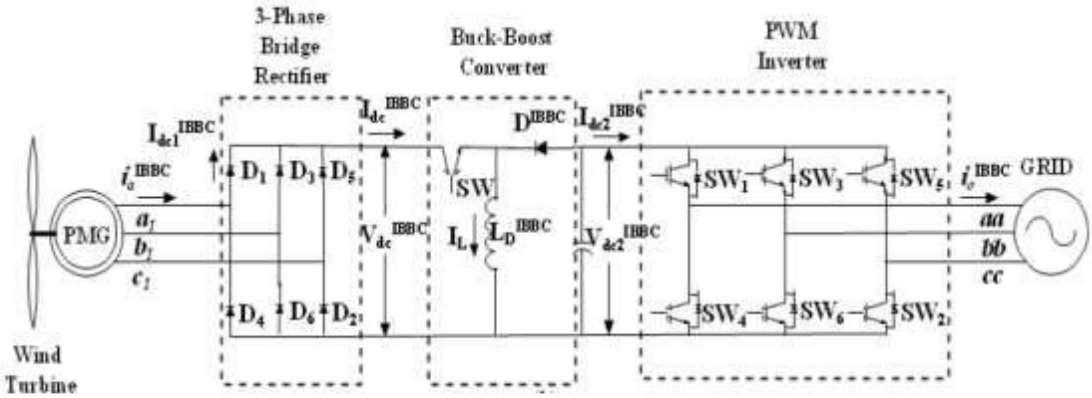

Figure [5.13]: Intermediate Buck-Boost Converter

Third topology with uncontrolled rectifier is shown in Fig.5.14. Using a Boost converter and three phase controlled inverter. In second and third topology has only difference in DC-DC converter.

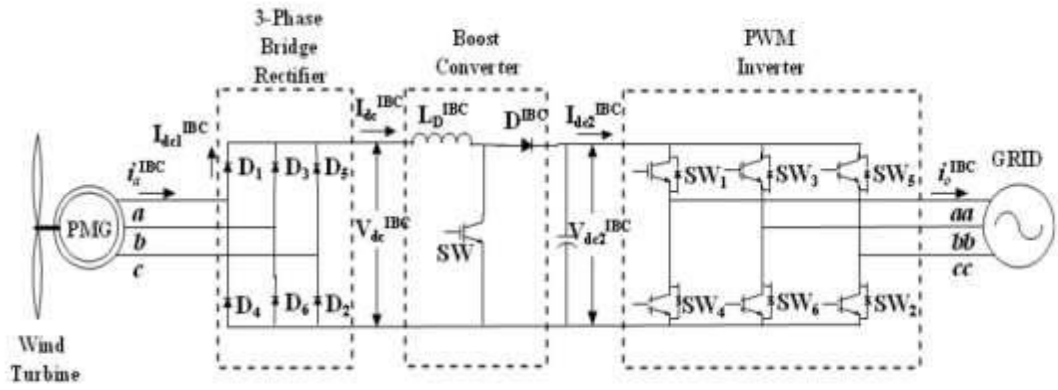

Figure [5.14]: Intermediate Boost Converter

Fourth topology is using bi-directional matrix converter that convert direct AC-AC, which is shown in Fig 5.15.

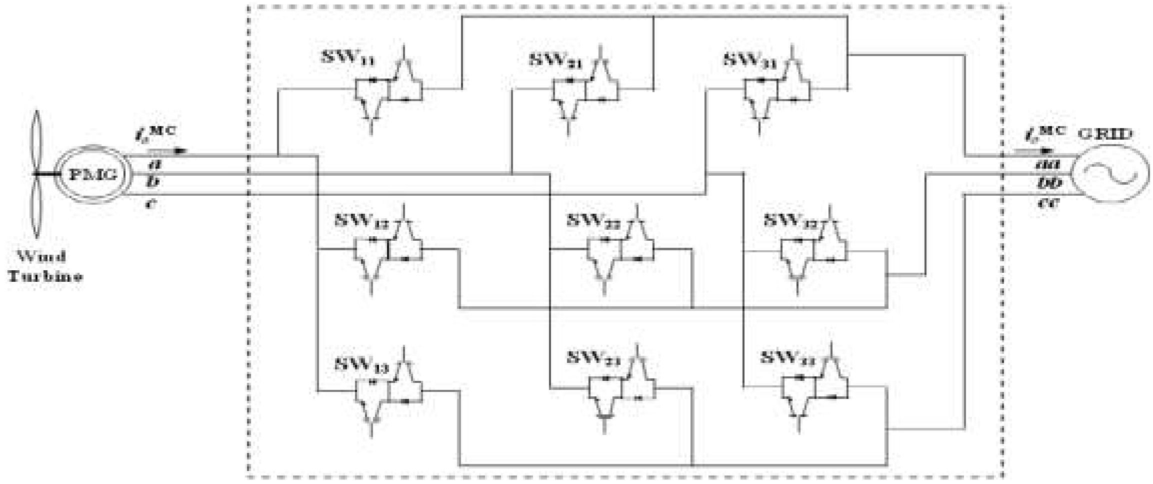

Figure [5.15]: Matrix Converter

CHAPTER-6

PROPOSED MAXIMUM POWER POINT TRACKING AND CONTROL STRATEGY

Mostly maximum power point tracking system is used in PV system. It is uses in WIND for tracking the wind. In this thesis back to back converter topology is used. As discussed in chapter 4, the back to back converter topology has uncontrolled rectifier, DC-DC converter and inverter (DC-DC to converter) has high reliability. Using intermediate boost converter topology is possible to introduce the Incremental Conductance algorithm in WECS.

6.1 Incremental conductance technique

The perturb and observe method has limitation to track the peak power under fast varying wind speed condition. This problem is overcome by Incremental Conductance (IC) technique [32, 33]. The IC method stops perturbation at operating point when MPPT has reached the Maximum Power Point. Perturbation can be calculated using dl/dV and –I/V when above condition is not fulfilled [21]. This relationship is came from the fact that, when MPPT will be right to the MPP then dP/dV will be negative conversely it will be positive when MPPT will be left to the MPP. The IC technique has benefits over P&O because it has disadvantage that, it oscillates across MPP. Also, the variation in wind speed can be tracked quickly by IC with higher accuracy than P&O but it increases the complexity as compare to P&O [32, 34].

$$P=V*I$$

Differentiating with respect to voltage gives;

$$\frac{\mathrm{dP}}{\mathrm{dV}} = \frac{\mathrm{d(V*I)}}{\mathrm{dV}}$$

$$\frac{\mathrm{dP}}{\mathrm{dV}} = \mathrm{I} + \mathrm{V} * \left(\frac{\mathrm{dV}}{\mathrm{dV}}\right)$$

$$\frac{\mathrm{dP}}{\mathrm{dV}} = \mathrm{I} * \left(\frac{\mathrm{dV}}{\mathrm{dV}}\right) + \mathrm{V} * \left(\frac{\mathrm{dI}}{\mathrm{dV}}\right)$$

If $\frac{dP}{dV} = 0$, maximum power point is reached

If $\frac{dP}{dV} > 0$, maximum power is left side of the point

If $\frac{dP}{dV} < 0$, maximum power is right side of the point

If $\frac{dP}{dV} \neq 0$, maximum power point is not reached suitable control action will be taken

$$I+V*\left(\frac{dI}{dV}\right) = 0$$

$$\left(\frac{dI}{dV}\right) = -\frac{I}{V}$$

From above equation $\frac{I}{V}$ shows the instantaneous conductance. $\frac{dI}{dV}$ is the change in instantaneous conductance. Since duty ratio defines ON and OFF of switch therefore, conductance of the circuit changes with the change of duty ratio of dc-dc boost converter. Optimal duty ratio is obtained, when negative instantaneous conductance will be equal to change in instantaneous conductance and at that instant power is maximum extracted from wind. Duty ratio is increased or decreased depends upon the change in sign of $\frac{dP}{dV}$. Kept duty ratio constant at constant wind speed.

6.2 Flowchart of Incremental Conductance Method

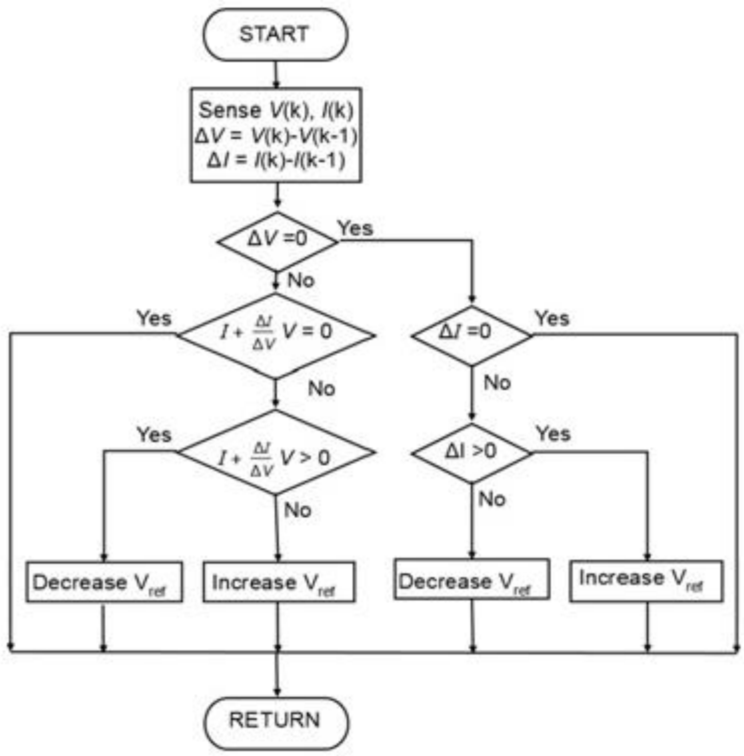

Figure [6.1]: Flowchart of the Incremental conductance algorithm

Decision making procedure in Incremental Conductance algorithm shown in above flowchart. First, voltage and current is measured V(k) and I(k), and dV(k) and dI(k) means it compares voltage and current instant with previous instant. After that checking whether to change in voltage ($\Delta V=0$) is zero or not.

2) If change in voltage is zero then it will check whether the change in current is zero ($\Delta I=0$).

- If change in current is zero so that power is maximum, there is no need of changing the pulse width modulation because maximum power point is attained.
- If change in current is already happens than check change in current ($\Delta I>0$) is greater than zero or not:
- If yes, then duty ratio increase and if no, then duty ratio decrease.

3) If no, change in voltage then check whether the $\frac{dI}{dV} = -\frac{I}{V}$ or not.

- If yes, then there is no need of changing the pulse width modulation because maximum power point is attained.
- If no, then check $\frac{dI}{dV} > -\frac{I}{V}$. If it is not satisfying the instantaneous conductance then decrease the duty ratio and if it satisfying then increase in duty ratio.

6.3 Seven-level Inverter

Flying capacitor seven level inverter topology has been shown in Fig 6.2. Proposed configuration consists H-bridge with three level flying capacitor branches. Voltage source inverter in all three phases has been used with capacitive energy storage devices. For each phase 8 switches are used. At a common coupling, two H-bridge inverters are connected by using tapped reactor. Typically this reactor is centre tapped, making the output line-to-ground voltages (*vag* for example) the average of the voltages from each side of the H-bridge. This line to ground voltage has five different level of voltage [35]-[36]. In this method tap of the reactor has been set as 1/3, then it will give seven different voltage. In fig. 6.3 shows the control diagram of seven level inverter.

