SIMULATION MODEL OF A PMSG BASED MICROGENERATION SCHEME UNDER VARIABLE WIND SPEED WITH NON-LINEAR LOAD

A Thesis Submitted

In the partial fulfillment of the requirements for the award of the degree of

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IN

ELECTRICAL ENGINEERING (POWER SYSTEMS)

By

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CERTIFICATE

This is to certify that this thesis entitled "**SIMULATION MODEL OF A PMSG BASED MICROGENERATION SCHEME UNDER VARIABLE WIND SPEED WITH NON-LINEAR LOAD**" is being submitted by Mr. **AEHASHAN AHAMMED** , with Roll No. **002010802027** in partial fulfillment of the requirements for the award of the degree of **Master of Engineering in Electrical Engineering** from **JADAVPUR UNIVERSITY**, KOLKATA, WEST BENGAL has been carried out by him under my guidance and supervision. The project, in my opinion, is worthy of its acceptance.

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The foregoing thesis is hereby approved as a creditable study of Master of Engineering in Electrical Engineering and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion therein but approve this thesis only for the purpose for which it is submitted.

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DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the candidate alone. This thesis is a presentation of my original research work and has not been submitted previously, in whole or in part, to quality for any other academic award. Furthermore, the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program.

The work was done under the guidance of Prof. (Dr.) Swapan Kumar Goswami & Prof. (Dr.) Debashis Chatterjee, Professor, Electrical Engineering Department of Jadavpur University, Kolkata.

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ABSTRACT

In response to rising fossil fuel prices and global warming concerns, renewable energy has become increasingly popular in the United States. These two main green energy sources have been extensively used in both large and small-scale energy production facilities. Consumers in small power plants store the extra energy they generate in a battery system. Battery packs are charged in various method, with the charging type determined by the battery's state of charge. As a result, when the produced energy is absorbed in the battery, a controller is required. An essential component of the charge controller is a power converter. It is common practise to use PMSG s in tiny wind turbine generators because of their high energy density. The charge controller for a 1.1kW PMSG wind turbine is examined in this thesis. A small load with a battery pack are supplied by a wind turbine that runs independently of the power grid. Using a 12V 30Ah battery pack and a steady 150W load, the system is designed. To ensure that the system's load receives a stable voltage, the controller must be charged. The charge controller's main power converter, the buck converter, supplies a controlled voltage to the continuous load as well as the battery package via a constant DC-link. Buck and boost converter components are intended to meet the specific power and voltage requirements of a given application. These converters' control loops have been meticulously crafted to ensure that electricity is delivered at a precisely controlled voltage. The transfer function of such system, which includes a DC-DC buck converter and a PI controller, is used to determine the efficiency of the control loops. The results show that the controller built can give the appropriate power to the load and storage system.

LIST OF CONTENTS

List of Abbreviations

PMSG	Permanent Magnet Synchronous Generator
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
DFIG	Doubly-Fed Induction Generator
PWM	Pulse Width Modulation
WECS	Wind Energy Conversion System
WRSG	Wound Rotor Synchronous Generator
SCIG	Squirrel Cage Induction Generators
EMF	Electro Motive Force
HVDC	High Voltage Direct Current
PES	Power Electronics Systems
PI	Proportional Integral
PLL	Phase Locked Loop
WTG	Wind Turbine Generator
THD	Total Harmonic Distortion
RES	Renewable Energy Source
SPST	Single Pole Single Throw
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
SOC	State Of Charge
WEO	World Energy Outlook

List of Symbols

ρ	Air Density
A	Area Swept By Rotor Blades
V	Velocity Of Air
r	Radius Of The Hub
l	The Length Of The Wind Blade
R	Gas Constant
p	Air Pressure
T	Air Temperature
H_m	Elevation Of Site In Meters
C_p	Power Coefficient Of Wind Turbine
ω	Angular Speed
λ	Tip Speed Ratio
V_{dc}	Average Output Voltage At The Load Side
V_m	Peak Value Of The Phase Voltage
V_{rms}	Rms Value Of The Output Voltage
I_m	Peak Value Of The Secondary Line Current
Δv_{pp}^{max}	Peak-To-Peak Switching Ripple
I_o^{max}	Maximum Value Of The Output Current I_o^{max}
Q (t)	System's Current Capacity
Q_n	Nominal Capacity
P_w	Power Harvested From Wind
β	Pitch Angle
v_{sd}	Direct Axis Voltage Of PMSG
v_{sq}	Quadrature Axis Voltage Of PMSG
ψ_{sd}	Direct Axis Flux Of PMSG
ψ_{sq}	Quadrature Axis Flux Of PMSG
L_d	Direct Axis Inductance Of PMSG

L_q	Quadrature Axis Inductance Of PMSG
I_0	Output Current Of Buck Converter
I_d	Input Current Of Buck Converter
V_d	Input Voltage Of Buck Converter
V_0	Output Voltage Of Buck Converter
I_{LB}	Inductor Boundary Current
Ts	Switching Period
C	Value Of The Capacitor
ΔV_0	Output Voltage Ripple
E_b	Emf Of a Loaded Battery
E_0	No-Load Battery Emf
K	Polarization Constant
Q	Maximum Capacity Of The Battery
A	Exponential Zone Amplitude
B	Exponential Zone Time Constant Inverse
Z	Internal Impedance Of The Battery
I	Load Current Delivered By Battery
I	Filtered Current
D	Duty Cycle Of The Dc/Dc Buck Converter
V_{an}, V_{bn}, V_{cn}	Phase Voltages Of The Inverter
V_{ab}, V_{bc}, V_{ca}	Line Voltages Of The Inverter
I_a, I_b, I_c	Load Current

Chapter 1
INTRODUCTION

1.1 Background and Motivation

Non-conventional resources like solar, hydro, and wind have gained attention because of the rapid depletion of fossil fuels. When compared to connecting to the grid, which necessitates the use of lengthy transmission lines and incurs associated losses, harvesting electrical energy from resources like these in remote areas can be less expensive and more straightforward. The use of such energy resources in a system has therefore become a preferred option. Integrating wind energy necessitates that it be capable of producing the same amount of electricity as a conventional power plant. It is now necessary for wind turbine technology to move beyond the generation of power from wind and play a supporting role in the bulk power system as wind penetration increases in the sector of power generation. Inertial and primary frequency responses should be possible with wind turbines. The frequency stability of the grid can be supported by wind generators with this capability. Induction generators with a full converter and a permanent magnet synchronous generator are commonly used for this purpose. Large interconnected power systems can be supported by Wind Power Plant's dynamic analysis. Fossil fuels (oil, coal and natural gas) have traditionally been used to generate electricity and now account for the majority of the global energy market. The rising cost of producing fossil fuels is a direct result of the diminishing supply of those fuels. In addition, the consumption of fossil fuels is one of the primary factors that contributes to the pollution of the earth and the acceleration of global warming. The use of renewable energy sources is becoming increasingly popular as a means of generating sustainable energy from the world's virtually limitless supply. In recent years, wind power has overtaken other forms of renewable energy, such as solar and hydroelectric, to become one of the most important sources of this type of electricity. Prior to the 21st century, the only or primary applications of wind energy were the pumping of water from wells and the grinding of grains. Wind energy has become the most cost-effective energy source over the past two decades, as a result of technological advancements and price reductions, which have made it easier to produce electricity for residential use. This technology has the potential to be a lifesaver for people who live in rural areas without access to electric grids. Due to their capacity to remove pollutants and lower the expenditure of DG fuel, stand-alone tiny wind turbines are a very tempting source of energy for isolated places or small companies.. Even these generators need a significant amount of polluting fuel, not to mention the high costs associated with their operation and maintenance. A standalone wind turbine can be installed anywhere if there is enough wind, or where connecting to the grid is highly expensive. Regardless of whether a wind energy conversion system is on or off-grid, their operating concepts are identical. The hardware and software requirements differ only because systems without a grid are considered to be more complex [1].

The wind turbine system makes it possible to generate power from wind energy and store it for usage at home.. The power that is produced by the wind turbines can be used to charge a battery to the required voltage, and the battery can then be put to use in homes to power various appliances and other items. Now with utilisation of wind energy to generate electricity, household appliances may operate effectively in any climate without consuming any conventional fuels, and electricity can indeed be made available at night using batteries charged during the day.. Batteries will automatically charge themselves, and there are no harmful emissions or drawbacks associated with this feature.

1.2 Method

The primary objective of this thesis is to design and conduct an analysis of a 1.1 kW wind turbine that is capable of charging a battery package and supplying power to a constant load. Due to their high efficiency, a PMSG will be utilized in this project for the design of a small-scale wind turbine that will be used to generate electricity for battery-charging applications. With the assistance of this generator, the kinetic energy produced by the wind turbines will be converted into electricity that operates in three phases. Power electronics in the form of a power converter are now needed to modulate the voltage of this electricity so that it may be utilised in residential houses because it cannot be used directly there.. Because they are straightforward and uncomplicated to put into action, single-stage power converters that are built with the assistance of rectifiers and dc/dc converters can be utilized for the process of converting power. DC/DC converters for wind turbine systems can be of any type, including buck, boost, or buck-boost converters.

However, because the rectifier's voltage output was higher than that of the battery's required charging voltage, a buck converter was employed after it. Batteries could be utilised to store electricity needed for future household consumption after it has been transformed to the proper levels. The voltage that is produced at the output of the converter and the reference point of the voltage that is required will be used in conjunction with a controller to maintain a constant output voltage for the converter. Control of duty cycle for PWM signal required to turn on converter switching devices will be done by this controller based on the error signal generated by difference between reference and outgoing voltages of the converter. The Simulink model of MATLAB is used for simulation of the entire system, beginning with the wind turbine and continuing through the battery charger.

1.2 Objectives of Project

Project objectives are to gain a solid understanding of wind turbines, which are needed to transform wind kinetic energy into electricity. Wind turbine type and power requirements are the primary considerations when it comes to this project's focus.

Along with this, another goal is to build power electronic devices which are necessary for converting generated electricity to the needed voltage and form, which involves creating link capacitors between rectification and converter stages and the inductor and capacitance of buck converters.

This is a secondary objective, but the major one is to build the control circuitry needed to maintain a constant voltage delivered to the battery by using PI controller. Below the schematic diagram of the Project is shown.

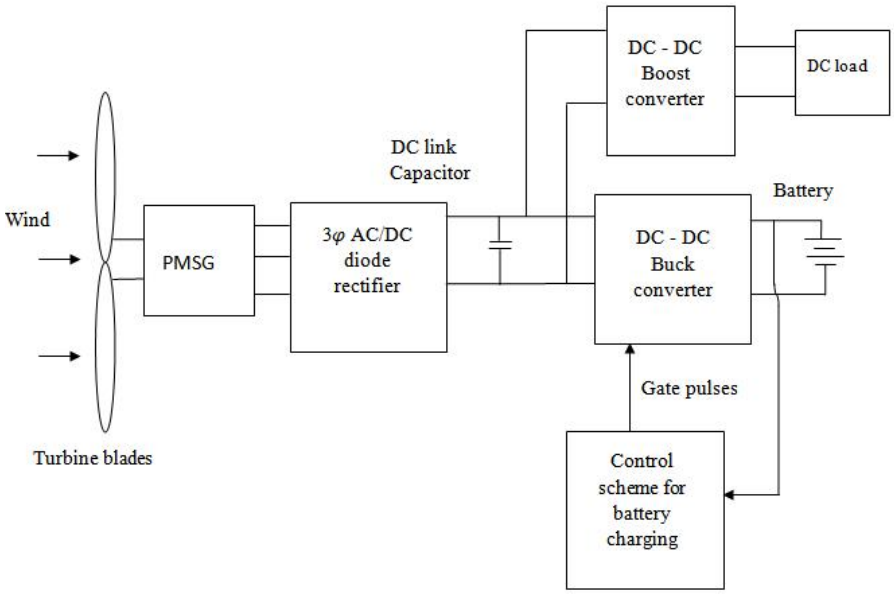


Figure (1.1): - Schematic diagram of WECS

Chapter 2

WIND ENERGY CONVERSION SYSTEM AND ITS COMPONENT

2.1 Wind Turbine

The wind turbine's mechanical energy is converted to electrical energy in the generator section of the wind energy conversion system in the first section of this chapter. Below, you will find more information about these components. The components of this thesis are first described in general terms, and then a specific section type is discussed.