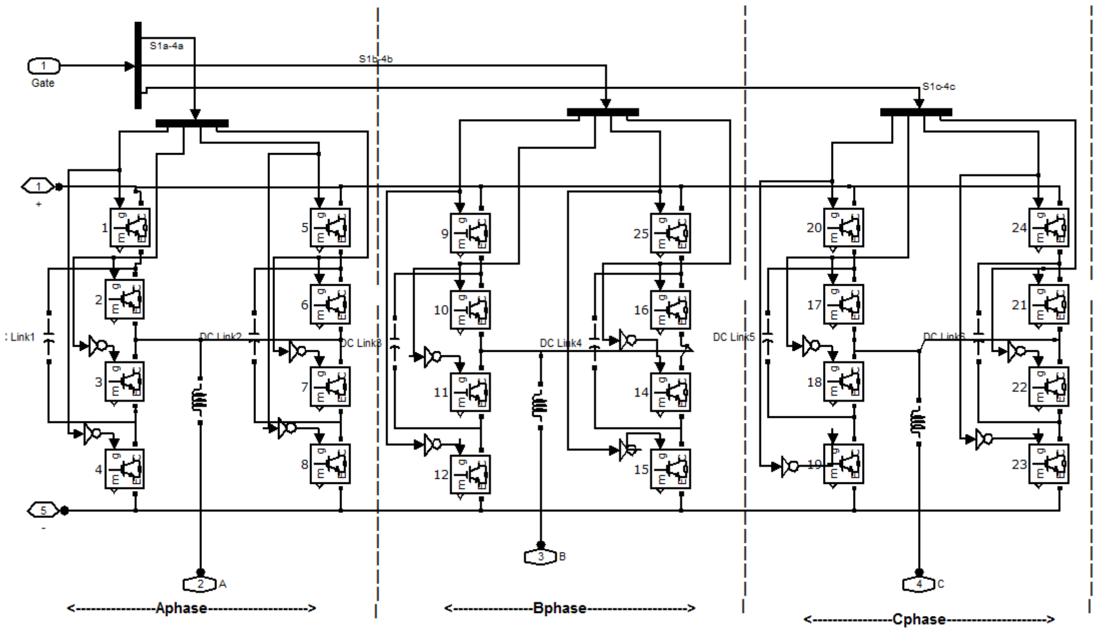

Figure [6.2]: Flying capacitor Seven-level inverter

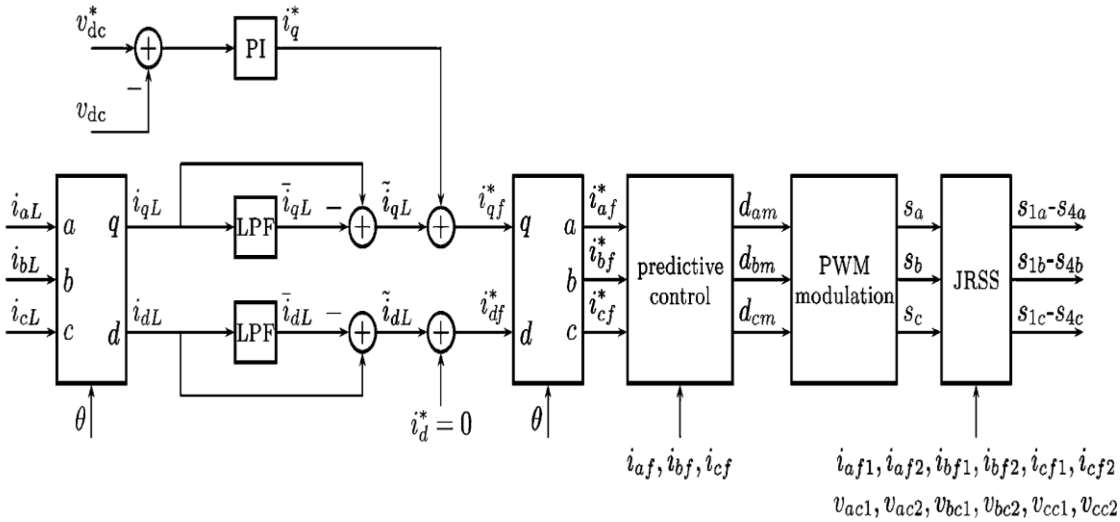

Figure [6.3]: Control diagram of seven level inverter

6.3.1 Multilevel Voltage-Source Modulation

By comparing duty cycle with six carrier wave, modulation of seven level voltage-source can be accomplished. In SVPWM technique AC reference voltage very high in order to compare all the vectors in the PWM technique in this topology six vectors running in SVPWM technique but in that 111 & 000 are considered as maximum & null vectors so we have taken only four carriers.

AC reference voltage to be higher in amplitude in order to compensate each & every vector directly without dependency.

6.3.2 Capacitor Voltage Balancing

TABLE 2: Voltage Balancing of Flying Capacitor

S_{1a}	S_{2a}	V_{a1}	$i_{af\,1}$	Charging
0	0	0	+	0
0	0	0	-	0
1	1	V_{dc}	+	0
1	1	V_{dc}	+	0
0	1	$V_{dc}/2$	+	-
0	1	$V_{dc}/2$	-	+
1	0	$V_{dc}/2$	+	+
1	0	$V_{dc}/2$	-	-

Table 1 shows the switching states relationship. In each leg has four switch, which means four switching states. The polarity of output current is shows by (+) and (-) sign. Charging of capacitor is denoted by + and discharging of battery is denoted by – also 0 shows battery neither charging nor discharging.

6.4 Five Level Inverter

Five level cascaded H-bridge inverter consisting two H-bridge connected in series. It consists eight switches in each phase and in all three phase it consists twenty four switches. It is connected in that proportion, the synthesized output voltage waveform is obtained. The output of two bridge (A- phase) is given by

$$V=V1+V2$$

From this output voltage is comes like that, -2V, V, 0, -V, -2V

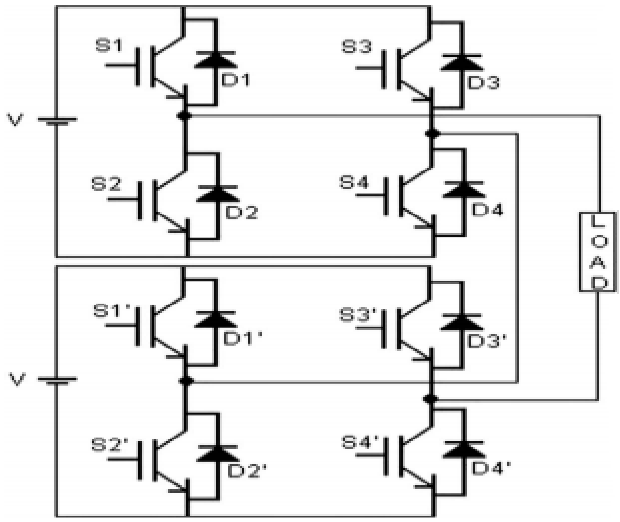

Figure [6.4] Five - Level Inverter

6.4.1 Sinusoidal Pulse Width Modulation

SPWM technique also has several number of pulses per half cycle as MPM but with different pulse width. In SPWM technique, firing pulses are generated by comparing sinusoidal reference signal with high frequency triangular carrier signal. Modulation index (MI) is the ratio of amplitude of reference signal and amplitude of carrier signal. MI can't be more than unity. If MI is less than one then number of pulses per half cycle is increased in comparison to the MI is greater than one [39]. Comparison of reference signal and carrier signal is shown below:

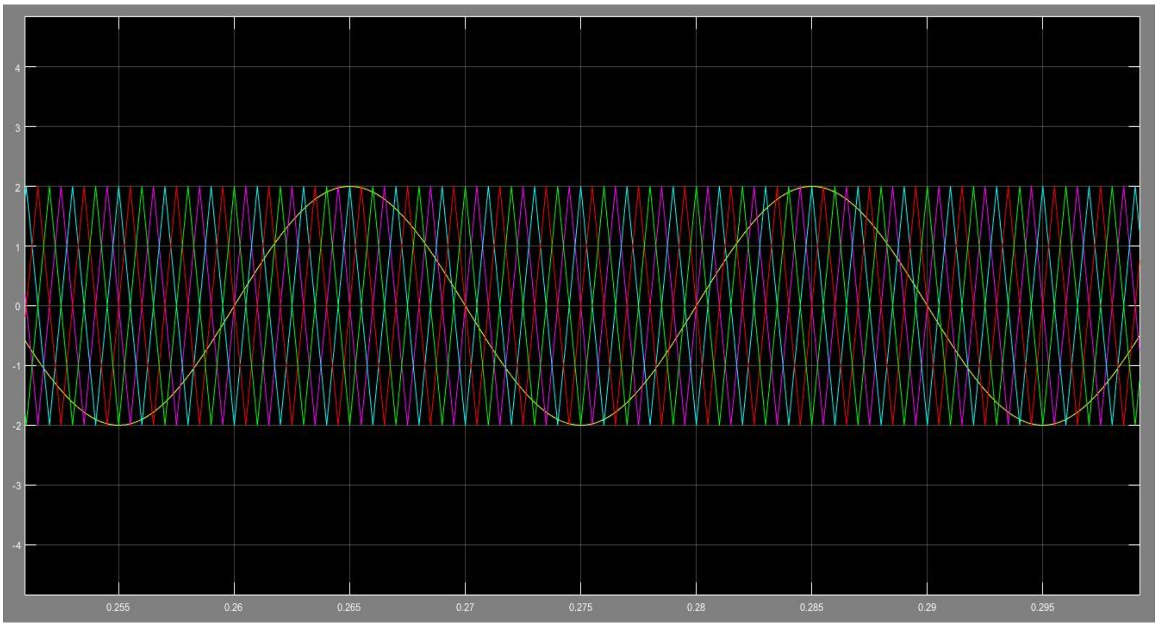

Fig. [6.5]: Comparison of reference signal and carrier signal.

CHAPTER – 7

RESEARCH METHODOLOGY

In this thesis work, Electric power has been generated from the wind by using wind turbine which is coupled to the generator. Here in this research, Permanent Magnet Synchronous Generator has been used for the production of electricity. Then produced voltage is given to the rectifier where bridge rectifier converts it into smooth DC voltage. To boost up the voltage boost converter is used as the input of the boost converter is DC in nature. The switch of the boost converter is controlled by Maximum Power Point Tracking (MPPT) algorithm. Now boosted voltage is again converted into AC by using a multi-level inverter. Here in this research, grid is integrated with WECS. Across the grid, voltage and current waveform can be analysed. Also, we will analyse total harmonic distortion at the grid side. So paper aim is that to improve power quality of the system in term of reducing total harmonic distortion. Output parameters of the boost converter and MLI can also be observe