2.1.1. Characteristics of Wind Energy

As a first step, we need to know more about wind energy's properties. As it moves forward, air has a special kind of kinetic energy.

a. Wind Power

Rate of flow of the kinetic energy of wind is defined in terms of KE which is given as KE= ½ * (mV^2)(m), where V is its velocity and m is the mass of the air

Mechanical Power coming in upstream wind can be found as

$$P = \tfrac{1}{2}\,(\text{mass flow per second})\,V^2 \quad (2.1)$$

$$P = \tfrac{1}{2}\,(\rho A V) V^2 \quad (2.2)$$

Where ρ is density of air, A is blade swept area and V is air velocity.

b. Blade Swept Area

Wind turbine output is also determined by the swept area of the blades. Wind turbines with larger blade diameters are able to extract more energy from the wind. The blade swept area can be determined by using by following equation (2.3).

$$A = \pi l\,(l+2r) \tag{2.3}$$

Where r is radius of the hub and l is the length of the wind blade.

c. Air Density

The density of the air is another factor that impacts the amount of wind power generated. As the temperature and pressure change, so does the wind density as given in (2.4).

$$\rho = \frac{p}{RT} \tag{2.4}$$

Where R is the gas constant, p is air pressure and T is air temperature.The following equation (2.5) demonstrates the combined effect on air density of changing temperature and pressure with increasing height.

$$\rho = \rho_0 e^{-\left\{\frac{.297\,H_m}{3048}\right\}} \tag{2.5}$$

Where H_m is elevation in m.

2.1.2. Wind Turbine Classification

Turbine generator configuration, airflow direction relative to the turbine capacity, turbine rotor, power supply mode and turbine location can all be used to categorize wind turbines. It is possible to classify wind turbines into either horizontal-axis or vertical-axis, or upwind and downwind. In addition to this, wind turbines can be classified as direct drive or geared drive, on-grid or off-grid, and finally, onshore or offshore. Here's a brief rundown of the various varieties.

a. Horizontal-Axis and Vertical Axis Wind Turbine

For most commercial wind turbines, the rotor's rotational axis is perpendicular to the direction of the wind. These turbines are highly efficient and have higher power density, a lower cut-in speed, and a lower cost per unit power output because to their blade arrangement.

Wind turbines with vertical axes rotate their blades in a direction perpendicular to the earth. As a result of their omnidirectional capability, these wind turbines do not require yaw control. In addition to lowering the overall cost of the turbine, the ability to assemble all of the necessary components on the ground makes the wind tower design and construction much simpler.

However, the blades must be rotated by an external energy source at the first stage. As the turbine is only supported on one side of the ground, the maximum practicable height is similarly limited. Due to their reduced wind power efficiency, these turbines make up just a small portion of wind turbines. wind turbine with horizontal and vertical shafts is shown in the following Figure (2.1).

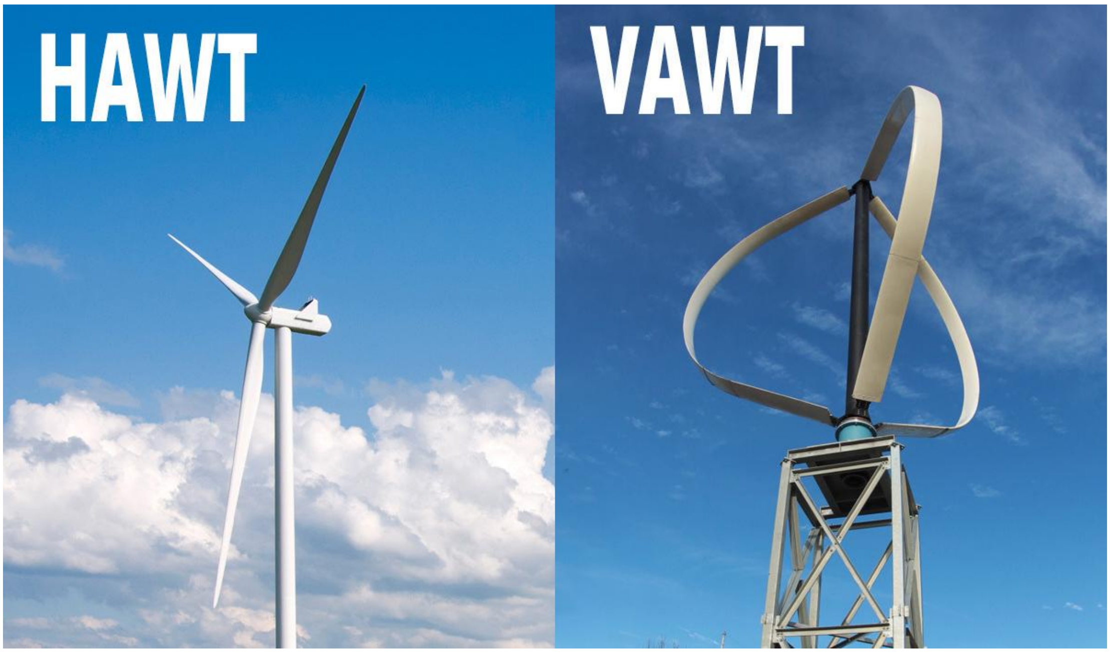


Figure (2.1):- View of HAWT and VAWT

b. Upwind and Downwind Wind Turbine

A horizontal axis wind turbine falls into one of these two groups on a regular basis. As far as wind turbines go, the vast majority of those in use today are of the upwind variety. Because the rotors face the wind, the flow field is less likely to be distorted as it flows through the wind tower and nacelle of this type of turbine.

The upwind wind turbine and downwind configuration is shown in Figure (2.2).

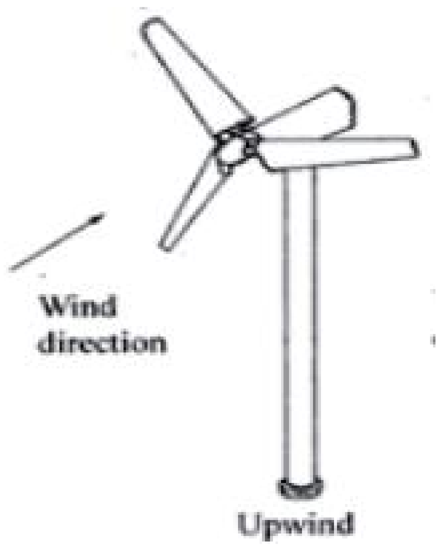


Figure (2.2): Diagram of upwind, three-bladed HAWT

c. Direct Drive and Geared Drive Wind Turbines

Most generators employ a multistage gearbox in order to improve the rotor's output power. There are several advantages to adopting gear generators, including lower costs, smaller dimensions, and lighter weight. Additional disadvantages of gearboxes include decreased turbine reliability, increased mechanical losses, as well as increased noise levels [2].

Direct drive turbines are turbines in which the generator shaft is directly linked to the blade rotor. In terms of energy efficiency, reliability, and design simplicity, these turbines are better to the geared drive turbines [2]. There are two wind turbines depicted in Figure (2.3).

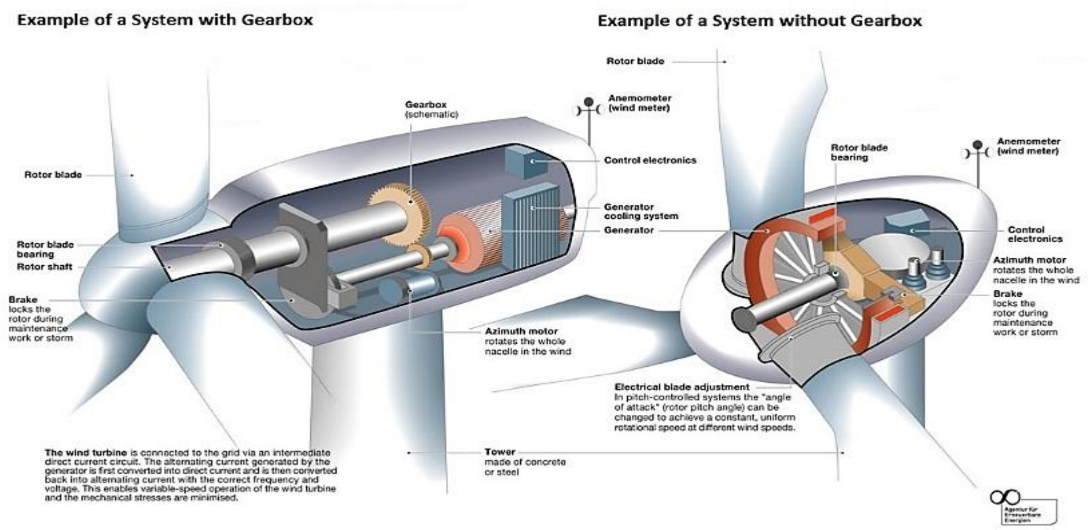


Figure (2.3): - Direct drive and Geared drive WT

d. On Grid and Off Grid Wind Turbines

Large and medium-sized wind turbines are typically linked to the grids for a variety of purposes. The biggest benefit of being linked to the grid is that energy storage will no longer be a concern.

All off-grid wind turbines, on the other hand, are small enough to be employed in private residences, farms, telecommunications towers, and other similar settings. Even with little warning, the amount of wind power generated by these turbines can shift substantially in a short period of time. As a result, batteries, diesel generators, and photovoltaic systems are all employed in conjunction with these turbines to improve the reliability of the electricity they supply.

e. Onshore and Offshore Wind Turbines

With a lengthy history of development, on-shore turbines offer many advantages, including quicker grid connectivity and reduced costs for foundations and turbines.

Offshore wind turbines, on the other hand, can produce more power and operate for longer periods of time than turbines built onshore. The noise generated by onshore wind turbines is no longer a problem because to these additional benefits.

2.1.3. Wind Turbine Configuration

These days, most wind turbines have three bladed horizontal rotor blades on a horizontal axis. The majority of the wind turbine's components are housed inside the nacelle. The wind tower has it atop its spire. The rotor hub is connected to the gearbox via the main shaft, which connects the three blades to the rotor as seen from Figure (2.4).

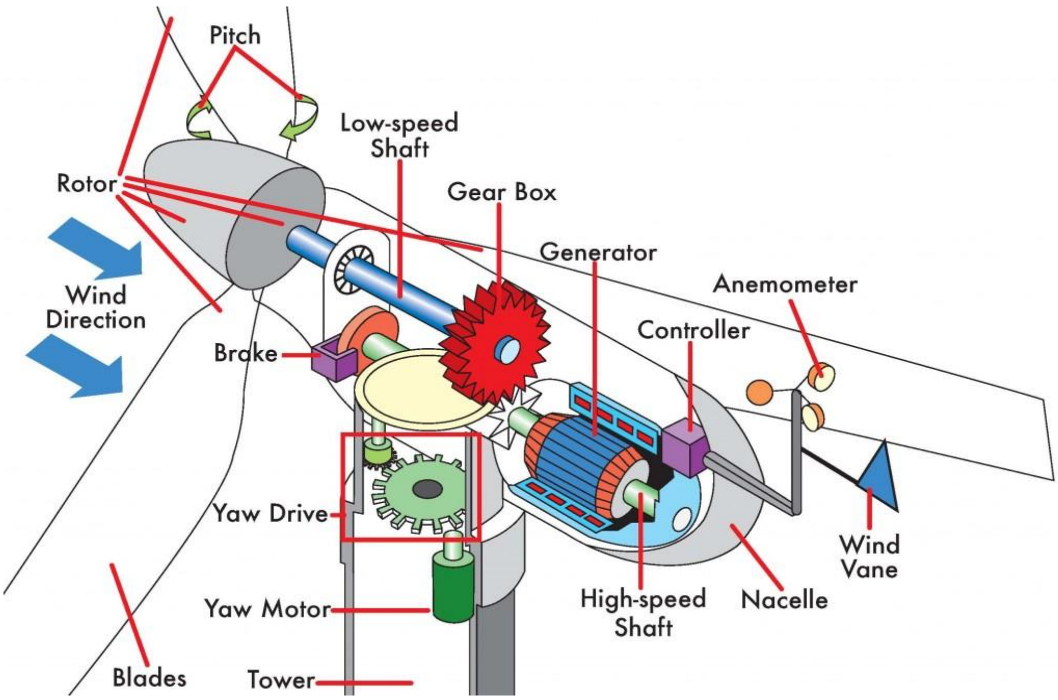


Figure (2.4):- Schematic of HAWT

This means that the rotor hub of the wind turbine can be connected to a gearbox output shaft to raise its slow speed to meet the generator's rotor's required speed.

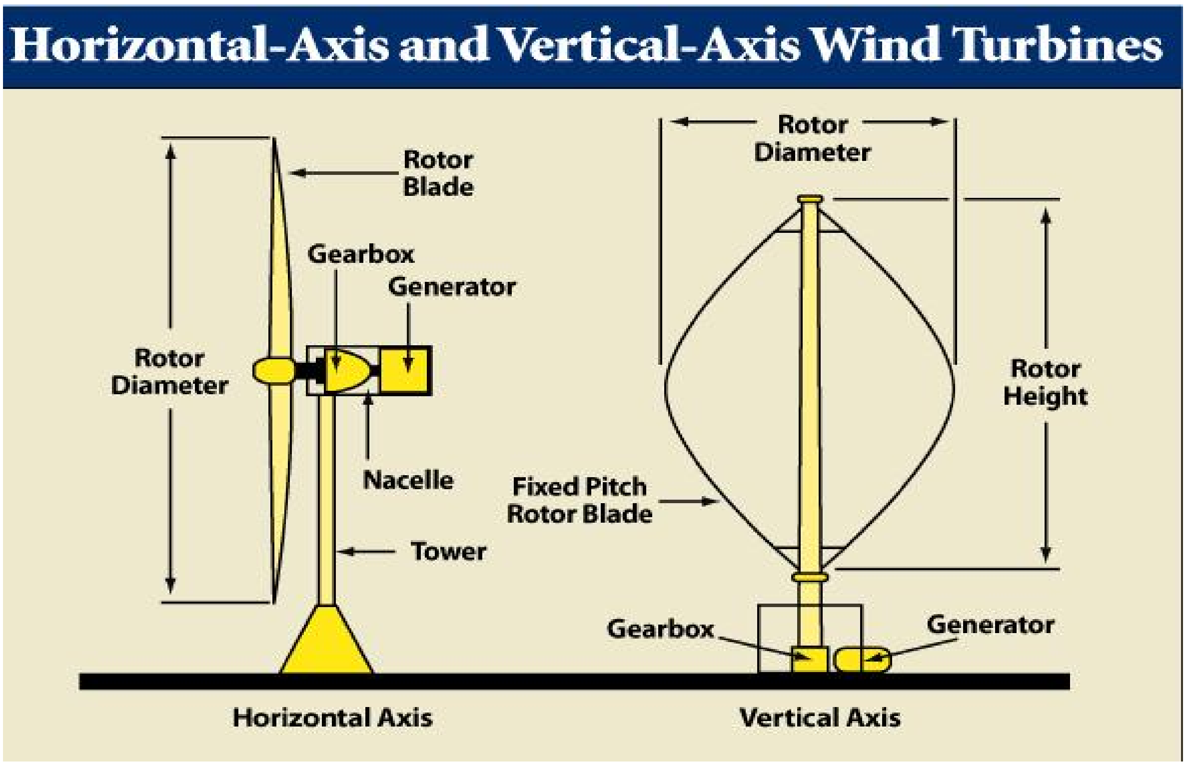


Figure (2.5): - Configuration of VAWT

Parts needed for vertical axis wind turbines are depicted in Figure (2.5). A guide wire is typically needed to keep the rotor's shaft in place. In addition, the rotor blades are linked to two hubs. The rotor is the heart of a wind turbine, absorbing wind energy and converting it to mechanical energy through the use of its blades. The rotor blades, in turn, are a component of the rotor, which turns the hub. The shaft is then turned by the rotating blades, and the generator is occasionally connected to the gearbox. When utilizing a gearbox to raise the speed of a generator, it is primarily for this purpose. The generator, the final component, is responsible for generating energy from rotational motion.

2.1.4. Wind Power Parameters

a. Power Coefficient

The power coefficient is a measure of the efficiency with which wind energy is converted from one step to the next. To drive the wind generator's shaft, kinetic energy must first be converted to mechanical energy using the first stage of this parameter's function. The power coefficient is expressed as a ratio of the mechanical power generated by the blades and the wind power that is expressed in terms of wattage as depicted in (2.6) [2].

$$C_p = \frac{P_{me,out}}{P_w} = \frac{P_{me,out}}{\frac{1}{2}\rho A\overline{V}^3} \tag{2.6}$$

b. Tip Speed Ratio

The tip speed ratio, defined as the ratio of the tangential speed at the tip of the blade to the actual wind speed, is another significant consideration in wind turbine design as given in (2.7).

$$\boldsymbol{\lambda} = \frac{(l+r)\omega}{\overline{V}} \tag{2.7}$$

Where l is the blade's length, r is its radius, and ω is its angular speed. A small number of angular speed may allow wind to travel through the blade swept area without being disturbed, but a greater ω may lead to a decreased power. As a result, an optimal value of ω for blade angular velocity is needed, and this may be found using the equation (2.8) [2].

$$\omega_{opt} = \frac{2\pi}{n}\frac{\overline{v}}{L} \tag{2.8}$$

Where n is the number of blades.So optimal tip ratio can be found from the following equation (2.9)

$$\boldsymbol{\lambda}_{opt} = \frac{2\pi}{n}\frac{(l+r)}{L} \tag{2.9}$$

c. Wind Turbine Capacity Factor

Wind turbines can't produce electricity all the time because of the unpredictable nature of the wind. If you want to know how much electricity you've actually generated from a wind turbine in a specific time period, you can look at the turbine's capacity factor. A suitable capacity factor is found to be between 0.25 and 0.30 [2].

2.2. Wind Turbine Generator

Turbines provide mechanical power that must be converted to electrical power using a generator, which uses the faraday law of electromagnetic induction to accomplish so. AC synchronous, DC, and AC asynchronous generators can all be employed with different wind turbine systems [4]. In theory, these devices are able to run at either a fixed or variable pace. Because of wind's fluctuating nature, it is preferable to run wind turbine generators at variable speed in order to reduce stress on the turbine blades and improve aerodynamic efficiency and transient torque behaviours of the system [4]. The following section explains the many types of generators, which will lead to a comparison between them in order to choose the best one for this project.

a. DC Generators

Traditionnal DC machines use field windings on the stator instead of rotating the armature, and their stators are made up of several poles energised by either permanent magnets or DC field winds. Shunt wound DC generators are used if the machine is excited electrically. When using DC shunt wound generators, there is an increase in field current as the speed of operation increases, but this does not necessarily translate into an increase in wind turbine speed. The split-slip ring commutator is coupled to the armature by the conductor windings that make up the rotor. Power is extracted from the commutator using brushes, which are also used to convert AC power to DC. Because of the commutators and brushes, these DC generators need to be maintained on a regular basis and are quite expensive [4].

There is less use of DC generators in wind turbine systems, compared to applications where the load is near to the wind turbine (e.g., heating applications or battery charging).

b. AC Asynchronous Generators

Accumulated experience and cheap maintenance costs are just some of the advantages of asynchronous generators (also known as induction generators) [4]. Continuous supply of reactive power is necessary for the generation of voltage and the provision of active power by these generators. Because the turbine spins at such a low speed, a gearbox is required in these generators. Depending on the type of rotor used, these induction generators or asynchronous generators can be divided into fixed squirrel cage induction generators (SCIG) and doubly fed induction generators (DFIG) . In contrast to the stator's three phase windings, the DFIG rotor's comprises of shirt-circuited conducting bars, whereas the SCIG rotor is designed like a squirrel cage. Figures (2.6) and (2.7) show the diagrams of squirrel cage induction generators and doubly fed induction generators, respectively.

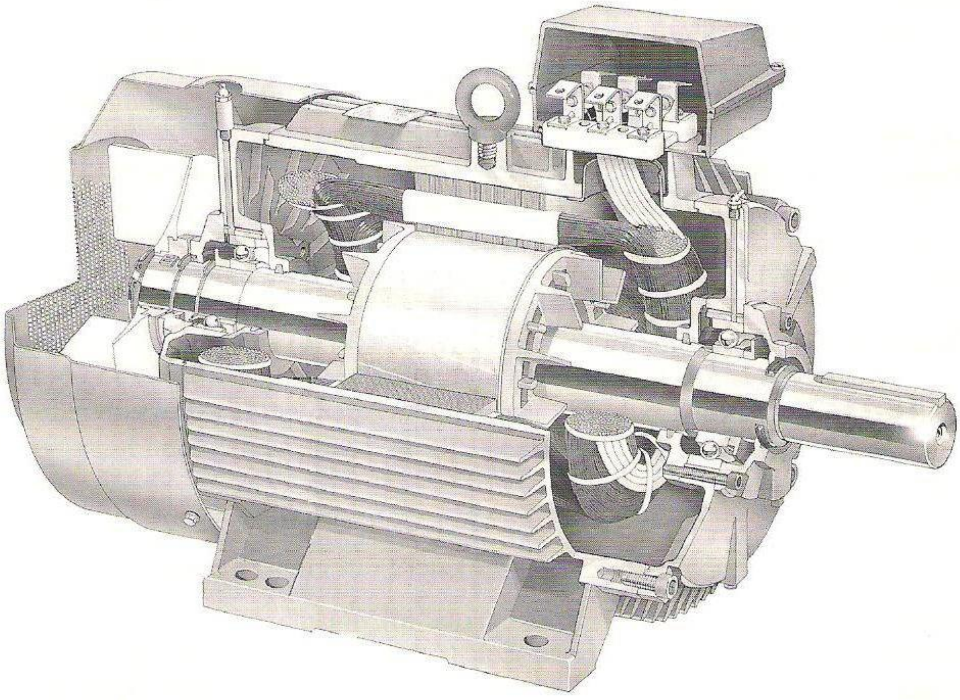


Figure (2.6): - Cutaway diagram of SCIG

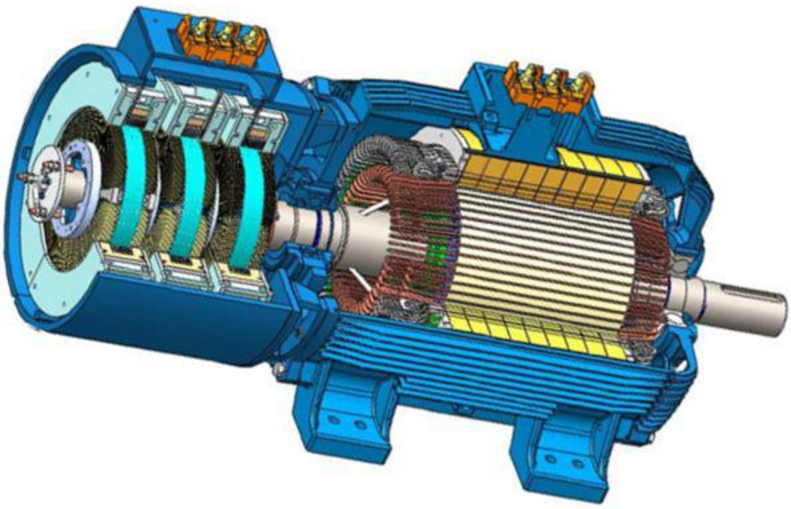


Figure (2.7): - Cutaway diagram of DFIG

When it comes to DFIG-based standalone WECS, the stator is the component that is connected directly to the load bus, while the rotor is connected via power converters. While the flow of power in the stator is always in the same direction, the flow of power in the rotor can go in any of several different directions, depending on how the generator is being operated. When the generator is operating subsynchronously, below the synchronous speed, the rotor works as a receiver, which means it is receiving the power. If the generator runs faster than the synchronous speed, known as super-synchronously, then the rotor is the component that delivers the power. Because of the smaller size of the power converters and filters that they use, these DFIG generators are the optimum option for high-power grid-connected wind energy conversion systems. This results in a significant increase in economic benefit. However, this DFIG cannot be used in a low power solo wind turbine system because of their power requirements. These generators have a number of advantages, one of which is that they do not require any external VAR compensators in order to excite the stator. Instead, they are able to obtain power from the rotor circuit by use of power converters. In addition to these benefits, the employment of brushes and slide rings in DFIG results in a decrease in the device's reliability as well as an increase in the amount of maintenance that must be performed [4].

The rotor of the SCIG is made up of longitudinal conductive bars that are put into grooves and then short circuited by other bars. The issues that plagued DFIG, such as brushes and slide rings, as well as the complexity problem, are addressed and resolved by SCIG.A Squirrel Cage Induction Generator based WECS requires full capacity power converters to receive the most power available from the wind and to fully regulate both reactive and active power, despite being the smallest, cheapest, and most resilient structure.This machine has also piqued the interest of several research projects such as simulator design, emulator setup and new power converters and control systems as well as self-excitation and voltage building up approaches in stand alone and hybrid microgrids. [4].

c. AC Synchronous Generators

A synchronous generator's stator is identical to an induction generator's stator in structure.However, the rotor form of a synchronous generator might be cylindrical or salient. A salient rotor has concentrated windings on the pole and an air gap that is not uniform, in contrast to the cylindrical rotor, which has a distributed winding and a consistent air gap. For applications that need a low rotational speed, salient-pole rotor synchronous generators are utilised because of their short axial length, big diameter, and high number of poles. Synchronous generators have a number of advantages over induction or asynchronous generators, the most significant of which is the capacity to function without a gearbox, which in turn lessens the amount of upkeep that must be performed, improves the system's dependability, and boosts its overall efficiency.