CHAPTER 8

SIMULATION AND RESULTS

8.1 Wind turbine model interconnected with the Grid using Permanent Magnet Synchronous Generator and five-level MLI

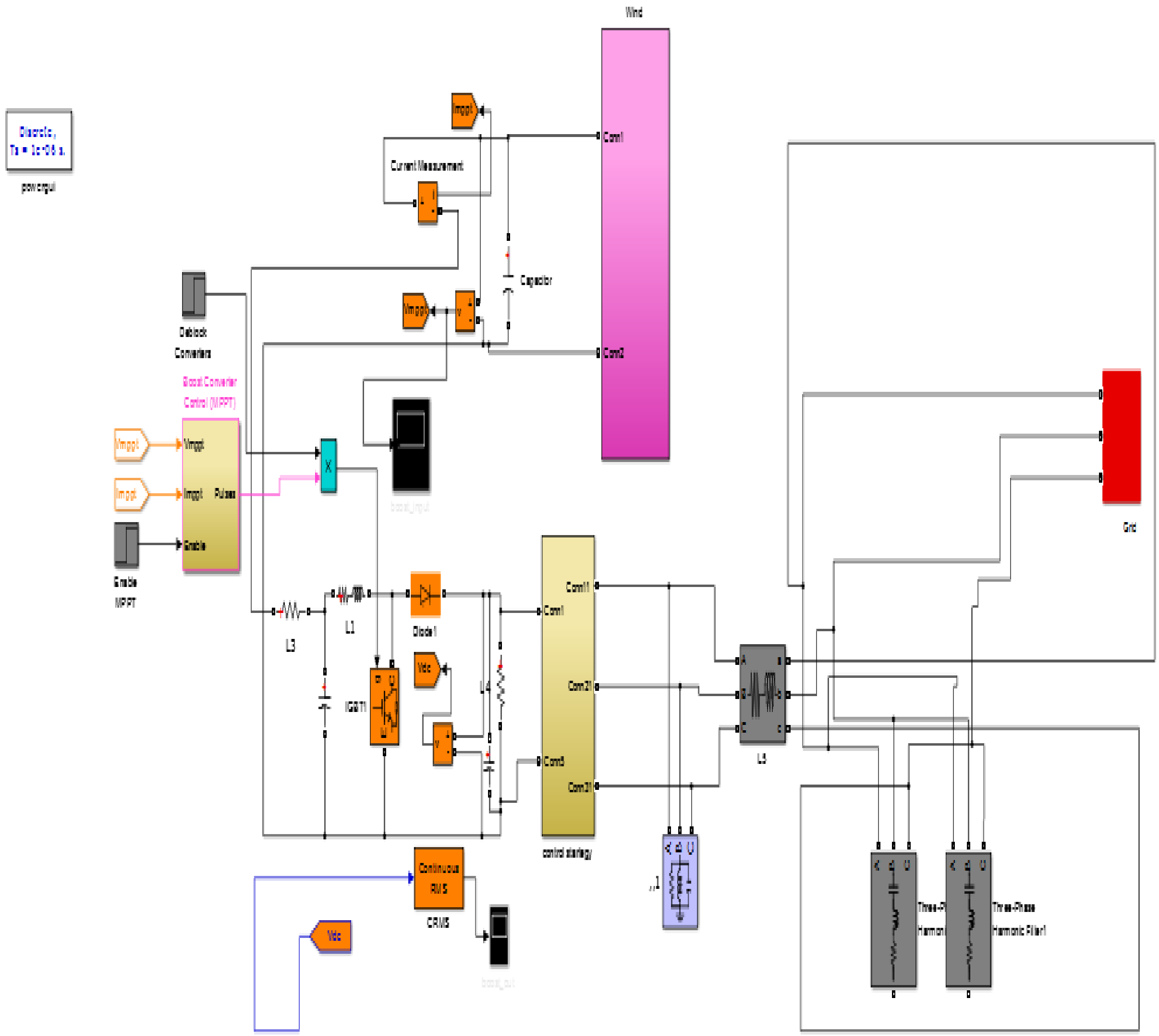

Fig [8.1]: Wind model with interconnected grid

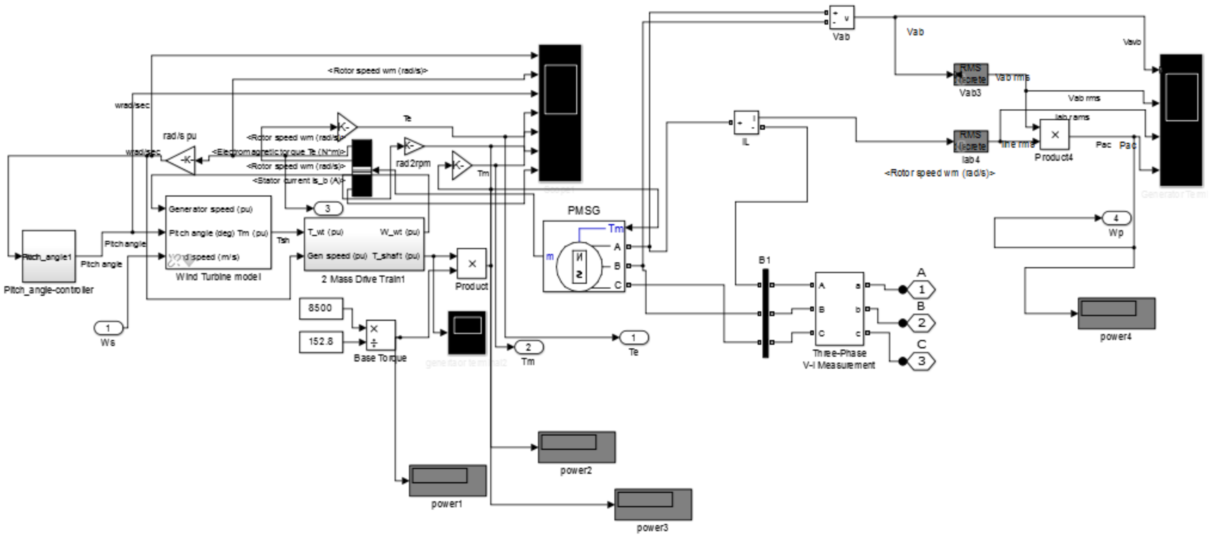

Fig [8.2]: Wind Turbine model interconnected with PMSG

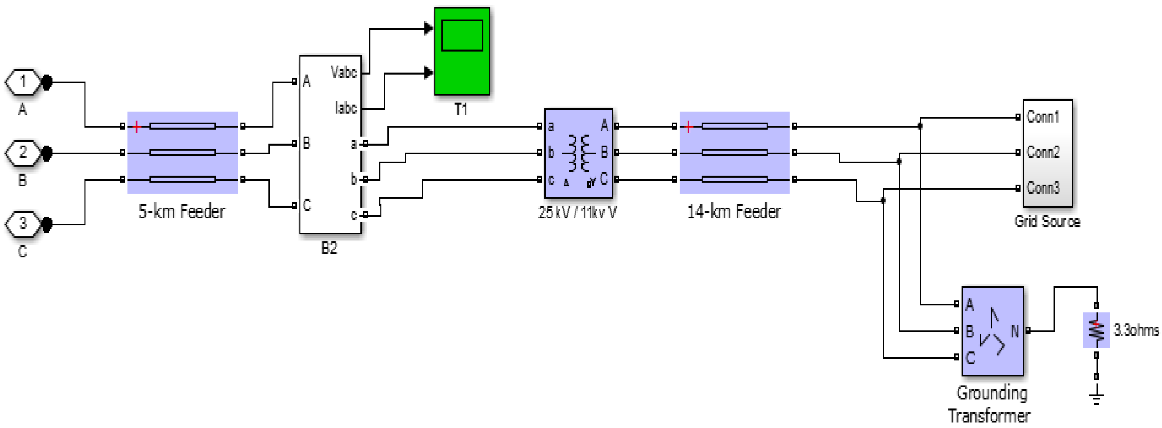

Fig [8.3]: Grid Model

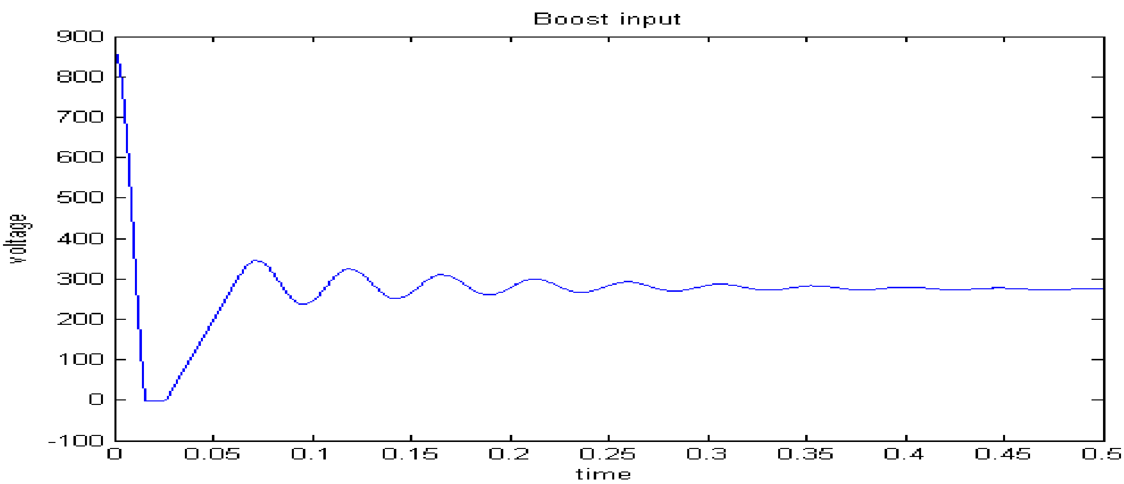

Fig [8.4]: Input voltage of Boost converter

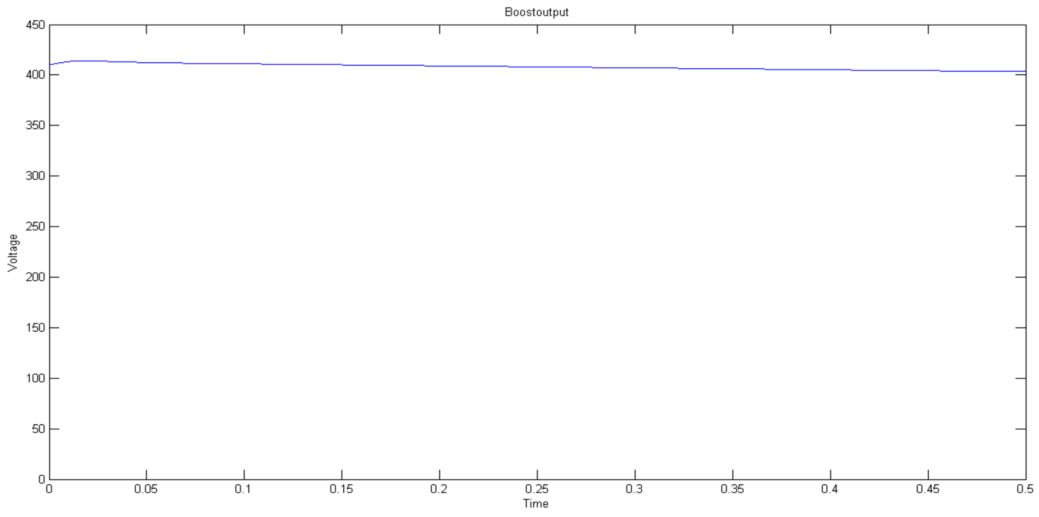

Fig [8.5]: Output voltage of Boost converter

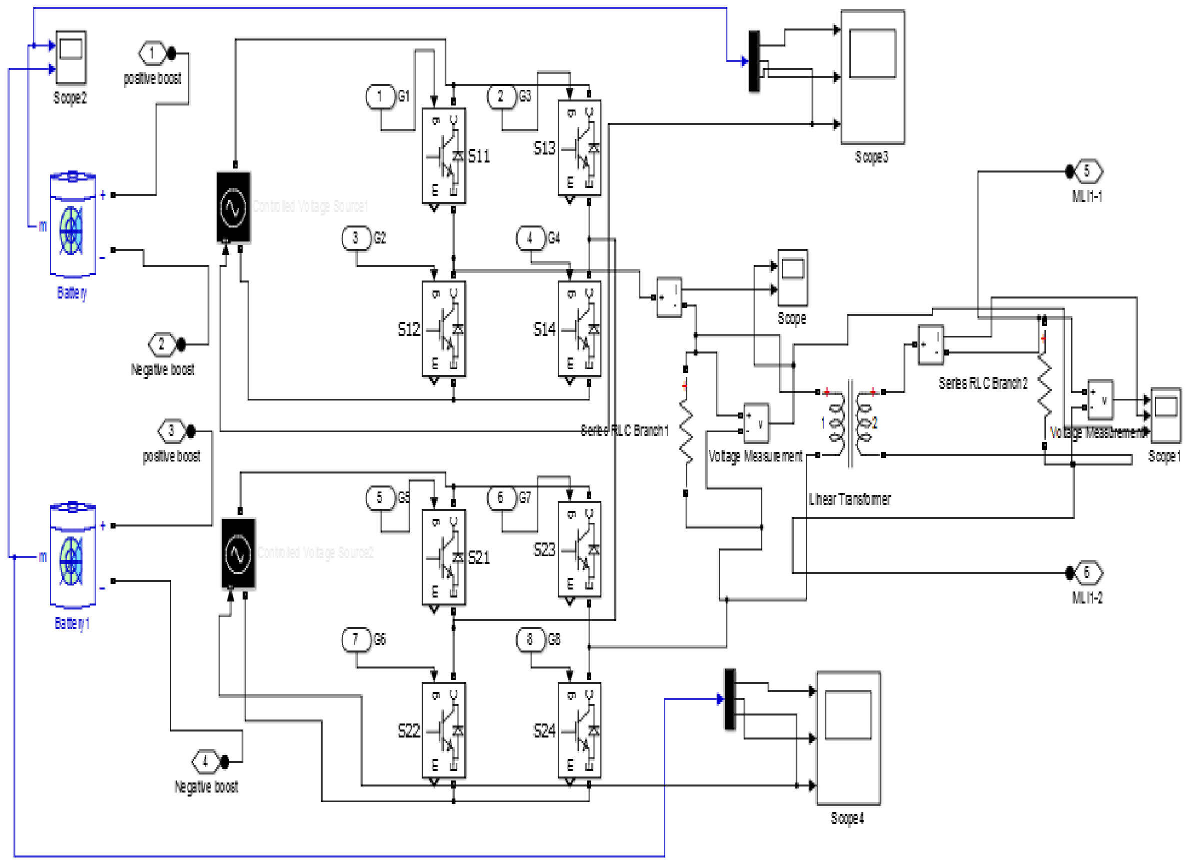

Fig [8.6]: Inverter Model