Wind turbines that utilise synchronous generators are frequently referred to as gearless wind turbines or direct drive wind turbines. This is because the gearbox is not present in these types of wind turbines [4]. Due to the necessity for a more number of poles in the rotor, direct drive generators are heavier, bigger, and more expensive.. This advantage comes with some drawbacks, however, which are that the elimination of the gear box saves money, but with this benefit comes some drawbacks as well. These drawbacks include: In order to lower generator speed needs and ensure that the turbine's speed is matched despite the lack of a gearbox, increase in number of poles is necessary. In general, AC synchronous generators for wind turbines can be broken down into two categories: wound rotor synchronous generators (WRSG) and permanent-magnet synchronous generators (PMSG). Both of these types of generators, as well as their applications in wind energy conversion systems, will be discussed in the following paragraphs. Figure 2.8 is a cutaway diagram of a synchronous generator that is traditionally utilized [5].

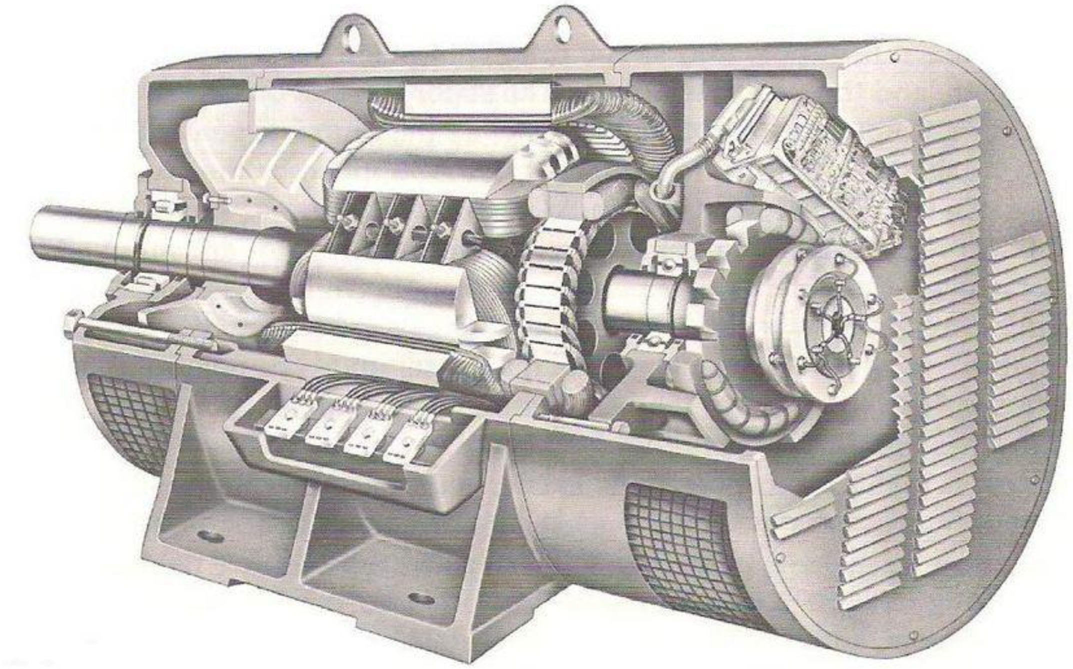


Figure (2.8): - Schematic diagram of synchronous generator

Brush-less exciter or DC source with slip rings and brushes are both viable options for the wound rotor type synchronous generator's rotor field winding. Brush-based excitation is a simple way, but it requires frequent brush and slip ring maintenance, whereas a more complex and expensive method involves power electronics and an auxiliary AC generator. Due to the excitation by DC current, these WRSG are also known as electrically excited synchronous generators [4]. With the help of DC/DC converters, the field winding of the rotor is typically energised. The stator terminal of these converters can be kept at a constant voltage thanks to the way they are managed. An automated voltage regulator might be useful in these situations. Wind turbines, particularly those located off-grid, could benefit from the use of stand-alone WECS powered by wound rotor type synchronous generators but the necessity for external DC power to excite the rotor windings through slip rings and brushes may raise the complexity and cost of the device[5].

The PMSG (permanent magnet synchronous generator) is another type of synchronous generator that uses brushless self-excitation for the rotor. The structure of the PMSG is relatively straightforward and is depicted in figure (2-9). The rotor is fitted with strong permanent magnets to provide a continuous magnetic field, and the generated power is collected in the stator (armature) using a commutator, slip rings, as shown in the diagram. Sometimes, in order to bring down the overall price, the permanent magnets might be combined into a cylindrical rotor made of cast aluminium [3]. Because of lack of brushes, slip rings, and commutators, these permanent magnet synchronous generators are durable, reliable, and straightforward. Due to the fact that magnets take the place of field windings in permanent magnet generators, these types of generators do not experience the power losses that are often associated with having windings in the field. On the other hand, this renders the control of the necessary field impossible, and the cost of the magnets employed in these generators will be greater for larger machines [3].

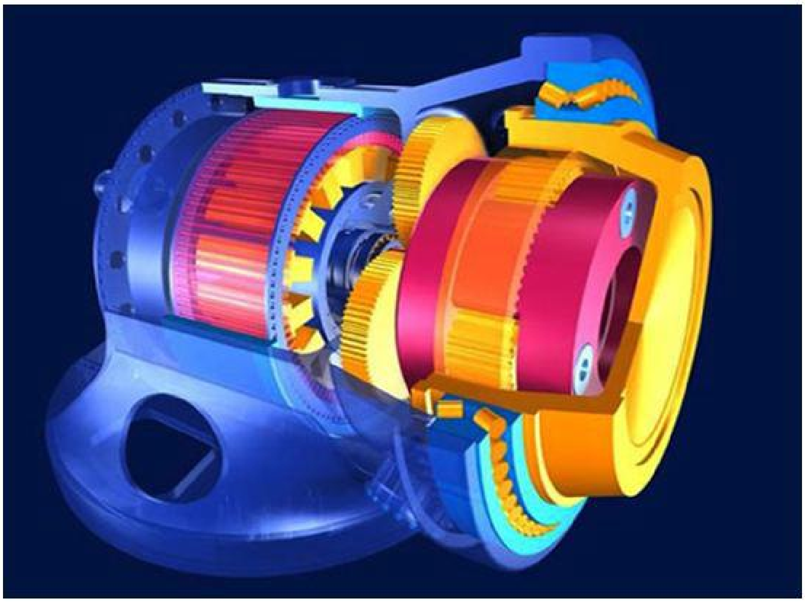


Figure (2.9): - Cutaway diagram of PMSG

There are two distinct categories that can be assigned to these generators on the basis of how the permanent magnets are attached to the rotor. There are two types of permanent magnet synchronous generators: the first type is surface-mounted permanent magnet generators, and the second type is inset-magnet permanent magnet generators. In the first type, the magnets are attached to the surface of the rotor, which compromises the mechanical integrity of the structure and creates the possibility that the magnets will come loose from the rotor as the rotational speed increases. Because the magnets in the later kind are installed inside the rotor body, this configuration is well suited for use in situations that involve high rotational speeds [4]. The high efficiency drive provided by these inset magnet permanent magnet synchronous generators is achieved through the combined application of reluctance and magnetic torque.

For small-scale direct-drive wind turbine systems, PMSG have emerged as the most popular choice in recent years.. This holds true for applications involving turbines connected to the grid as well as those using stand-alone wind turbines. Higher efficiencies are provided for a variety of rotor structures by inset permanent magnet synchronous generators used in large-scale wind turbines. However, due to the fact that these permanent magnet synchronous generators include hefty and huge magnets, it is possible that they are not the best choice for large-scale wind turbines. Numerous articles have proposed a lightweight construction for permanent magnet synchronous generators as a solution for large-scale direct drive wind turbines so that this issue can be resolved. The structure would reduce the weight of the generators [5]. presents a contrast between the two distinct kinds of generators that can be used in wind turbines, namely the geared or indirect-drive squirrel cage induction generator and the direct drive permanent magnet synchronous generator. These generators are compared in terms of the benefits and drawbacks that each one offers [5].

Table 1: Benefits and drawbacks of SCIG-WECS and PMSG-WECS

Topology	Indirect-drive SCIG	Direct-drive PMSG
Common properties	Brushless machine	
	No windings in rotor	
	Full active and reactive power control	
	Good control bandwidth	
Advantages	Robust operation	Gearless
	Low cost	Self excited
	Low maintenance	High PF operation
	Easier in control	High efficiency
		No rotor Copper loss
Disadvantages	Gear box losses and maintenance	Magnet cost
	Need for external excitation	PM Demagnetization
	Low efficiency	Large size
		Complex control
		Cogging torque

To compare the performance of these generators, along with their benefits and drawbacks, see table 2.

Table 2: - performance comparison of different generators used for wind turbines

Performance indicator	DC generator	SCIG	PMSG
Speed	variable	Fixed	Variable
Power supply	Directly to grid	Directly to grid	Totally via converters
Voltage fluctuations	high	High	Low
Converter Scale	100%	0%	100%
Controllability	Poor	Poor	Good
Active-reactive power Control	No	Dependant	Separate

Grid support capability	Low	Low	Very High
Efficiency	Low	Low	Very high
Reliability	Poor	Medium	High

2.3 Model of Generator Used in Project

After considering all of the available generators and learning about the benefits that each one offered, it was determined that the best choice for this particular small scale wind turbine project would be a permanent magnet synchronous generator. This was the type of generator that had the capacity to demonstrate the benefits that were necessary for this project. It was decided to make use of an already given model of a permanent magnet synchronous generator in Matlab Simulink. Created in Matlab, this PMSM has a three-phase back EMF and a round shape. The machine was given a sinusoidal back EMF. Figure (2.10) illustrates the parameters for the permanent magnet synchronous machine selected.

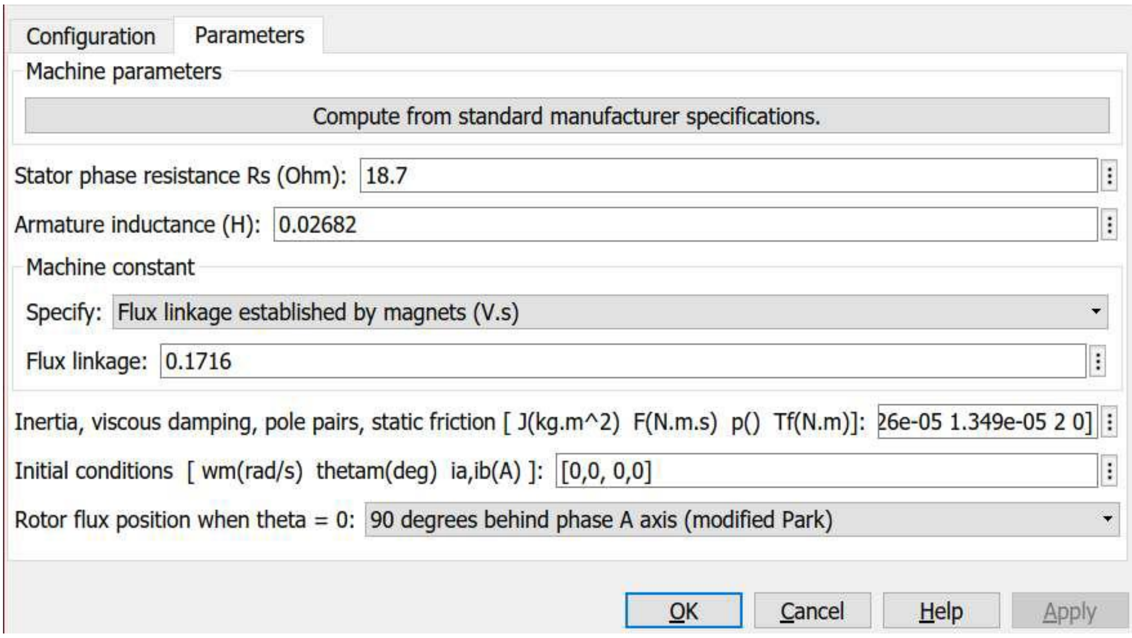


Figure (2.10) :- Parameters of PMSM in Matlab in project

2.4 Power Electronics for Project

After the wind turbine and generator have generated the electrical energy from the kinetic energy of the wind, the power electronics are required. In the last 30 years, the microprocessor technologies and semiconductor devices have advanced significantly, resulting in a growth in the number of applications that use power electronics [6]. The growth of technology has led to an increase in performance and a decrease in the cost of equipment . An integrated system of electricity, electronics, and control is referred to as "power electronics." Power electronics control is concerned with the steady-state and dynamic characteristics of the closed-loop system. Electricity production, transmission, and distribution are handled by Power. Solid-state devices are used to process signals in electronic components to satisfy desired control objectives [7].