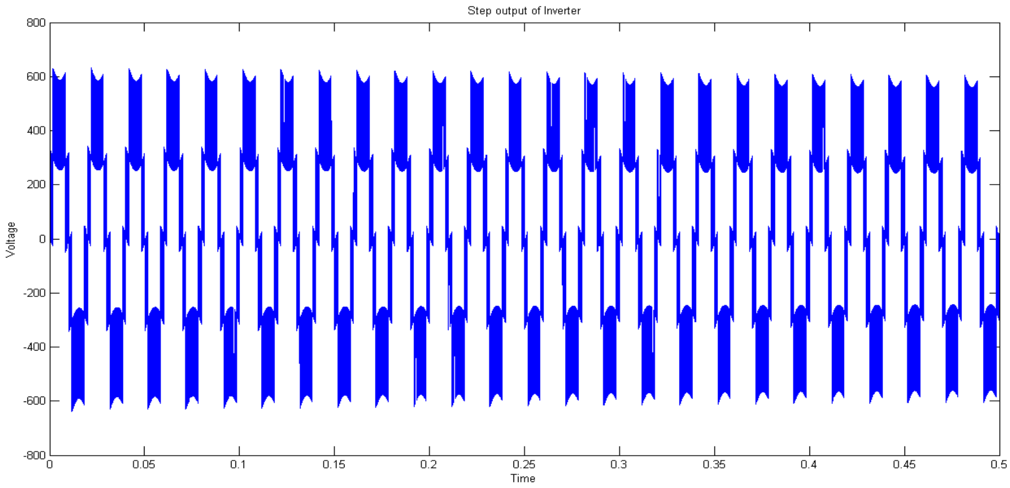

Fig [8.7]: Step output voltage of Five-Level Inverter

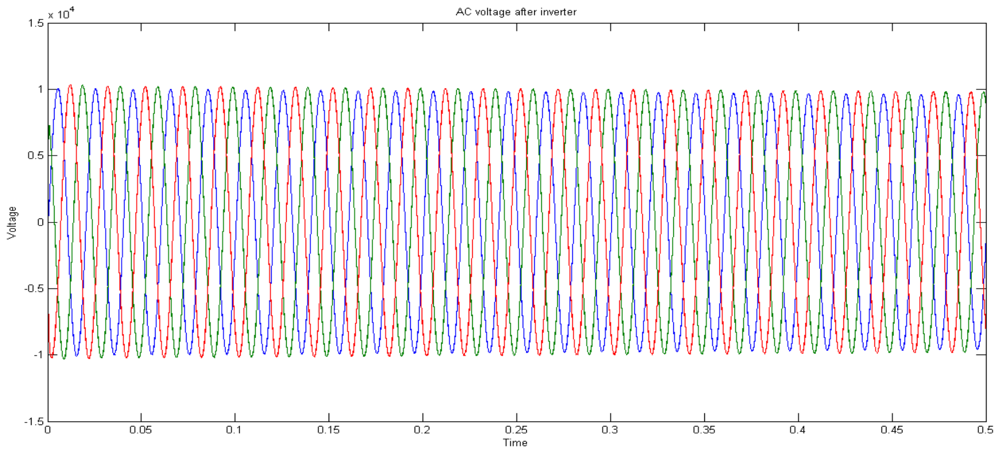

Fig [8.8]: AC voltage after Inverter

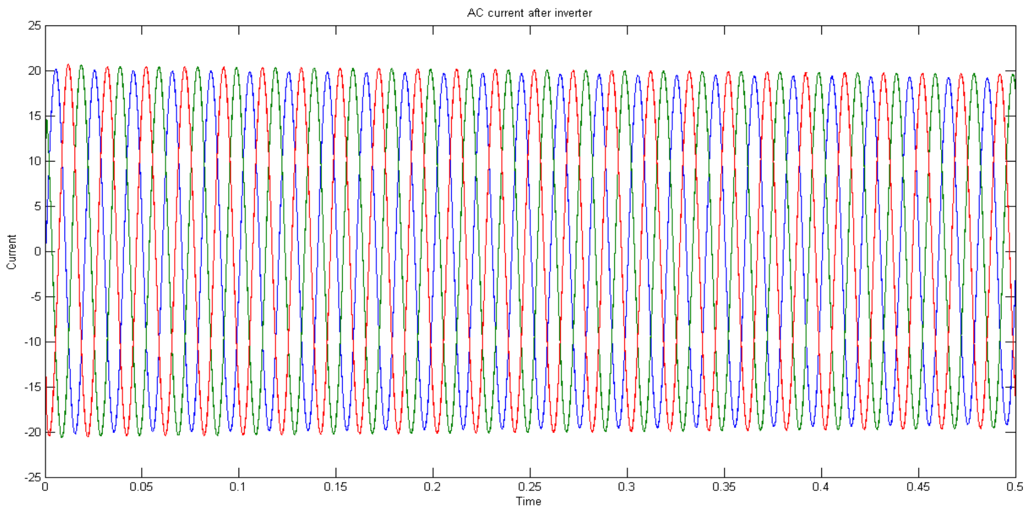

Fig [8.9]: AC current after Inverter

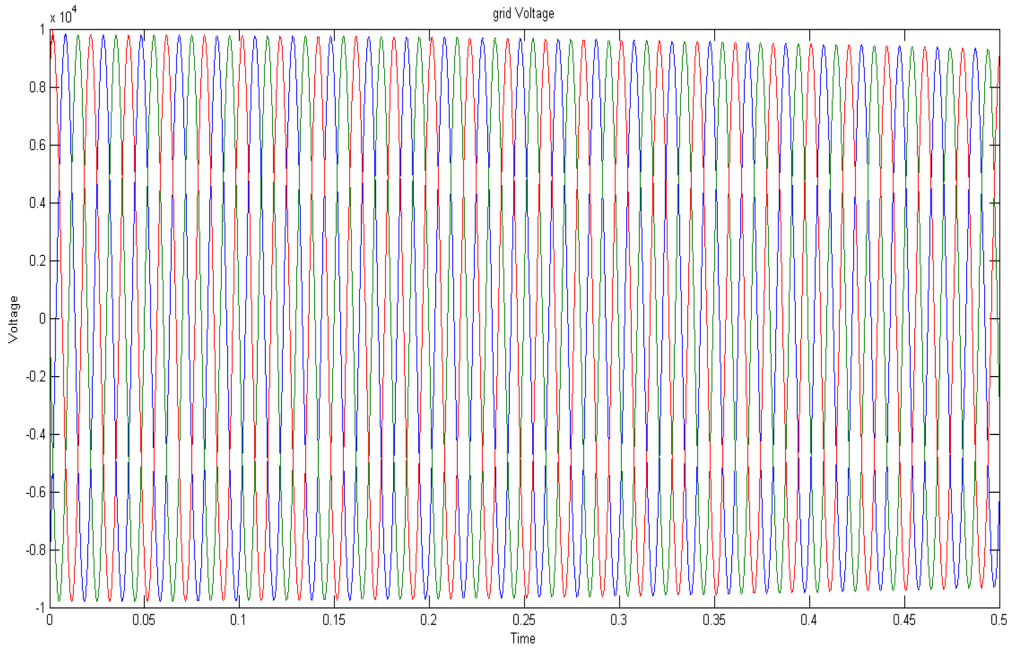

Fig [8.10]: Grid Voltage

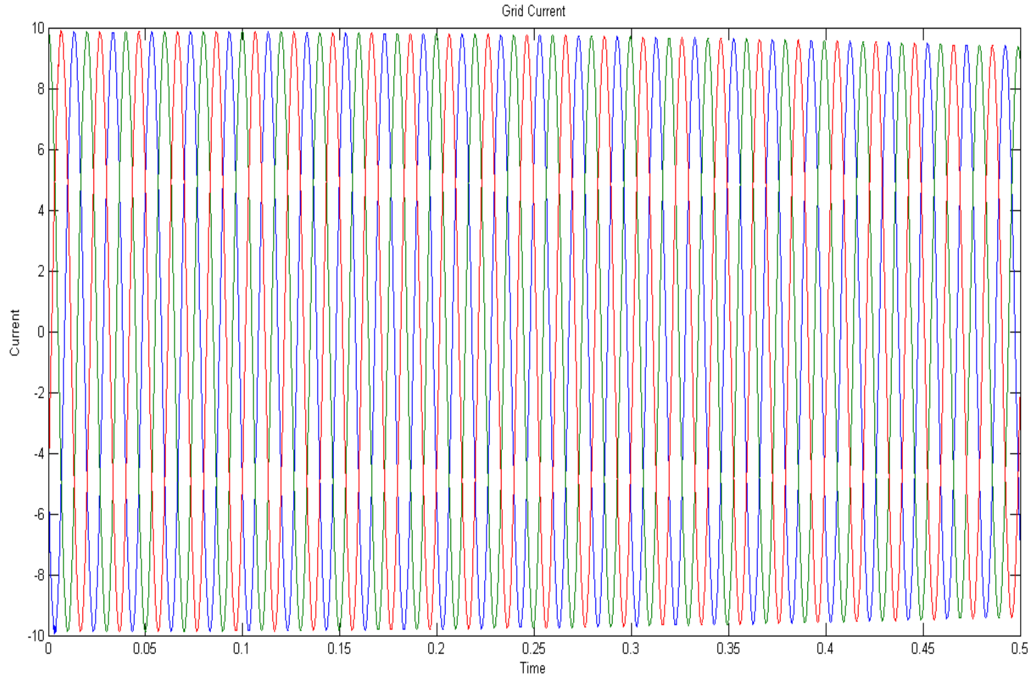

Fig [8.11]: Grid Current

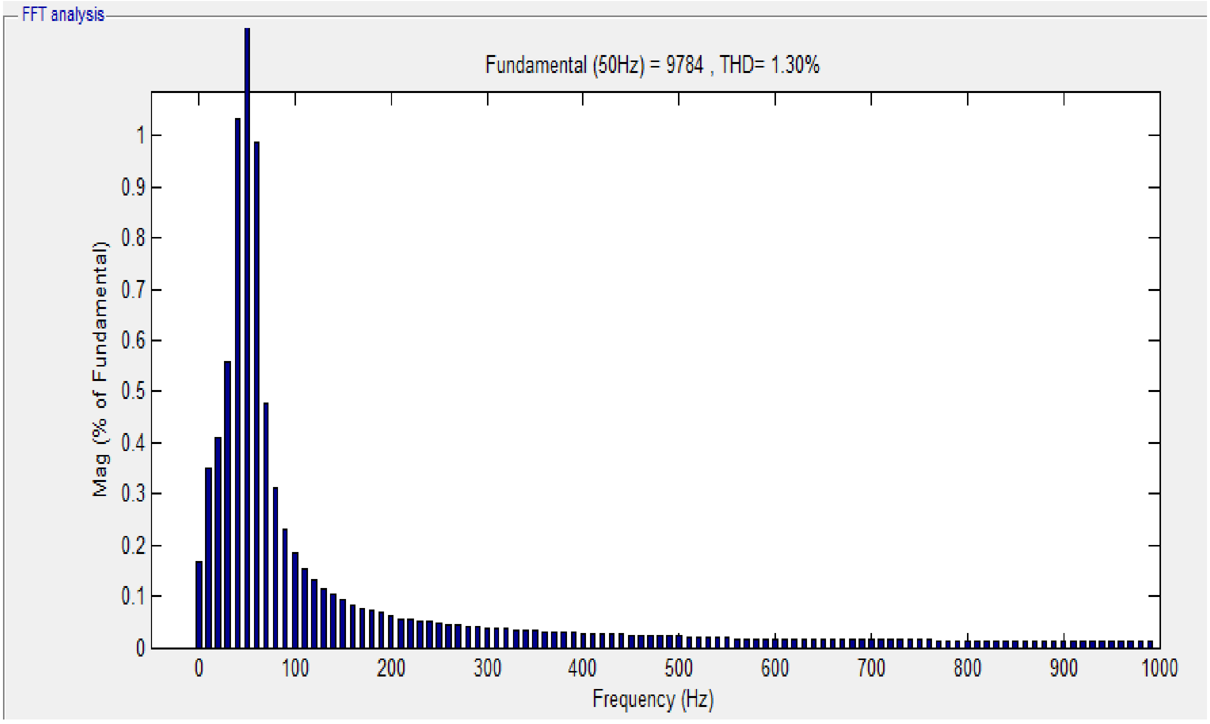

Fig [8.12]: THD on grid Voltage

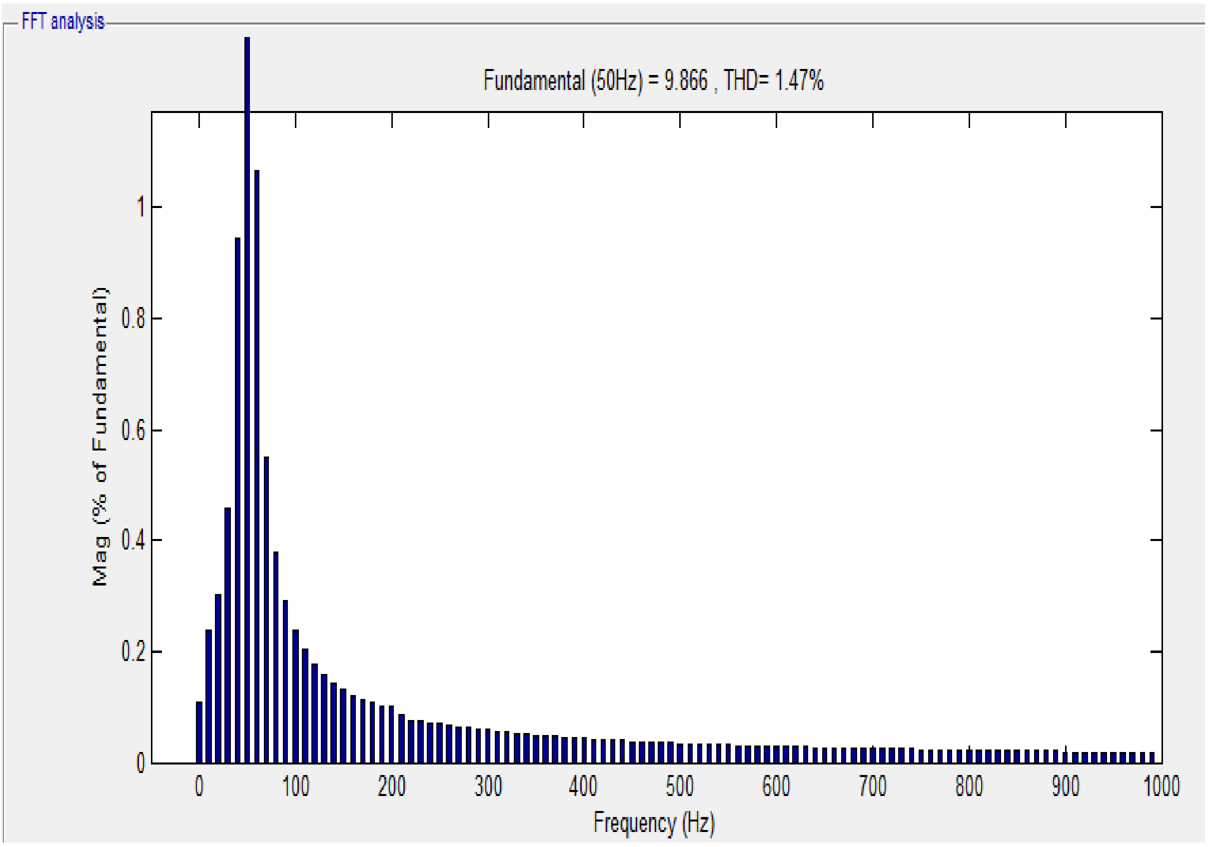

Fig [8.13]: THD on grid current

8.2 Wind turbine model interconnected with the Grid using Permanent Magnet Synchronous Generator, seven-level MLI and using battery