Semiconductors are used in the construction of power electronic converters, which perform conversion operations and regulate voltage magnitude and conversion. There are converters that can allow the passage of electricity in both directions depending on the circuits and applications. In terms of power converter systems, there are two primary categories: grid-connected converter systems and self-commuting converter systems. A thyristor with a large power capacity of six, twelve, or even more pulses is utilised in grid-commuted converter systems. Reactive power cannot be controlled by a thyristor converter because it uses inductive reactive power. As a result, thyristor converters are commonly found in high-voltage direct current (HVDC) systems [8].

It is common for self-commuting converter systems to use a pulse width modulation (PWM) control mechanism in which the majority of semiconductor devices with the ability to turn off are used. Active and reactive power can be transferred in both directions using these converters (ac-dc or dc-ac). There is a need for reactive power, and a PWM converter can supply it. Since the PWM converter uses high frequency switching in the range of kilohertz to generate harmonics and inter harmonics, they are susceptible. Due to the high frequency of harmonics, it is easier to remove them with the use of small-size filters [8]. Pulse width modulation (PWM) converters were employed after the generator portion in this small wind turbine installation. To adjust voltage and frequency, convert DC to AC, and convert DC back to DC are all primary functions of power electronic circuits or converters.After a generator produces power in three-phase AC form, a circuit is needed to convert the alternating current into direct current, which can then be stored in a battery. After the generator part, a three-phase bridge rectifier was employed to achieve this goals. As an alternative to using a rectifier, buck or boost converters were commonly employed in power electronic circuits to achieve the desired load-side DC voltage. A DC connection capacitor was also required between the rectifier and the buck or boost converter to limit the value of the ripples permitted at the output section. As may be shown in Figure (2.11), the power electronics project's basic block diagram.

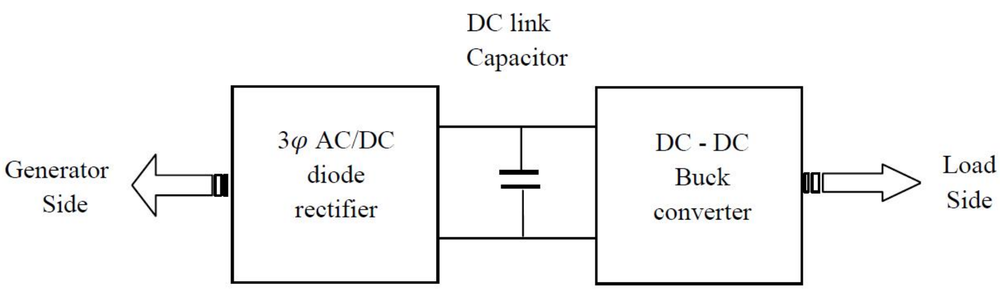


Figure (2.11): - Schematic diagram of the power electronics components of the WECS

The description of each of these blocks are provided in the following sections.

a. Three Phase Bridge Rectifier

A rectifier is a circuit that uses a diode semiconductor device to convert an ac signal into a dc signal or unidirectional signal. Due to its functionality, a rectifier is also known as an ac-dc converter. Only the negative portion of the waveform appears as a positive value at the output of the rectifier, which is exactly the same as the waveform of the input voltage. The rectifier can be divided into two varieties based on the type of input signal it receives: single phase and three phase. Additionally, these rectifiers can be either half- or full-wave rectifiers, depending on the model. Full wave output is accessible for both positive and negative cycles of the input voltage, whereas half wave output is only available for positive cycles of the input voltage [7].

It was necessary to employ a three-phase full-wave rectifier for this project, as the generator's output voltage was three-phase. In high power applications, a three phase full wave rectifier (sometimes referred to as a 3- ϕ rectifier) is widely employed. In this project's model of the project, the source inductance for the bridge rectifier was regarded as inconsequential. Figure (2.12) shows a three-phase bridge rectifier circuit with a solely resistive load.

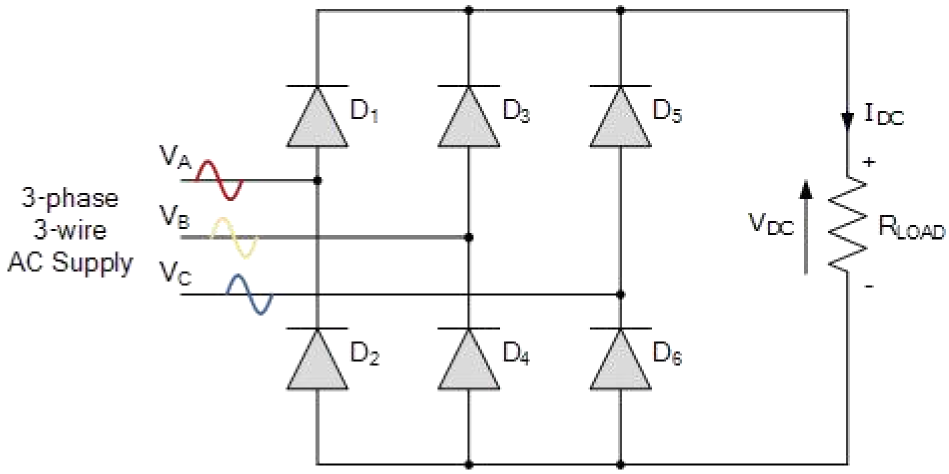


Figure (2.12): - Circuit diagram of 3- ϕ bridge rectifier [7]

The circuit diagram reveals that the 3- ϕ bridge rectifier consists of six diodes that can function even without a transformer, resulting in six ripples in the output voltage. Circuit diagram diodes are numbered in the same order as diodes are turned on in a conduction sequence. Diodes are turned on sequentially in the order D_1 - D_2, D_3 - D_2, D_3 - D_4, D_5 - D_4 , D_5 - D_6 and D_1 - D_6, with every diode conducting for a 120 degree angle. Connected diode pairs with the highest instantaneous line-to-line voltage tend to be conductors between supply lines. The line voltage is usually shown as a multiplication of the single-phase voltage [7]. Figure (2.13) shows the waveform of the three-phase bridge's input and output voltages, as well as the diodes that will be on.

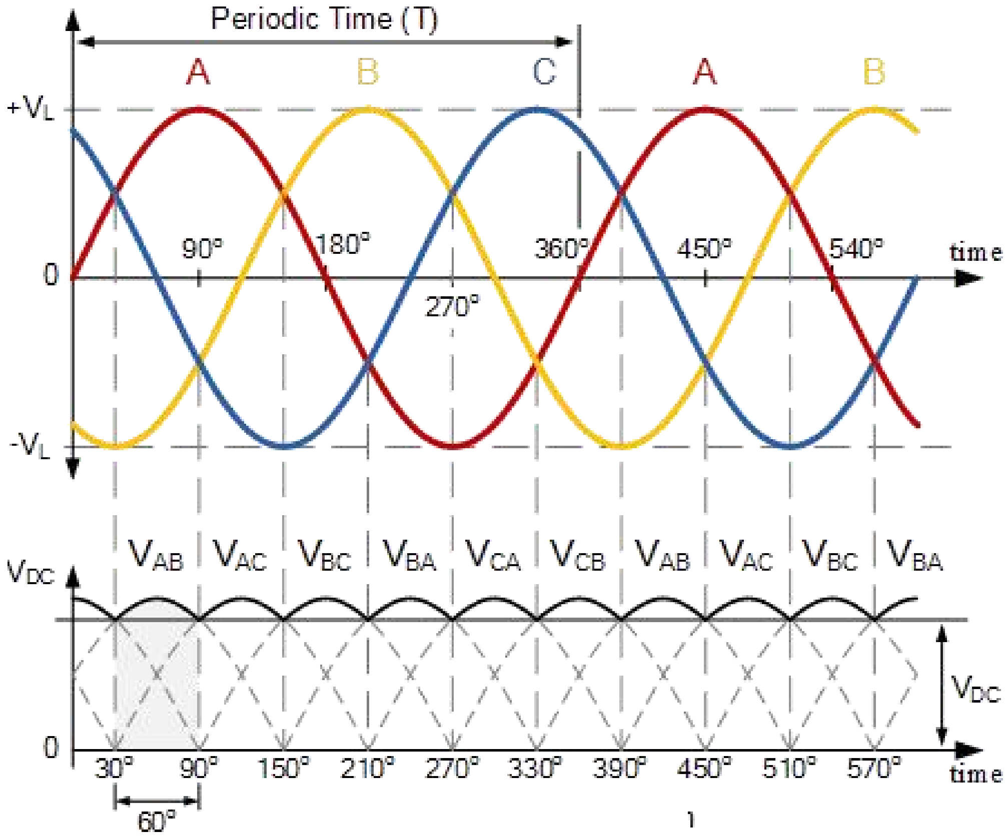


Figure (2.13): - Waveform of input and output voltage of three phase bridge rectifier [7]

The output voltage can be determined from the peak value of the phase voltage. Equation (2.10) shows the average output voltage at the load side of the final rectifier.

$$V_{dc} = \frac{2}{\frac{2\pi}{6}} \int_0^{\frac{\pi}{6}} \sqrt{3}\ V_m \cos wt\, d(wt) = \frac{3\sqrt{3}}{\pi} V_m = 1.6542\ \mathrm{V_m} \qquad (2.10)$$

The RMS value of the output voltage is given in equation (2.11) [7]

$$V_{rms} = \left[\frac{2}{\frac{2\pi}{6}} \int_6^{\frac{\pi}{6}} 3{V_m}^2 cos^2 wt\ d(wt)\right]^{\frac{1}{2}} = 1.6554\mathrm{V_m} \qquad (2.11)$$

If the load is entirely resistive diode current is calculated by the value of the the input voltage and load voltage as $I_m = \sqrt{3}\frac{V_m}{R}$ in which of diode current is given as $I_d = 0.5518 I_m$ in RMS and similarly the RMS value of the transformer secondary current can be found as $I_s = .7804 I_m$ where I_m being the peak value of the secondary line current [7].

As a result of the non-linear nature of the diodes in the rectifier, harmonic distortion of the input current is increased at its output. A DC link capacitor is used between the rectifier output and the input of the inverter part of the power electronic circuit for this project. This helps to eliminate any ripples or harmonics that may be present in the output voltage.

b. Designing of Dc Link Capacitor for Rectifier and Converter Section

In general, the DC link capacitor should be located between the rectifier portion as well as the inverter section. The DC link capacitor's principal job is to maintain a constant DC voltage with just minor output ripples during steady state. Additionally, the DC link capacitor acts as a storage element for energy, which allows it to supply the real power difference between the load and the source during transients [8].

Real power must be given by the source in steady state, together with a tiny amount of power to compensate for active filter losses; this is the assumption in steady state. As a result, a reference value may be established for the voltage of a DC link [8].

If, on the other hand, the state of the load changes, the relationship between the source and the load will be thrown off. To make up for the power discrepancy, a DC link capacitor is used. The DC link voltage, which varies from the reference voltage, is likewise affected by this discrepancy. Active filters must work successfully if the peak value of the reference current is modified to match the real power drawn from the source.. The DC link capacitor is used to charge and discharge the real power in order to compensate for the power that the load has utilised. The real power supplied by the source should match the load power used again once the DC link voltage is recovered and has reached the same value as the reference voltage . By adjusting the DC link capacitor's average voltage, the peak current of the reference source could be achieved. The real power drawn from the source has to be raised in order to fulfil the demands of the load. In contrast, a lower reference source current is sought by using a higher DC link voltage in comparison to the reference voltage .

The DC link capacitor is also responsible for giving a low impedance channel current of high frequency. DC voltage at the capacitor's input and cable inductance increase impedance as signal frequency rises. This is known as ripple current because the DC connection capacitor becomes the preferred path for the AC current to flow when the impedance of the DC link diminishes. In addition to the DC link capacitor, a DC bus stiffener is employed. Since voltage ripples on the DC bus are shown in a phase current as ripples, a stiff DC bus is necessary. The DC bus ripple voltage standard is used to determine the capacitance value necessary [9].

In general, there are more ripples in the DC-link voltage when there is an unbalanced load than when there is a balanced load. Voltage ripples also cause ripples in the currents that are used to balance the voltage. So, the three phase compensated currents don't have the same RMS value and total harmonic distortion (THD). So, to limit the ripples in the DC link voltage, a capacitor with a higher value is needed. This produces a reference current with no ripples. Also, this reference current with no ripples makes a compensated source current better.

When choosing the value of the capacitor, you can take into account the of the peak-to-peak switching ripple's highest value Δv_{pp}^{max} or the switching ripple's RMS value ΔV_{rms} to reduce voltage ripples.

So, you can figure out the value of the DC link capacitor by using the equation (2.12) below, which also takes into account the maximum value of the output current I_o^{max} [10].

$$C = \frac{1}{8f_s}\frac{I_o^{max}}{\Delta v_{pp}^{max}} \tag{2.12}$$

c. Buck Converter/ DC-DC (Step Down) Converter

The primary purpose of a DC – DC converter, which is often referred to simply as dc converters, is to convert the voltage straight from DC to DC. It is possible to think of it as the dc equivalent of an AC transformer that has a turn ratio that varies continually. It is possible to use it an AC transformer in order to increase or reduce a direct current voltage. In the instance of a DC converter, as it operates in DC, and the converter is able to DC output voltage according to our requirement by starting with either a fixed or variable DC voltage as its input. In an ideal situation, the DC-DC converter's output voltage and input current would both be pure DC. However, in practise, the converter exhibits harmonics and ripples in both its output voltage and its input current [7].

In order to change an unregulated DC voltage into a regulated one, switching mode regulators, also known as DC Converters, are utilised. Pulse width modulation is the technique that is used in conjunction with switching devices like as MOSFETs, BJTs, and IGBTs in order to provide this regulation. In this project, a buck converter was utilised to bring down the value of the voltage that was created after the section that rectified the current [7].

A buck converter is characterised by having an output voltage that is typically lower than the input voltage. It is made up of one active switch, which can be turned on or off depending on the duty cycle of the pulses that are sent to it, a diode, and a filter. Figure (2.14) presents the schematic representation of the buck converter's circuitry.

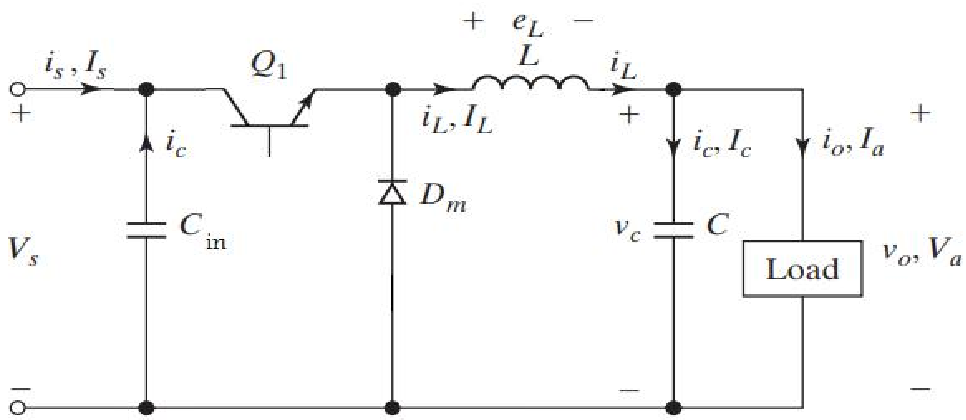


Figure (2.14):- Circuit diagram for buck converter [7]

The diode in this circuit is an uncontrolled switch, while the transistor in this circuit functions as a controlled switch. They are designed to function as a pair of single pole single through (SPST) bidirectional switches [7].

The dynamic character of the input current is due to the transistor's exposed input. This is unwanted because it causes noise to be introduced into the system. Because of this, there must be a capacitor located at the input of the converter, and the DC link capacitor is responsible for fulfilling this function.

This buck converter is capable of operating in two distinct modes (CCM) with a constant frequency and high current, and (DCM).

Through Mode 1, the transistor is turned on at time t = 0 in mode 1. The input current increases as it runs through the filter inductor L, the filter capacitor C, and the load resistor R. Figure (2.15) 1 depicts the equivalent schematic diagram of the buck converter in mode 1.

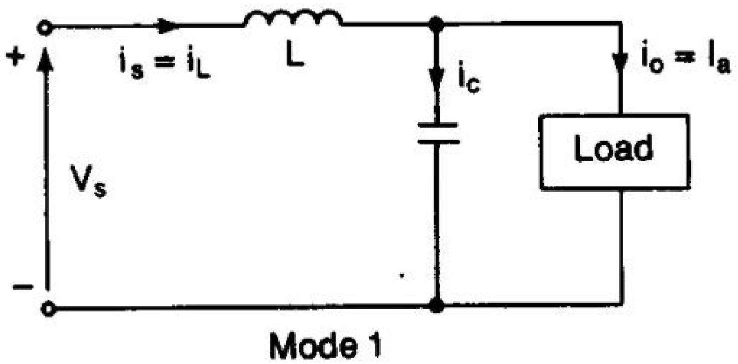


Figure (2.15): - Equivalent circuit diagram of buck converter for mode 1 [7]

Mode 2 commences when transistor is turned off at t =. Because of inductor's stored energy, the freewheeling diode starts conducting and the inductor's current passes through the filter inductor L, the filter capacitor C, a load resistor R, and the diode. When the transistor is turned on for the following cycle, the inductor current falls again. Figure (2.16) depicts the corresponding circuit diagram of the mode 2 functioning of the buck converter [7].

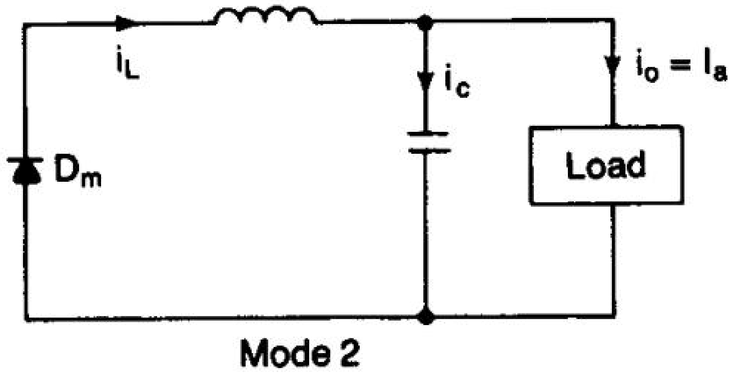


Figure (2.16):- Equivalent circuit diagram of buck converter for mode 2 operation [7]

Figure (2.17) illustrates the waveform of the input and output voltages and currents for a filter inductor L that has a continuous flow of a current through it. It is assumed that the current goes up and down in a linear fashion in the figures that represent waveforms.

However, in real circuits, a switch will have a certain amount of nonlinear resistance. This resistance will be finite. The effect of the switch's nonlinear resistance is essentially inconsequential in the vast majority of implementations. Inductor current could have a discontinuous quality to it, depending on the values of the switching frequency and the values of the filter's capacitance, inductance, and inductance, respectively.

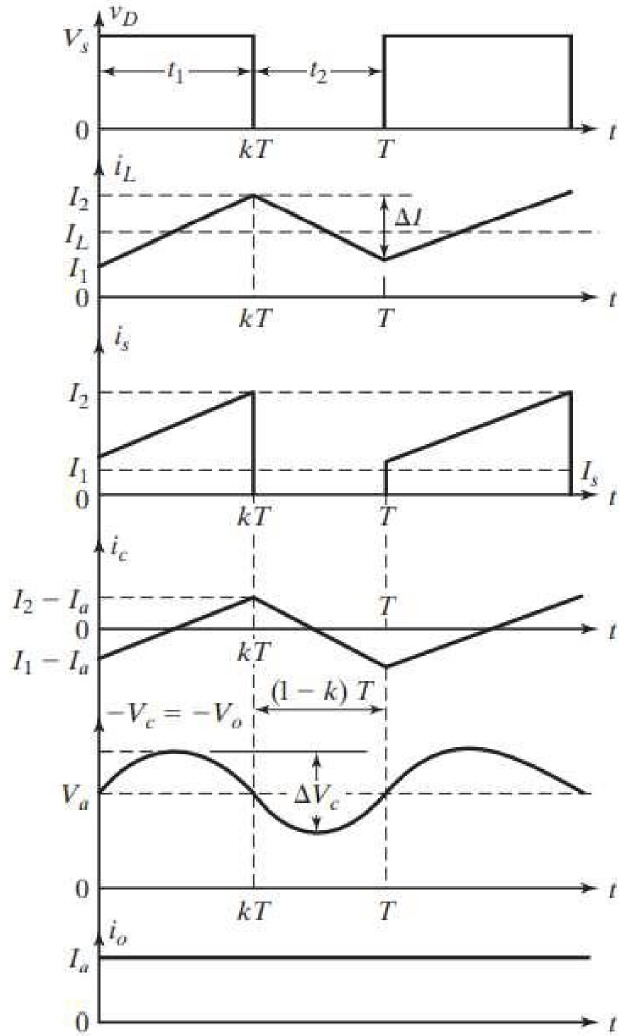


Figure (2.17):- Waveforms of the input and output voltage and current of buck converter for the continuous flow of inductor current

2.5 Energy Storage System

Energy storage units are devices that are able to gather and store energy from either directly from the grid or from other renewable energy sources.

As a result of the fact that electricity is a highly organised form of energy that is capable of being changed from one form to another in a very effective manner, it is more adaptable than other sources of power. For example, there is a very high efficiency with which electricity may be turned back into mechanical and heat form. However, due to the disordered nature of the heat energy, it is not possible to transform it back into an electrical form with the same level of efficiency.

The most significant drawback associated with wind power is that it does not consistently deliver the same amount of power and is unable to meet the requirements of the load at all times. Since an energy storage system is required to meet load requirements, it can compensate for changes in wind output power by storing power when it is higher than the goal value. Compressed air energy storage, hydrogen-based energy storage (fuel cells), flywheel energy storage, super conducting magnetic energy storage, super capacitors, and battery energy storage are some energy storage methods. [11].

The type of energy storage system known as a battery, which stores energy of charges in electrochemical cells, is by far the most common and widely used of the various types of energy storage systems described above. Multiple cells are typically connected together in a power system application. This is done so that the required output voltage can be brought up to the desired level. Electrolyte and an electrode are present in each and every cell . During the electrochemical reaction that takes place in cells, the movement of the ions inside the electrolyte causes the electrons to move, which either provides electrical energy or accumulates electrical energy [11].

2.5.1 Types of Electrochemical Batteries

There are typically two categories of electrochemical batteries to choose from. The first type of battery is known as a primary battery, and it works by converting chemical energy into electrical energy. Since this reaction in primary batteries is irreversible, the battery must be thrown away once it has been completely discharged. In most cases, they are utilised in applications that do not permit charging because of the nature of the device. These batteries is being used in a wide variety of devices, including military grade gadgets, battery driven devices, pace makers, animal trackers, wrist watches, and many others [12].

There is also something called a secondary battery, which is more commonly known as a researchable battery. These batteries contain an electrochemical reaction that can be reversed at will. By adding a specific voltage level in the opposite direction, it is possible to halt and even revert this reaction. These batteries are capable of converting chemical energy into electrical energy while they are in the discharging mode, but when they are in the charging mode, the process is reversed. There are two types of secondary batteries: those with a relatively low capacity (like those found in mobile phones) and those with a very large capacity (like those used to power electric cars). The chemistry that goes into making secondary batteries allows for further classification into a variety of sub-types [12].

The rating of the batteries is expressed in terms of the average voltage that is maintained during the discharge process as well as the ampere-hour capacity that can be delivered by the battery before the voltage falls below the limit that has been defined. The watt-hour (W-h) energy rating of a battery is calculated by multiplying its voltage by the amount of ampere-hour capacity it has. In a completely charged state, the battery is able to give this amount of energy to a load.

2.5.2 Battery Condition

a. State of Charge (SOC) %

The capacity which is already available in a cell is referred to as the state of the charge (SOC), and it is defined as a function of the rated capacity of the cell. The value of the SOC might range anywhere from 0% to 100% of its maximum potential. If the value of SOC is 100 percent, then the cell is considered to be totally charged, but if the value of SOC is 0 percent, then the cell is considered to be completely discharged. When the cell's state of charge (SOC) reaches 50 percent, it is time for it to be recharged because it is not permitted for the state of charge to go over that level in practical applications. Similar to how when a cell begins to age, the maximum value of its SOC starts to decrease. This implies that a fresh cell with 75% to 80% of its initial SOC would be similar to an elderly cell with 100% of its initial SOC [13].