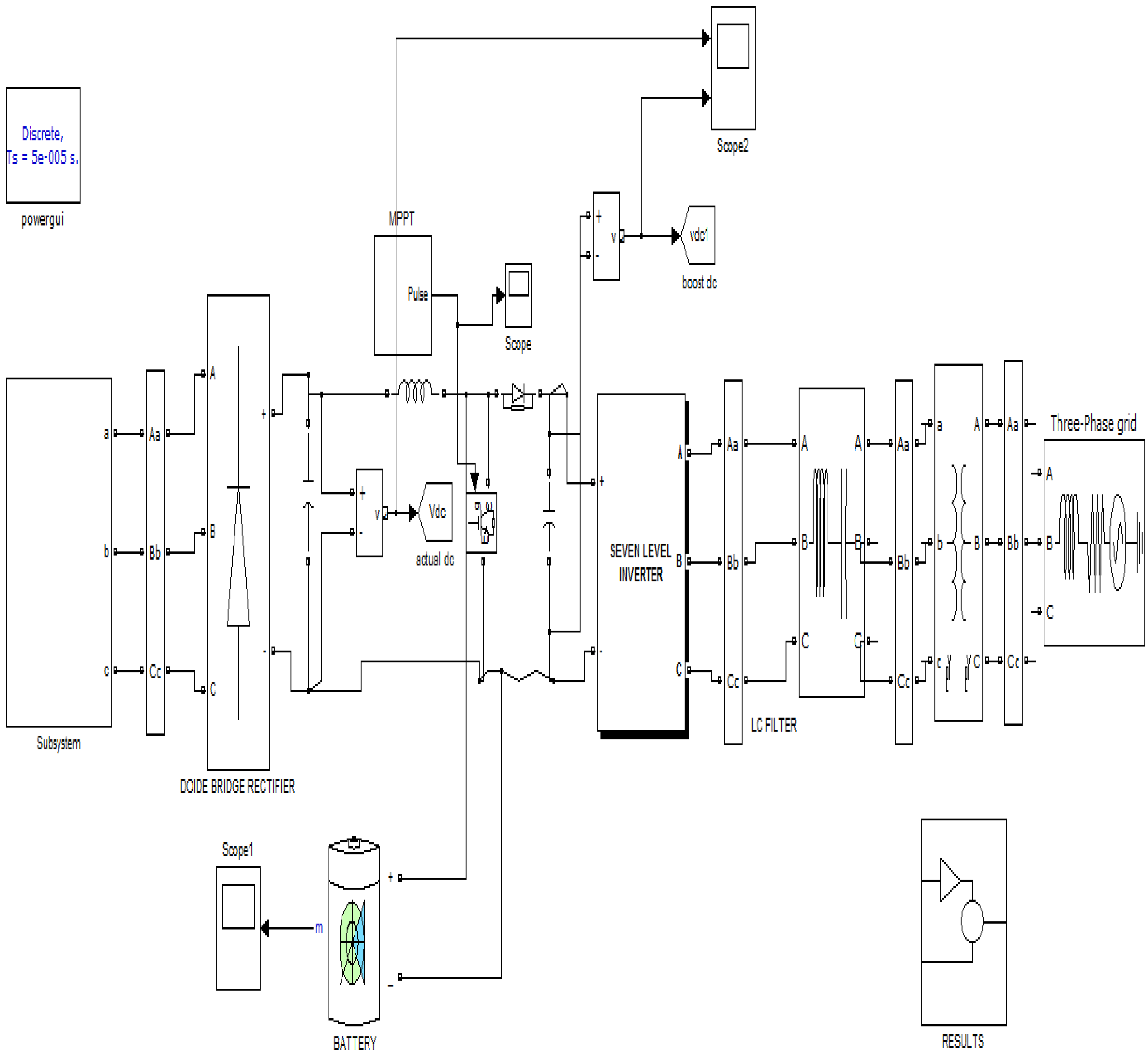

Fig [8.14]: WECS model using Seven-Level inverter

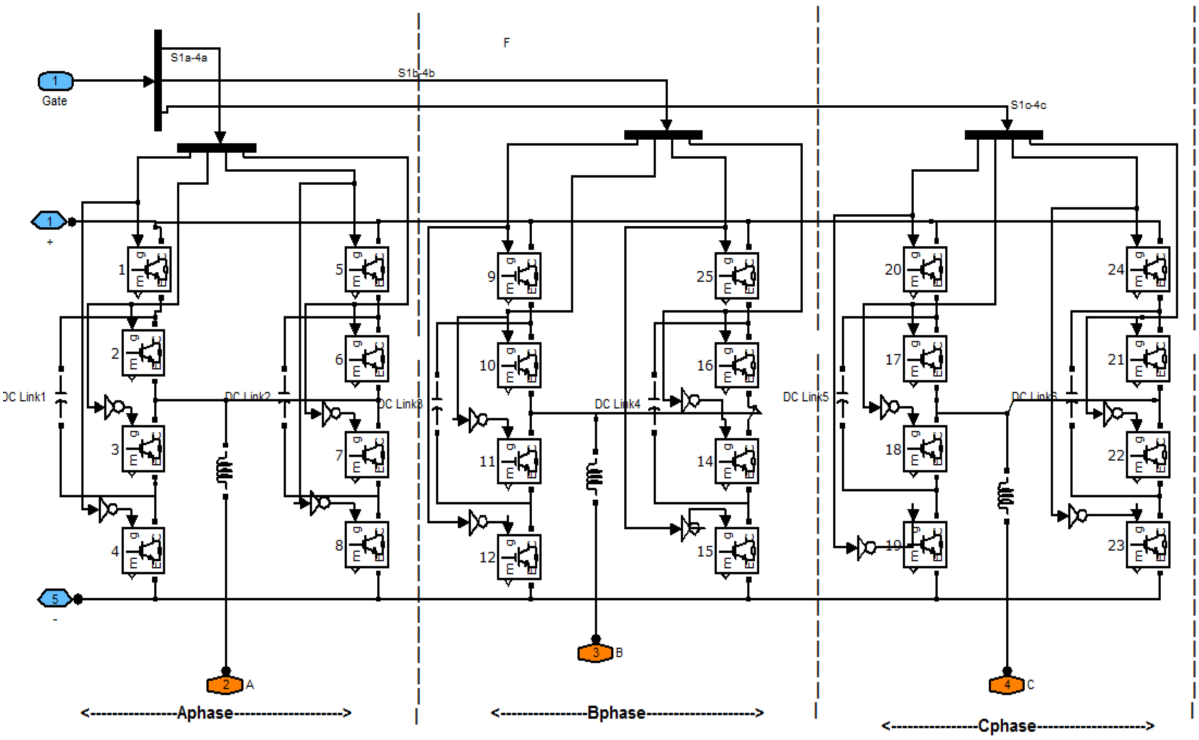

Fig [8.15]: Seven-level inverter

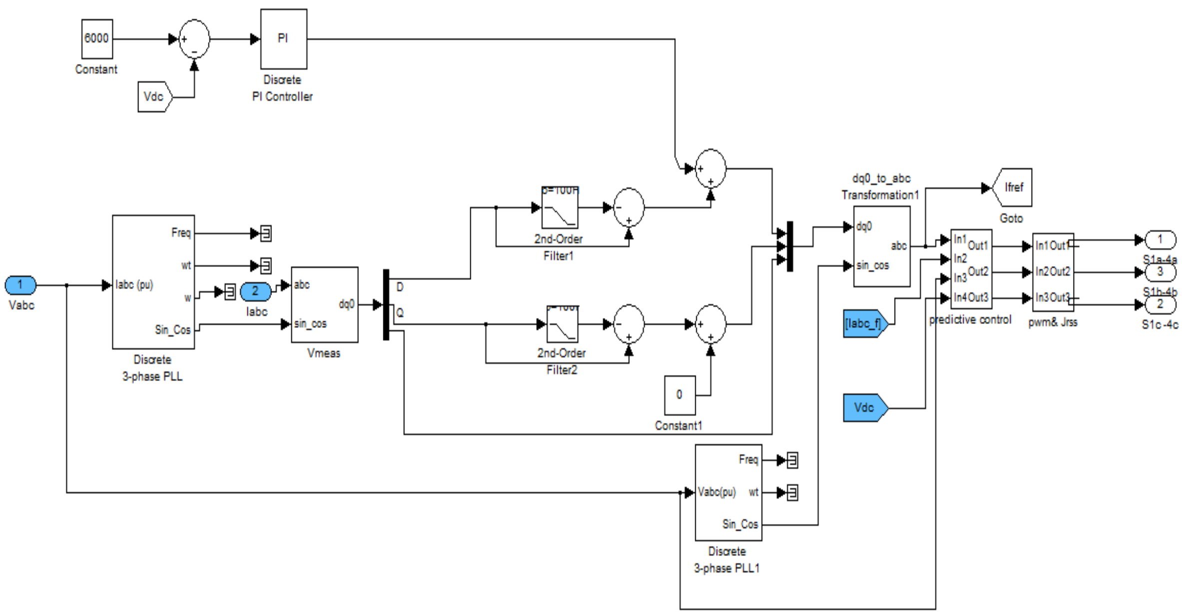

Fig [8.16]: Inverter Controlling

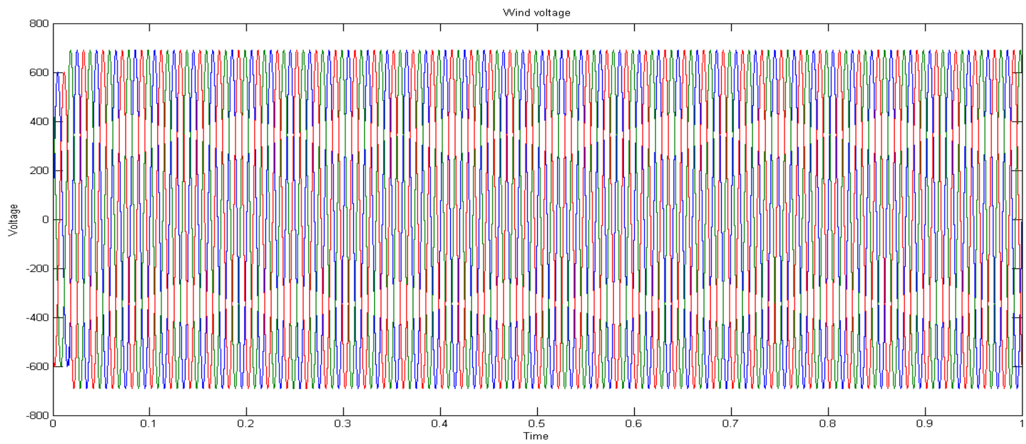

Fig [8.17]: wind output voltage before rectifier

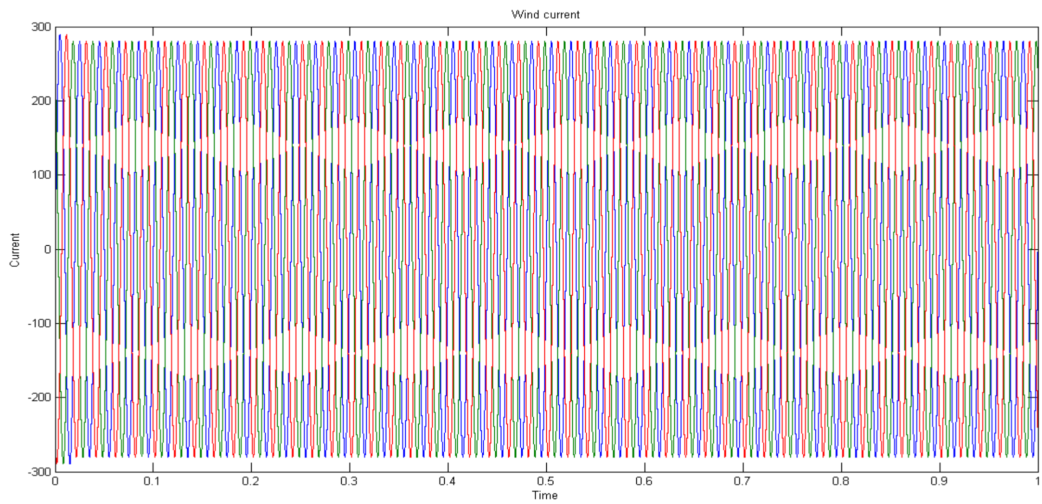

Fig [8.18]: wind output current before rectifier

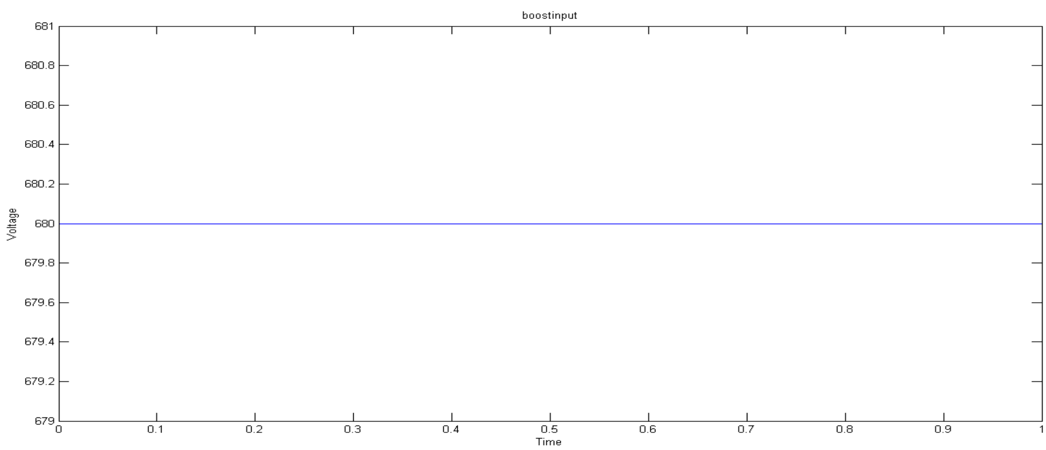

Fig [8.19]: Boost input

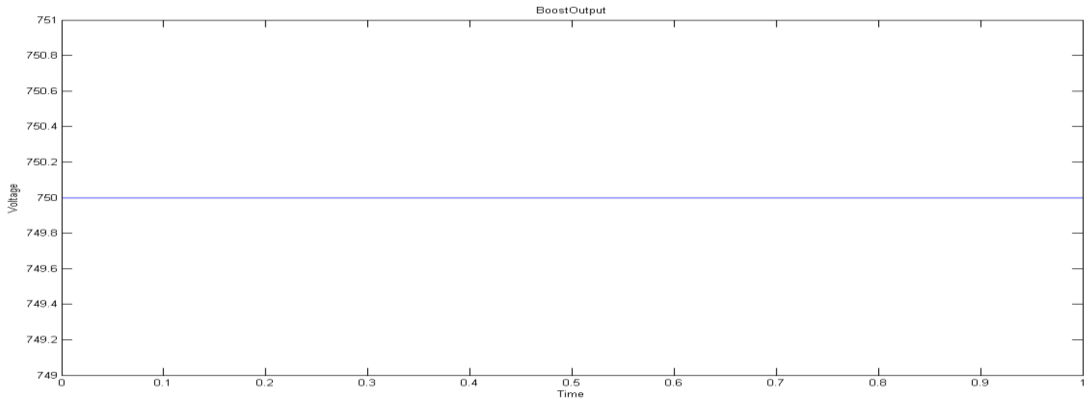

Fig [8.20]: Boost output

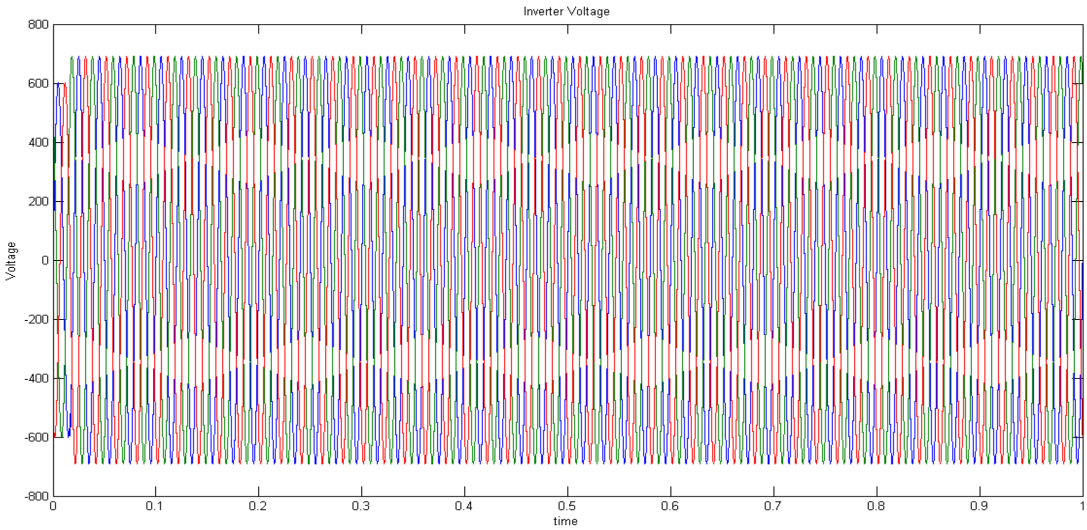

Fig [8.21]: Inverter Voltage

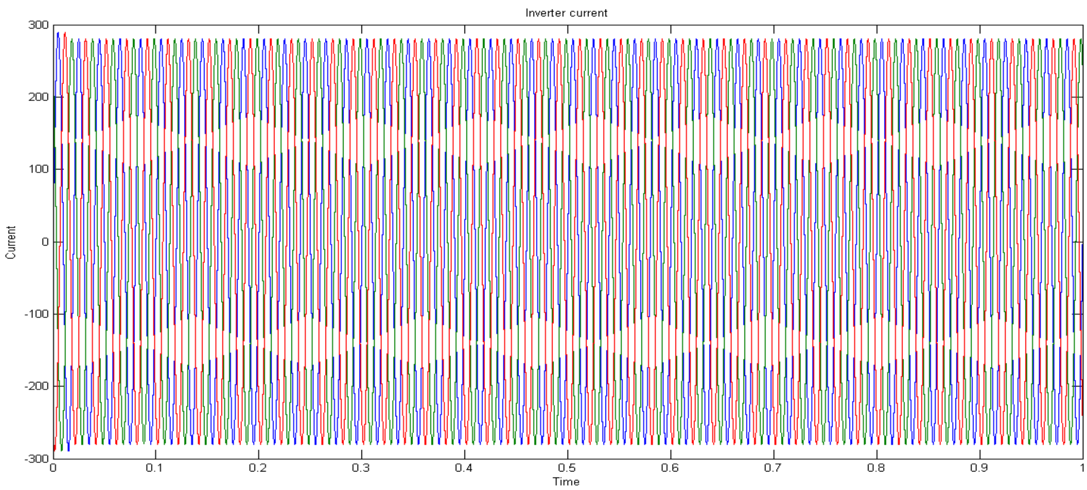

Fig [8.22]: Inverter Current

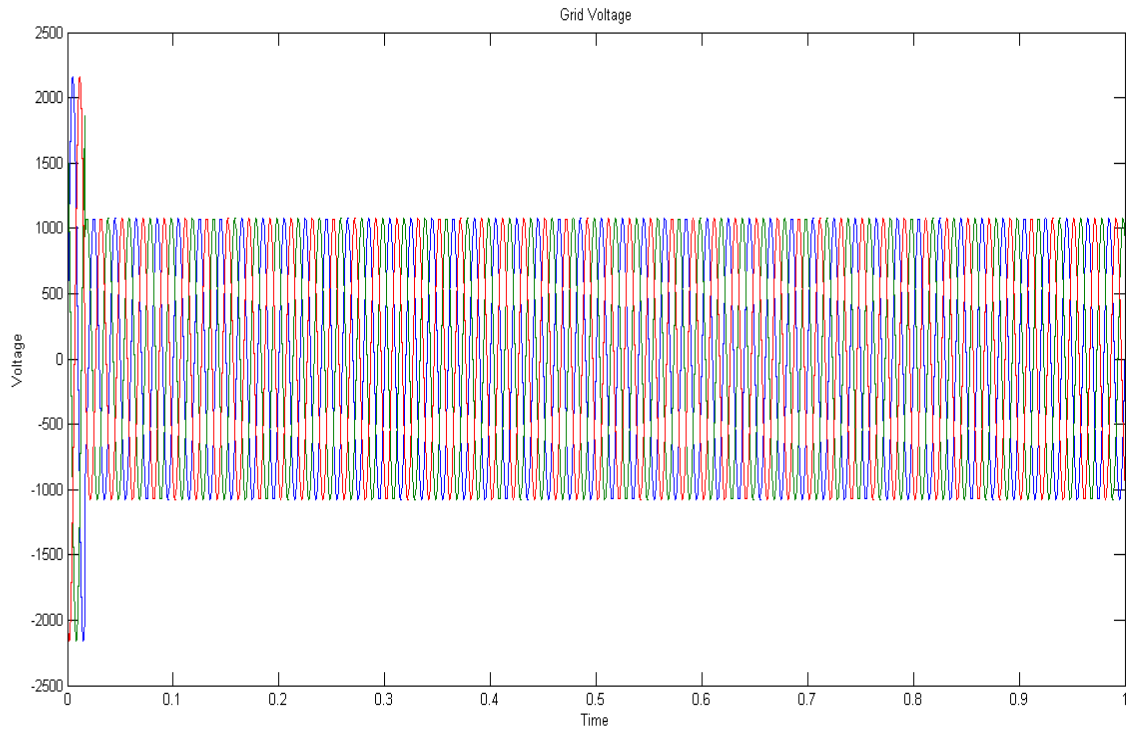

Fig [8.23]: Grid Voltage

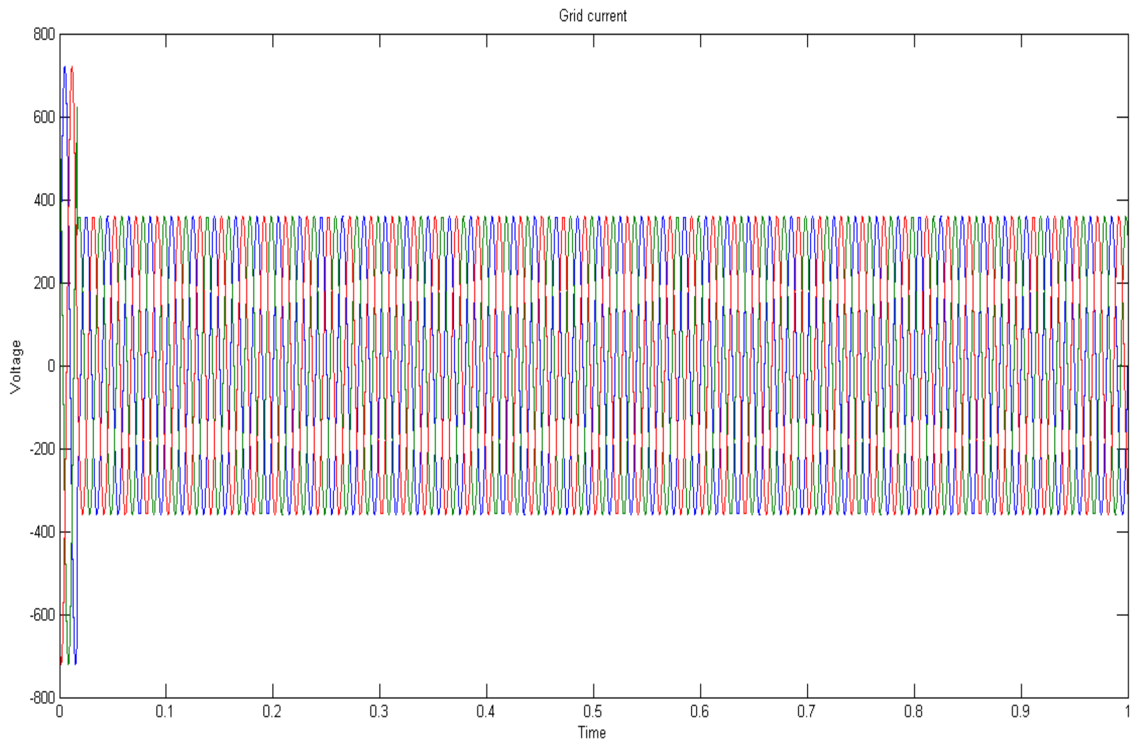

Fig [8.24]: Grid Current