In a broad sense, the term "state of charge" (SOC) refers to the ratio of a system's current capacity [Q (t)] to the nominal capacity [Q_n]. The greatest amount of charge that a battery is capable of storing is indicated by the battery's nominal capacity, which is often stated by the battery's manufacturer. According to [12], the formula for SOC can be found in the equation (2.13).

$$SOC(t) = \frac{Q(t)}{Q_n} \tag{2.13}$$

b. Self-Discharge Rate

Self discharge occurs when a cell's chemical processes leak current between both the anode and cathode. Even if the cell is not being used, it is possible for it to still become discharged to a certain degree as a result of some internal reactions. The chemistry of the cell, in addition to the temperature at which it is being run, determines the pace at which the cell discharges its own contents, known as self-discharge. The rate of self-discharging tends to accelerate along with a rise in temperature [13].

c. Discharge Rate

The pace at which a cell is discharged is another important feature that plays a role in influencing the performance of a battery. It has been demonstrated through a series of practical experiments that the capacity of the cell to hold charge reduces after it has been discharged for an extended period of time.

d. Charge/Discharge Ratio (C/D Ratio)

The ratio C/D is defined as the amount of ampere hours that are input relative to the amount of ampere hours that are output while there is no net change in SOC. This ratio is also dependent on the temperature, in addition to the pace of charging and the rate of discharging.

2.5.3 Control Strategies for Keeping Voltage of Battery Constant

A hybrid WECS with battery charging can employ one of two control algorithms to maintain the battery's voltage at a consistent level. Constant voltage and constant current charging systems are the two most fundamental and straightforward techniques of control. It is possible to integrate these two control systems into a single method of charging These strategies are described in more depth below.

a. Constant Voltage

A constant voltage is used to charge it up in this form of control. The battery's DC output voltage is compared to a reference voltage in this technique, and the difference is utilised to generate an error signal. An error signal and a triangle waveform are then supplied into a comparator. Pulse width modulation (PWM) signals are generated by the comparator and utilised to modulate the output voltage. PI controllers can also execute the comparator function. This controller can also be used to regulate a duty cycle. Figure (2.18) depicts the circuit diagram for this control [14].

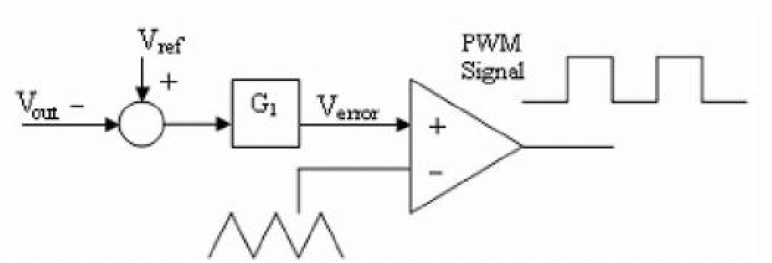


Figure (2.18): - Image depicting the constant voltage control

This approach can be harmful to the battery early in the cycle due to the high initial charging currents, which must be kept to a minimum to safeguard the circuit and the battery. Battery temperature can rise during this charging process, reducing battery lifespan [14].

b. Constant Current

The battery is charged with a constant current until it reaches a predetermined voltage using this control technique. The DC output voltage is compared to a reference voltage to obtain an error signal in this method of charging a battery at a constant current. It is then compared to battery current to get a second error signal, as illustrated in the Figure (2.19). When combined with a comparator and either a triangle waveform or a controller, this error signal can be utilised to modulate the output current using pulse width modulation [14].

At the conclusion of the cycle, this algorithm does more harm to the battery than good. Using a wind energy battery charging system, the wind determines the quantity of available current for a constant current charging method. Due to the high currents generated by this charging method, it has the potential to damage the battery and shorten its lifespan [14].

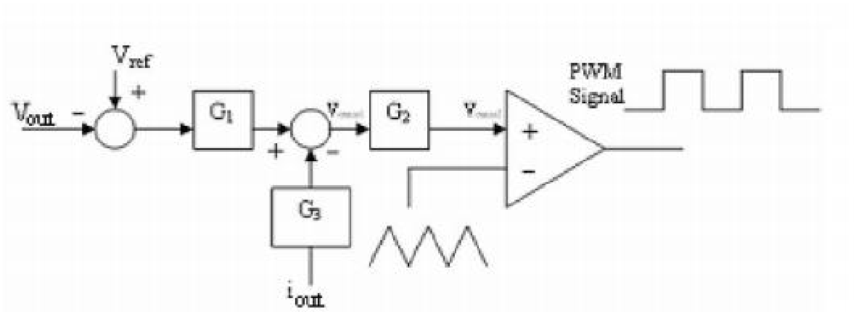


Figure (2.19): - Image depicting the constant current control

c. Constant Current-Constant Voltage

This method maintains a constant battery voltage by combining the ways of controlling the battery voltage using a constant current and a constant voltage. In the beginning of the charging cycle, the constant current charging method is utilised, and it stays in use until the predetermined voltage level of the battery is not reached.

The type of charging that uses a constant voltage is applied during the second phase of the charging cycle. In most cases, the development of this kind of algorithm takes place with consideration given to the specific drawbacks posed by both of the different approaches of charging. In most cases, charging with constant current and charging with constant voltage take place during the phases of the cycle in which the battery is subjected to the least amount of stress.

This technique of charging has its own set of drawbacks, including the fact that it does not take into consideration the current SOC of the battery. As a result, this method can be sluggish and inefficient, and it may cause gassing [14].

d. Pulse Charging

Pulse charging is another technique that can be utilised in the process of recharging the battery. A method known as current pulse is utilised to charge the battery in this approach. In order to lengthen the amount of time needed for charging, pulses with a wider width are utilised. Because this technique does not lead to gassing, it is more successful than the others, which in turn results in an increase in the efficiency of the battery as well as an extension of its life cycle. When using this method, gassing is avoided since the majority of the current would be used for battery charging instead of creating gas. This is possible because the current pulses are kept short [14].

2.6 Battery and Control Scheme

The Simulink model contained the simulation's battery. This device uses a standard battery model for most popular battery types. Lithium-ion batteries were used. In this instance, the nominal voltage is 12 V and the rated capacity is 30 Ah to provide 360 watts of power.The parameters configuration is depicted in Figure (2.20).

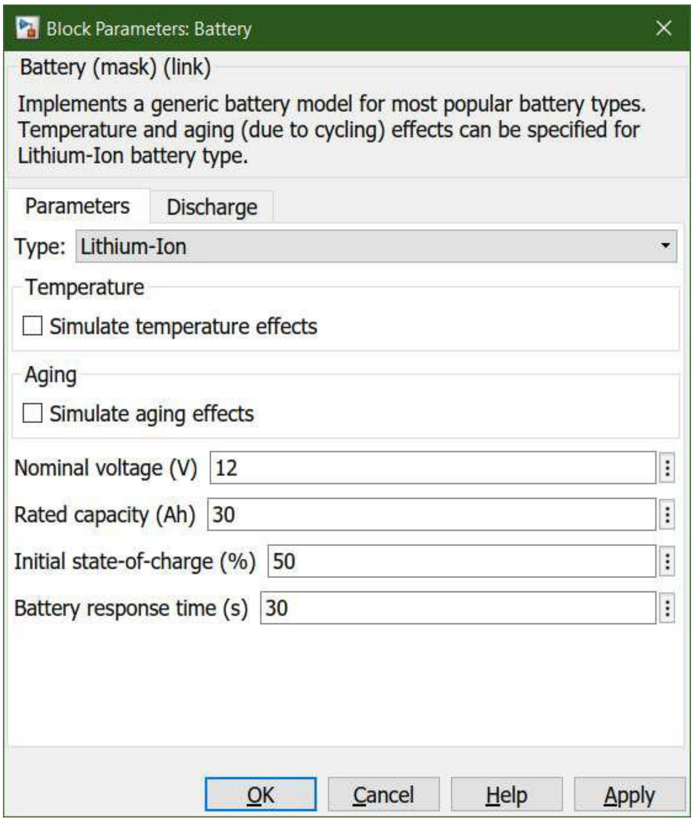


Figure (2.20):- Parameters set for battery for wind energy conversion system

The discharge characteristics of the battery are depicted in figure (2.21), which accounts for the settings that have been set for the battery. It was obvious from looking at the figure that when the value of the discharging current was high, the battery voltage dropped more quickly than when the value of the discharging current was low current.

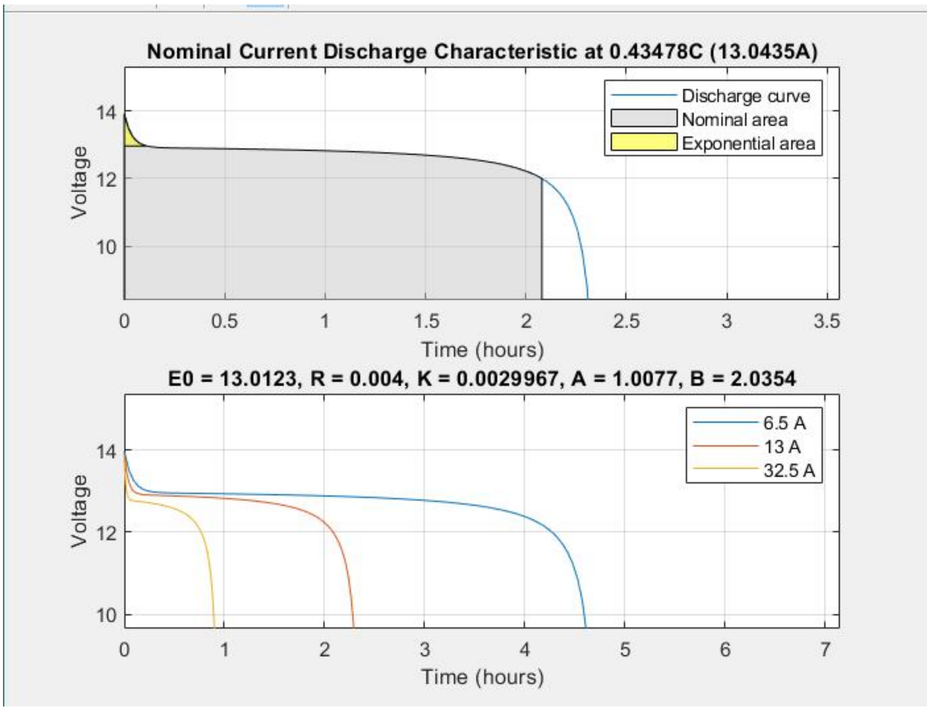


Figure (2.21):- Nominal current discharge characteristics of Battery

Sections of a typical discharge curve can be divided into three. The battery's charge-induced voltage drop is described in the first section. The width of the drop is determined on the battery type. Until the battery reaches its nominal voltage, the second part of the battery reflects the amount of charge that can be recovered from the battery. Finally, the battery's total discharge is depicted in the third part, which occurs as the battery voltage rapidly declines.

In this project, a constant voltage charging approach was employed to implement a control strategy for battery charging. To obtain an error signal, the buck converter's output was attached to the battery and then used with a reference voltage. The duty cycle of the buck converter switch was calculated using this error signal and a PI (proportional integral) controller.

Chapter 3
PROPOSED METHODOLOGY

3.1 Wind Turbine Mathematical Modelling

The equation (3.1) can be used to express the mathematical relationship for wind mechanical power extraction.

$$P_m = C_P(\lambda,\beta).P_w = C_p(\lambda,\beta).\frac{\rho.A.V_w^3}{2} \tag{3.1}$$

The equation (3.2) for the tip speed ratio of the wind turbine is as follows:

$$\lambda = \frac{R \times \omega_m}{V_w} \tag{3.2}$$

where ω_m denotes the angular velocity of the turbine rotor and R represents the blade radius of the turbine.

It's possible to write the power coefficient Cp as equation (3.3) [16, 17].

$$C_p\,(\lambda,\beta) = C_1(C_2\frac{1}{\lambda_i} - C_3\beta \;-\; C_4)e^{-\left(C_5.\frac{1}{\lambda_i}\right)} + \;C_6\lambda \tag{3.3}$$

Where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1})$$

And C1=0.5176, C2=116, C3=0.4, C4=5, C5=21 and C6=0.0068.

The equation (3.4) provides a way to express the torque that is produced by the wind turbine [18].

$$T = C_p(\lambda,\beta).\frac{\rho.A.V_w^3}{2.\lambda} \tag{3.4}$$

Figure (3.1) illustrates how the $C_p - \lambda$ characteristics of a wind turbine change depending on the value of the pitch angle β. It is obvious from the picture that a maximum C_p value of can be attained for a fixed pitch angle of or $\beta = 0^{\circ}$ given that the tip speed ratio λ_{nom} must be at its nominal value of 8.1.