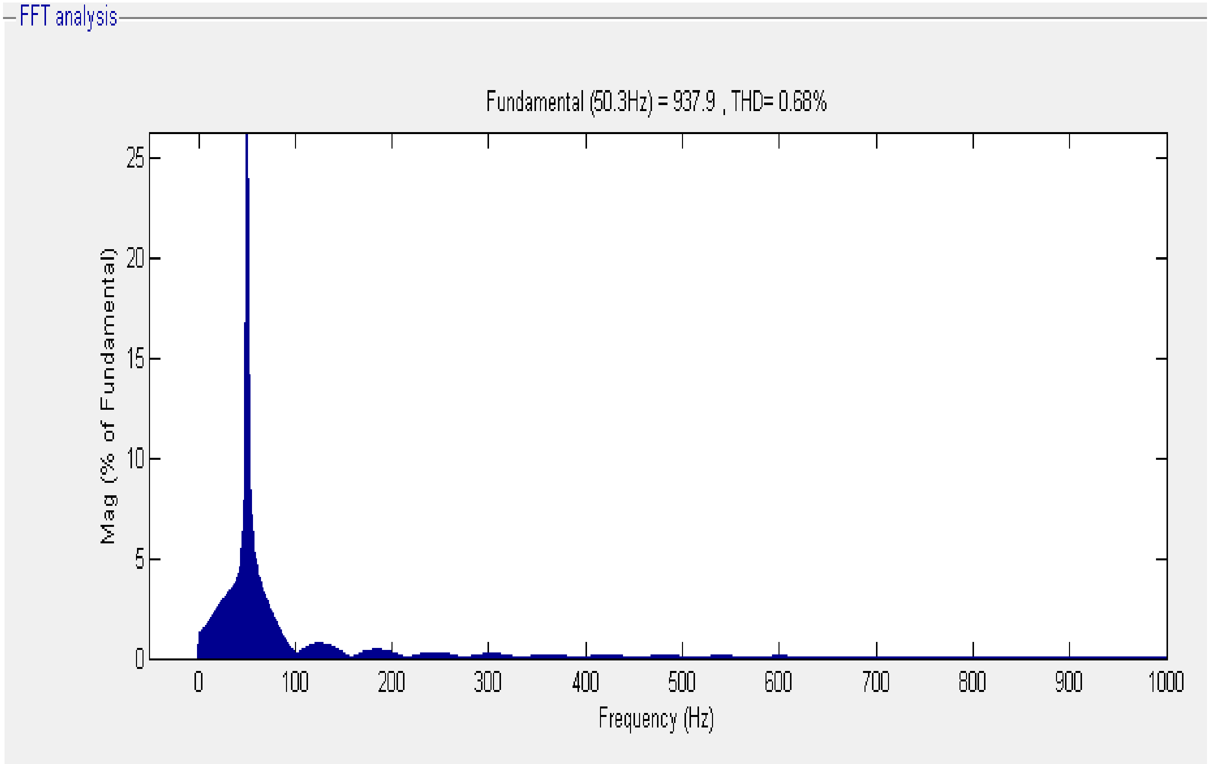

Fig [8.25]: THD on Grid voltage

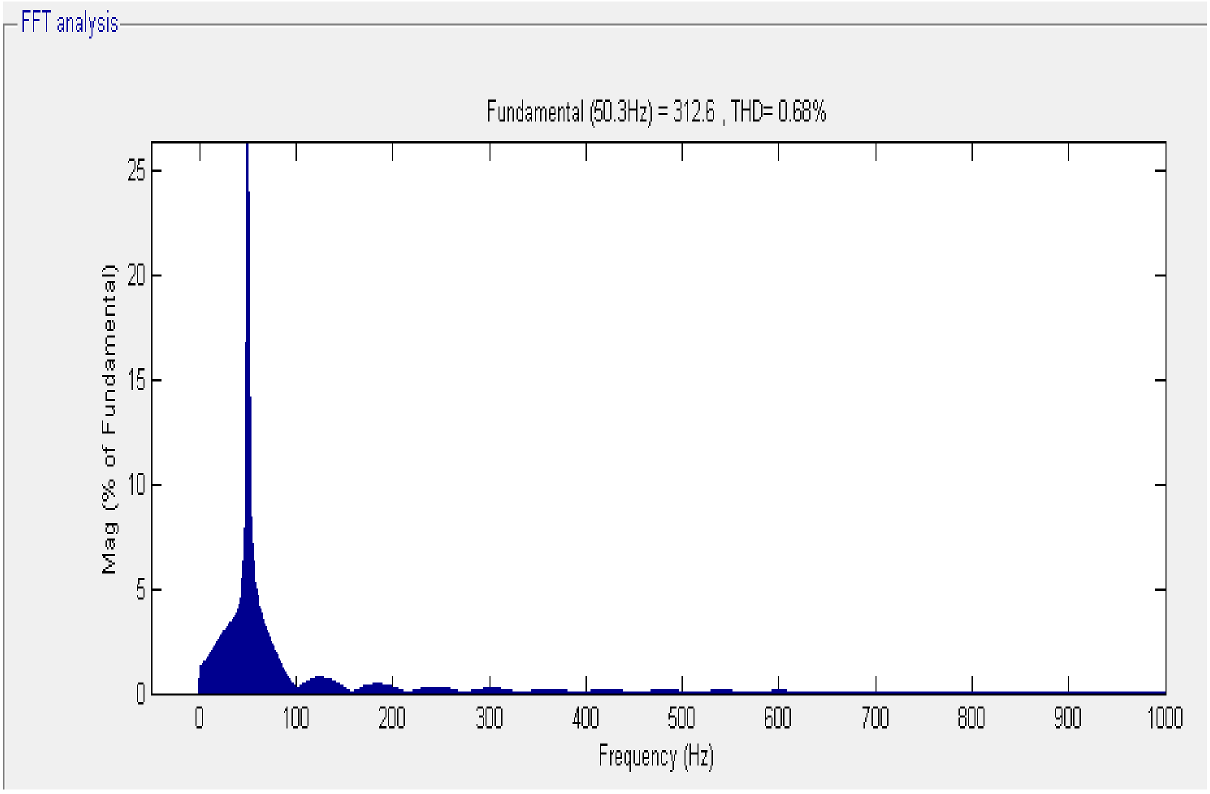

Fig [8.26]: THD on Grid current

8.3 Simulation design of Maximum power Point Tracking (INC) Technique

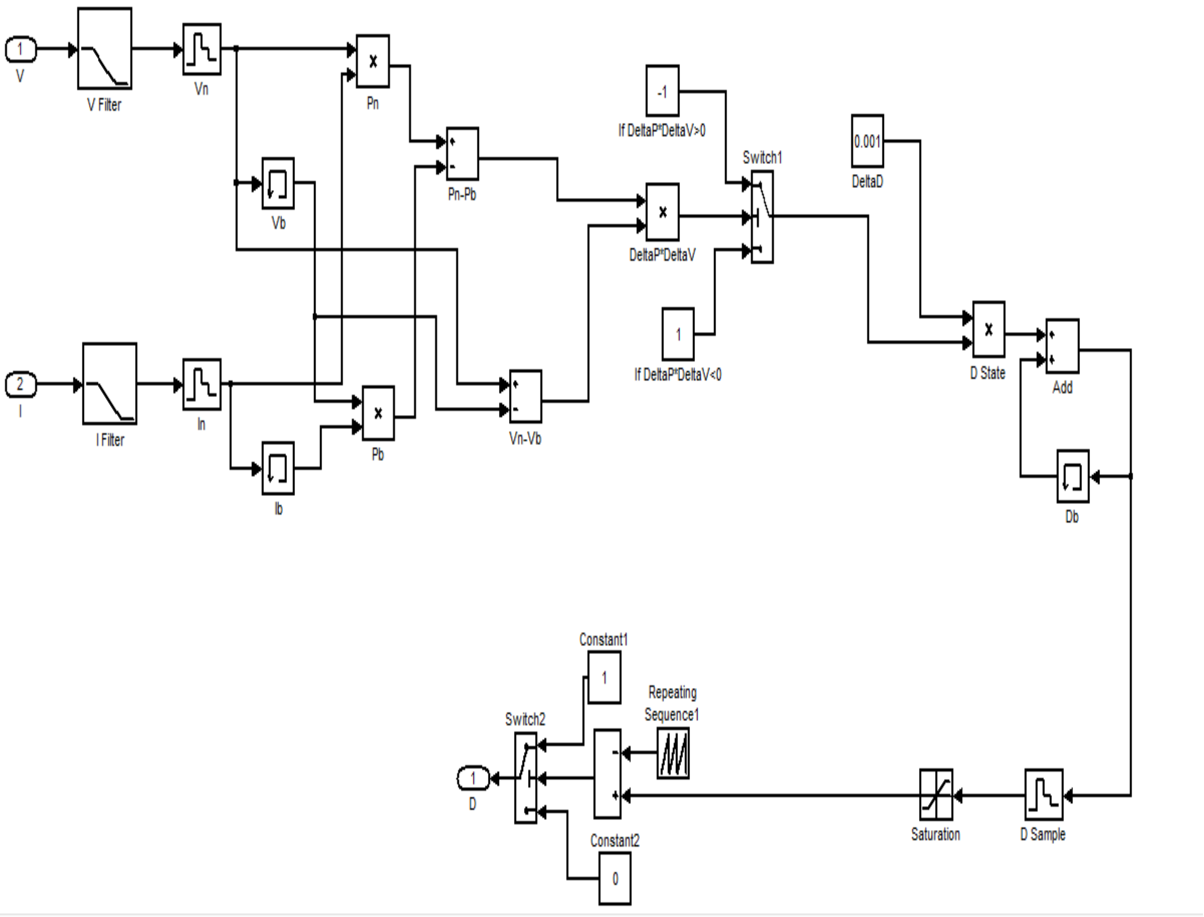

Fig [8.28]: Simulink Diagram of MPPT

CHAPTER 9

CONCLUSION

Wind energy conversion system is becoming the most interesting area of research and researcher are doing their best to improve the efficiency of plant and power quality as well. This dissertation proposes two works which are given below:

First is to design MPPT technique with the help of MATLAB/Simulink 2013-A. The MPPT is used to track maximum power from fluctuating wind speed. The main objective of MPPT is to sense the voltage and current and with help of these quantities pulses are generated for switch used in boost converter.

Second is to design novel topology of DC-AC converter, which helps in reduction of THD from AC side of converter

Table [3] Percentage of THD present in output of MLI

LEVEL	THD in Voltage	THD in Current
5-Level	**1.30**	**1.47**
7-Level	**0.68**	**0.68**

CHAPTER 10

FUTURE SCOPE

- The Wind and PV systems have made a successful conversion from islanding mode to interconnected mode. Because or renewable plants main two important factors which are overall economy and availability of load will improve. When excess power available at site grid, power generated by renewable plants is stored and will be delivered to load side when a shortage of power is there in the grid. Power delivered to the grid and power drawn from the grid can be recorded with KWh meter and counter KWh meter respectively.

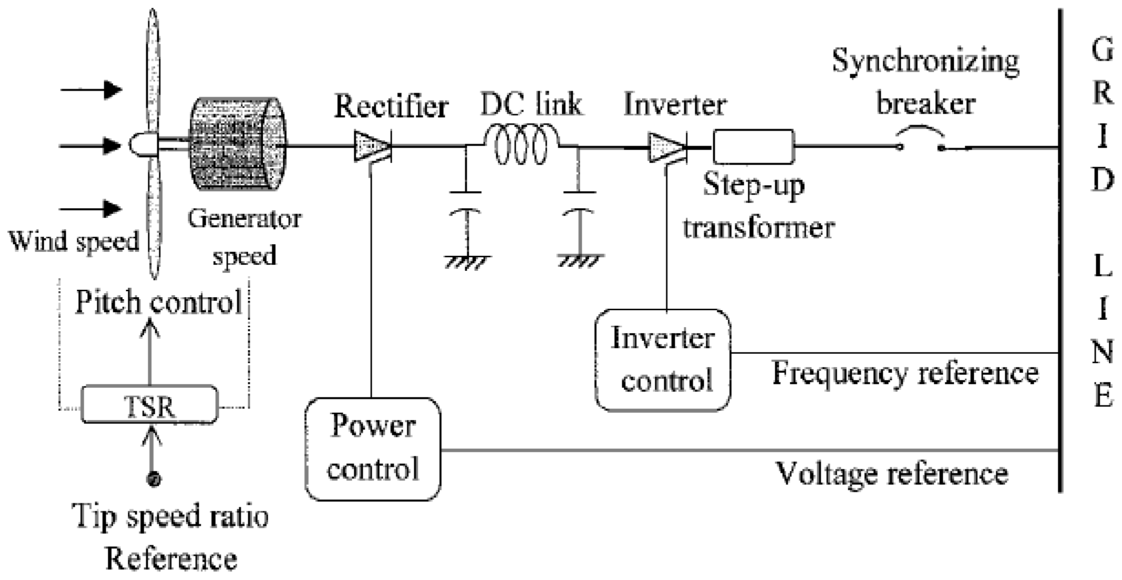

Figure [10.1]: Electrical Schematic of the Variable Speed Wind Turbine with Grid-Connected

- Wind farms can be designed with integrated grid and one can also include tower shadow effect and further analysis can be done by considering this effect in mind.
- DC power can be sent to HVDC (High Voltage DC) grid for long distance transmission.
- Utility grid or traditional three-phase AC grid requires the DC power to be converted to fixed voltage and fixed frequency AC power.
- Control of DC to AC converter specified on providing high power factor and high quality power can be topics for future study.

- Harmonics produced with the operation of variable speed wind turbines can be analysed and that can be reduced by designing active filters or passive filters and voltage and current waveforms can be smoothened well.
- By using FACTS devices with the system transient response of the wind turbines can be improved.
- MPPT is used for the maximum power generation combined with ant colony methodology and another methodology. By using this method master turbine will automatically change its position towards the wind flow direction and it will send signals to other wind turbines to rotate in the same direction only. Such that maximum output can be obtained.

REFERENCES

1) K. Araujo, "Wind Power Fundamentals," MIT Wind Energy Group & Renewable Energy Projects, 2010.

2) "Advanced Wind Turbine Drivetrain Concepts," U.S. Department of Energy, 2010.

3) t. s. o. L.-V. Ltd," Principles of Doubly-fed Induction Generator (DFIG)," 2011 [Online]. Available: http://www.labvolt.com/downloads/86376_F0.pdf.

4) J. Puigcorbe and A. d. Beaumont, "Wind Turbine Gearbox Reliability,"3 June 2010.[Online].Available:http://www.renewableenergyworld.com/rea/news/article/2010/06/wind-turbinegearbox- reliability.

5) Ajami, Ali, Rana Alizadeh, and Mahdi Elmi. "Design and control of a grid tied 6-switch converter for two independent low power wind energy resources based on PMSGs with MPPT capability." *Renewable Energy* 87 (2016): 532-543.

6) Raju, S. Krishnama, and G. N. Pillai. "Design and real time implementation of type-2 fuzzy vector control for DFIG based wind generators." *Renewable Energy* 88 (2016): 40-50.

7) Lee, Jinsik, Eduard Muljadi, Poul Sorensen, and Yong Cheol Kang. "Releasable Kinetic Energy-Based Inertial Control of a DFIG Wind Power Plant." *Sustainable Energy, IEEE Transactions on* 7, no. 1 (2016): 279-288.

8) Nguyen, Danvu, and Goro Fujita. "Analysis of sensorless MPPT method for hybrid PV–Wind system using DFIG Wind Turbines." *Sustainable Energy, Grids and Networks* 5 (2016): 50-57

9) Fateh, Fariba, Warren N. White, and Don Gruenbacher. "A Maximum Power Tracking Technique for Grid-Connected DFIG-Based Wind Turbines."*Emerging and Selected Topics in Power Electronics, IEEE Journal of* 3, no. 4 (2015): 957-966.

10) Nayanar, V., N. Kumaresan, and N. Ammasai Gounden. "A Single Sensor Based MPPT Controller for Wind-Driven Induction Generators Supplying DC Microgrid." (2015).

11) M. F. ELmorshedy, S. M. Allam, Ahmed I. A. Shobair and Essam M. Rashad "Voltage and Frequency Control of a Stand-alone Wind-Energy Conversion System Based on PMSG", *Electric Power and Energy Conversion Systems (EPECS), 2015 4th International Conference*, pp.1-6 Nov 2015.

12) Xiaoyan Du and Huajie Yin. "MPPT Control Strategy of DFIG-based Wind Turbines Using Double Steps Hill Climb Searching Algorithm." *2015 5th International Conference on*

Electric Utility Deregulation and Restructuring and Power Technologies (DRPT) Pages: 1910 -1914, DOI: 10.1109/DRPT.2015.7432585

13) G. Hima Bindu, Dr. P. Nagaraju Mandadi, "Design and Modelling of Induction Generator Windpower Systems by using MATLAB/S SIMULINK*", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering Vol. 3, Issue 8, August* 2014.
14) Dalala, Zakariya M., Zaka Ullah Zahid, Wensong Yu, Younghoon Cho, and Jih-Sheng Jason Lai. "Design and analysis of an MPPT technique for small-scale wind energy conversion systems." *IEEE Transactions on Energy Conversion* 28, no. 3 (2013): 756-767.
15) Jlassi, Imed, Jorge O. Estima, El Khil, Sejir Khojet, Najiba Mrabet Bellaaj, and Antonio J. Marques Cardoso. "Multiple Open-Circuit Faults Diagnosis in Back-to-Back Converters of PMSG Drives for Wind Turbine Systems.*"Power Electronics, IEEE Transactions on 30, no. 5 (2015): 2689-2702.*
16) A. Bharathi Sankar and R. Seyezhai, "MATLAB Simulation of Power Electronic Converter for PMSG Based Wind Energy Conversion System", *International journal of innovative research in electrical, electronics, instrumentation, and control engineering, Vol.1, Issue 8, Nov 2013.*
17) G. Estay, L. Vattuone, S. Kouro, M. Duran, B. Wu, "Dual-Boost-NPC Converter for a Dual Three-Phase PMSG Wind Energy Conversion System", pp. 1 – 6, Dec. 2012
18) Joanne Hui, Alireza Bakhsha and Praveen K. Jain, "Control and Modeling of a Wind Energy System With a Three-phase DCM Boost converter and a Sensorless Maximum Point Power Tracking Method", *Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES, pp.1-7, 7-10 May 2012*
19) Ms. Srushti R. Chafle*, Mrs. Megha A. Gadekar, "Converter design using MPPT technique," *International Journal of Engineering Science & Research Technology, Volume 30; 4(6): 208–221,june 2015.*
20) Rajaei, Amir Hossein, Mustafa Mohamadian, Seyed Mohamad Dehghan, and Ali Yazdian. "*PMSG-based variable speed wind energy conversion system using Vienna rectifier." European Transactions on Electrical Power 21, no. 1 (2011): 954-972.*
21) Xin Wang, Subbaraya Yuvarajan, and Lingling Fan, "MPPT Control for a PMSG-Based Grid-Tied Wind Generation System", *North American Power Symposium (NAPS), 2010 IEEE, pp.1-7, 26-28 Sept. 2010.*

22) Peng Xiao, Ganesh Kumar Venayagamoorthy, and Keith A. Corzine "Seven-Level Shunt Active Power Filter for High-Power Drive Systems" in *IEEE Transaction on power electronics*, VOL. 24, NO. 1, January 2009.

23) Xiong Xin and Liang Hui, "Research on multiple boost converter based on MW-level wind energy conversion system*", International Conference on Electrical Machines and Systems IEEE 2005, pp. 1046 - 1049 Vol. 2, 29 Sept. 2005.*

24) A. Rolan, A. Luna, G. Vazquez, D. Aguilar and G. Azevedo, "Modeling of a Variable Speed Wind Turbine with a Permanent Magnet Synchronous Generator," in *IEEE International Symposium on Industrial Electronics (ISIE 2009),* Seoul, Korea, 2009.

25) G. M. Masters, Renewable and Efficient Electric Power Systems, Hoboken, New Jersey: John Wiley & Sons, Inc., 2004.

26) "Dqo transformation - Wikipedia, the free encyclopedia," [Online]. Available: http://en.wikipedia.org/wiki/Dqo_transformation#Park.27s_transformation.

27) J. S. Thongam, P. Bouchard, R. Beguenane, I. Fofana and M. Ouhrouche, "Sensorless Control of PMSG in Vatiable Speed Wind Energy Concversion Systems," in *The 2010 International Power Electronics Conference*, 2010.

28) Hairul Nissah Zainudin, Saad Mekhilef, "Comparison Study of Maximum Power Point Tracker Techniques for PV Systems", *Cairo University, Egypt, December* 19-21, 2010, Paper ID 278.

29) Katherine A. Kim and Philip T. Krein, "Photovoltaic Converter Module Configurations for Maximum Power Point Operation", *University of Illinois Urbana-Champaign Urbana,* IL 61801 USA.

30) M. M. Hussein, T. Senjui, M. Orabi, M. A. A. Wahab and M. M. Hamada, "Simple Maximum Power Extraction Control for Permanent Magnet Synchronous Generator Based Wind Energy Conversion System," in *Japan-Egypt Conference on Electronics, Communications and Computers*, 2012.

31) M. Arifujjaman and L. Chang, "Reliability Comparison of Power Electronic Converters Used inGrid-Connected Wind Energy Conversion System," in *3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2012.

32) Vikrant.A.Chaudhari, "Automatic Peak Power Traker for Solar PV Modules Using dSpacer Software.," in *Maulana Azad National Institute Of Technology vol. Degree of Master of Technology In Energy. Bhopal: Deemed University, 2005*, pp. 98.

33) S. Mekhilef and M. N. A. Kadir, "Voltage Control of Three-Stage Hybrid Multilevel Inverter Using Vector Transformation," *IEEE Transactions on Power Electronics*, vol. 25, pp. 2599-2606, 2010.
34) S. Azadeh and S. Mekhilef, "Simulation and Hardware Implementation of Incremental Conductance MPPT with Direct Control Method Using Cuk Converter," *IEEE Transaction on Industrial Electronics*,vol. DOI:10.1109/TIE.2010.2048834, 2010.
35) Dr. P.S Bimbra, “Power Electronics”, *Khanna Publication*, Fourth Edition
36) Muhammad H.Rashid, “Power Electronics Circuits, Devices, and Applications”, Third Edition.
37) Dr. Keith Corzine, Operation and Design of Multilevel Inverters, Developed for the Office of Naval Research December 2003.
38) José Rodríguez, *Senior Member, IEEE*, Jih-Sheng Lai, *Senior Member, IEEE*, and Fang Zheng Peng, *Senior Member, IEEE*, Multilevel Inverters: A Survey of Topologies, Controls, and Applications, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 49, NO. 4, AUGUST 2002.
39) Pablo Correa, *Student Member, IEEE*, Mario Pacas, *Senior Member, IEEE*, and José Rodríguez, *Senior Member, IEEE*, Predictive Torque Control for Inverter Fed Induction Machines, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 54, NO. 2, APRIL 2007.
40) http://www.gwec.net/wp-content/uplpoads/vip/GWEC_PRstats2016_EN_WEB.pdf