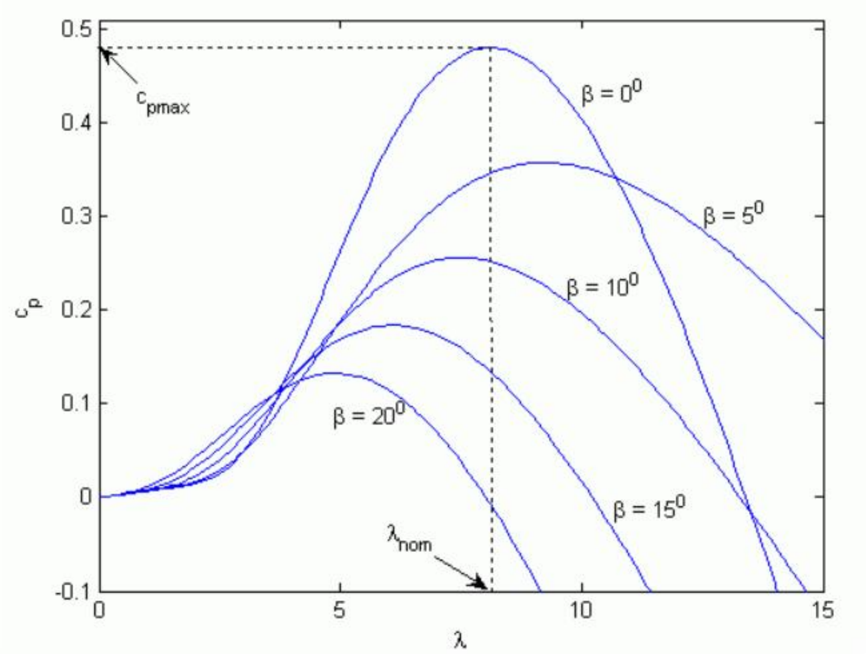


Figure (3.1):- characteristics of a wind turbine for different values of pitch angle

3.2 PMSG Mathematical Modelling

If iron is assumed to have infinite permeability, the magnetization curve, which represents the relationship between and, will have a linear shape. In the event that the magnetization curve is linear, the relation can be demonstrated numerically as in equation (3.5).

$$\phi_f = pF_f \tag{3.5}$$

According to Faraday's law, the value of the induced electromagnetic field (EMF) is proportional to the number of turns in the coil which is depicted in equation (3.6) & (3.7).

$$e_{af} = -N\frac{d\lambda}{dt} \tag{3.6}$$

$$e_{af} = N\omega_s\phi_f \sin\omega_s t \tag{3.7}$$

λ refers to the flux linkage of a single coil. The coil has a root-mean-square (RMS) value of induced EMF that is given as

$$E_f = \sqrt{2}\pi f N\phi_f \tag{3.8}$$

Where Φ represents the flux between poles.The amount of torque is denoted using the formula:

$$T_t = \frac{\pi}{2}\left(\frac{p}{2}\right)^2 \phi_r F_f \sin\delta \tag{3.9}$$

Where δ is the angle by which leads F_f leads F_r.

It is the induced emf that determines which way the positive current flows during motor motion. The mechanical power is generated as a result of the electromagnetic torque acting in the rotational direction on the field poles; as a result, it functions as a motor. It is possible to use an external 3 phase source known as an infinite bus to maintain an air gap emf of the same magnitude as the machine's terminal voltage i.e. $V_t = E_r$. This results in the machine acting as either a generator or a motor depending on its mechanical condition. The machine that serves as a generator is depicted in Figure (3.2). The dynamic equation is described in (3.10)

$$V_t = E_r - I_a(R_a + jX_L) \tag{3.10}$$

Where R_a is the machine resistance and X_L is the resistance between the terminal voltage and the air gap EMF.

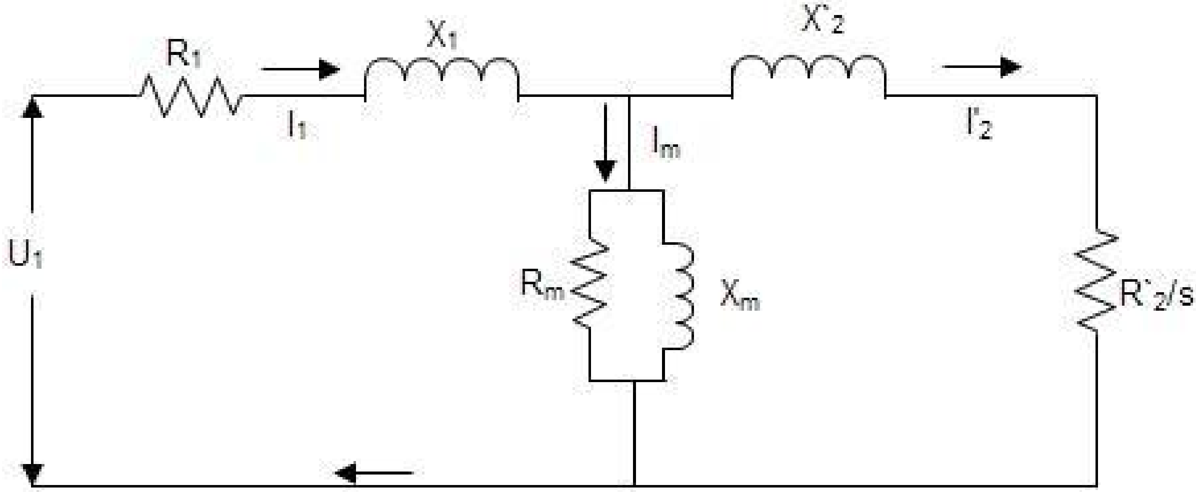


Figure (3.2) :- PMSG Circuit diagram

It's common practise to employ dynamic models in a two-phase coordinate reference frame, rotating at a reference speed, instead of the real three-phase abc frame for control and simulation [19,20]. For example, under steady state operation, sinusoidal values in the synchronous reference frame appear as DC quantities in the synchronous reference frame. Decoupling of torque and flow in three-phase systems becomes possible thanks to the mathematical reduction of linear equations [21,22].

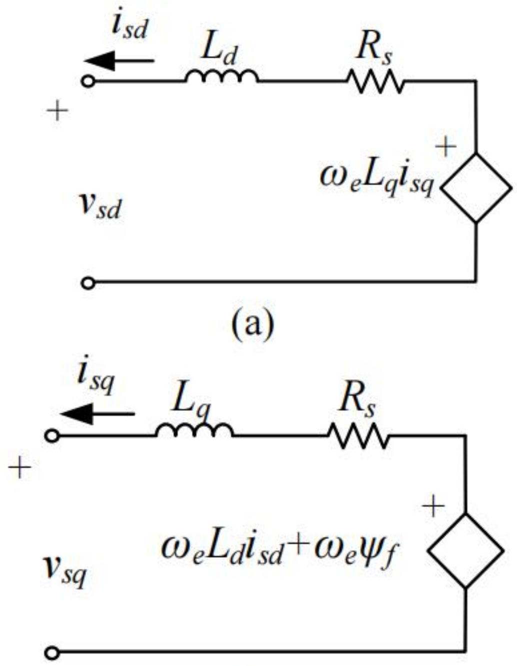


Figure (3.3):- The eq. circuit of a PMSG (a) d loop, (b) q loop.

PMSG model ignores stator core losses, hysteresis losses, magnetic saturation, and skin effect while assuming sinusoidal EMF. PMSG voltage are depicted in equation (3.11) and (3.12), assuming that the axes d_q rotate at a reference speed of ω.

$$v_{sd} = R_s i_{sd} + L_d \frac{di_{sd}}{dt} - \omega_e \psi_{sq} \tag{3.11}$$

$$v_{sq} = R_s i_{sq} + L_q \frac{di_{sq}}{dt} + \omega_e \psi_{sd} \tag{3.12}$$

For example, suppose d_q loops rotate at synchronous speed and the d loop aligns with the rotor flux, the components of stator flux are as follows:

$$\psi_{sd} = L_d i_{sd} + \psi_f \tag{3.13}$$

$$\psi_{sq} = L_q i_{sq} \tag{3.14}$$

Consequently, in the d_q synchronous reference frame the voltage equations are as follows:

$$v_{sd} = R_s i_{sd} + L_d \frac{di_{sd}}{dt} - \omega_e L_q i_{sq} \tag{3.15}$$

$$v_{sq} = R_s i_{sq} + L_q \frac{di_{sq}}{dt} + \omega_e L_d i_{sd} + \omega_e \psi_f \tag{3.16}$$

In equations Eq. (3.15) and Eq. (3.16), the d loop voltage component dependent on the q loop component also.

The stator current in the dq axis determines the electromagnetic torque which is given by equation (3.17)

$$T_e = \frac{3}{2} p[\psi_f i_{sd} + (L_d - L_q) i_{sd} i_{sq}] \tag{3.17}$$

3.3 Buck Converter Mathematical Modeling

It is inappropriate for charging batteries because of the tiny number of ripples in the DC voltage generated by the rectifier portion. Buck converters can be used as a solution to this problem because the power produced may be too high and volatile, causing harm to the battery. The fundamental function of the buck converter is to step down and stabilise this changing dc voltage so that the charging strategy may be applied. Figure shows the buck converter's equivalent circuit (3.4).

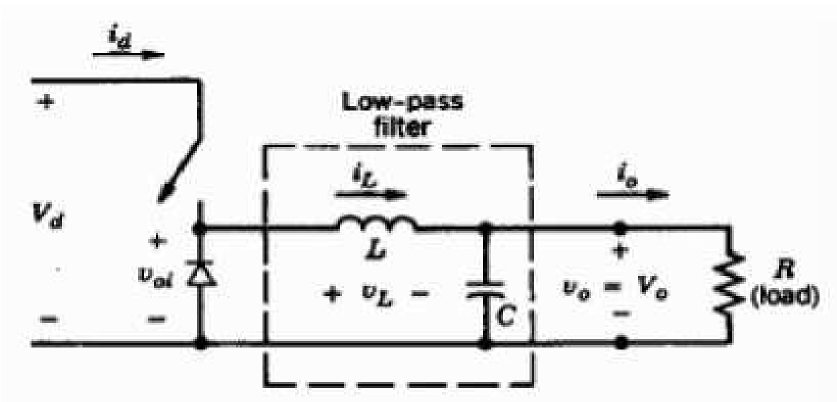


Figure (3.4): - Equivalent circuit of buck converter

The buck converter's output voltage is determined by multiplying the input voltage by the duty cycle, which can be anywhere from 0 to 1.

Modifying the duty cycle of the buck converter, which is used to regulate the switch of the converter, allows the current output and output voltage of the buck to be controlled. When calculating the values of the components that must be included in the converter, the duty cycle is an additional factor that must be considered. The equation (3.18) was utilised in order to obtain the value of the duty cycle.

$$\frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1}{D} \quad (3.18)$$

Where

I_0 is output current

I_d is input current

V_d is input voltage

V_0 is output voltage

The following equations were utilised so that the minimal value of the inductor could be calculated:

$$I_{LB} = \frac{DT_s(V_d - V_o)}{2L} \tag{3.19}$$

$$L = \frac{DT_s(V_d - V_o)}{2I_{LB}} \tag{3.20}$$

Where,

I_{LB} = inductor boundary current

Ts = switching period

Because the dc-dc converter's output voltage ripple must be less than 5%, the capacitor's value can be calculated using equation. (3.22)[23]:

$$\Delta V_o = \frac{T_s^2 V_o(1-D)}{8CL} \tag{3.21}$$

$$C = \frac{T_s^2 V_o(1-D)}{8\Delta V_o L} \tag{3.22}$$

Where,
C = value of the capacitor
ΔV_0 = output voltage ripple

Because the value of the capacitor and inductor are inversely related to the switching frequency of the buck converter, it is necessary to increase the frequency in order to reduce the overall cost [14].

3.4 Battery Mathematical Model and Controller for Battery Charging

The lithium-ion variety of Simulink model was chosen to represent the battery that will be utilised in the project. The charging state of the battery can be described by using the equation (3.23).

(3.23)

$$E_b = E_0 - Z * I - K * (Q/Q - it) * (it + I') + A * e^{(-B*it)}$$

Where,

E_b = EMF of a loaded battery (V)

E_0 = No-load battery EMF (V)

K = polarization constant (V/(Ah)) or (Ω)

Q = Maximum capacity of the battery (Ah)

it = $\int idt$ Remaining charge of the battery (Ah)

A = exponential zone amplitude (V)

B = exponential zone time constant inverse (Ah)

Z = internal impedance of the battery (2)

I = Load current delivered by battery (A)

I'= filtered current (A)

Because the DC/DC buck converter used for charging was connected to the first order output of the system, the voltage of the first order system was able to control the voltage of the lithium-ion battery. This allowed the charging method to maintain a constant voltage during the charging process. In a structure with a constant voltage, the feedback output voltage of the battery is controlled by a PI controller in order to maintain a constant duty cycle.

The Proportional Integral controller reduces high-frequency noise to improve the system and eliminate steady-state error, the battery's output voltage stabilises.[24]. Figure (3.5) displays the logical layout of the battery-charging mechanism for the second order .

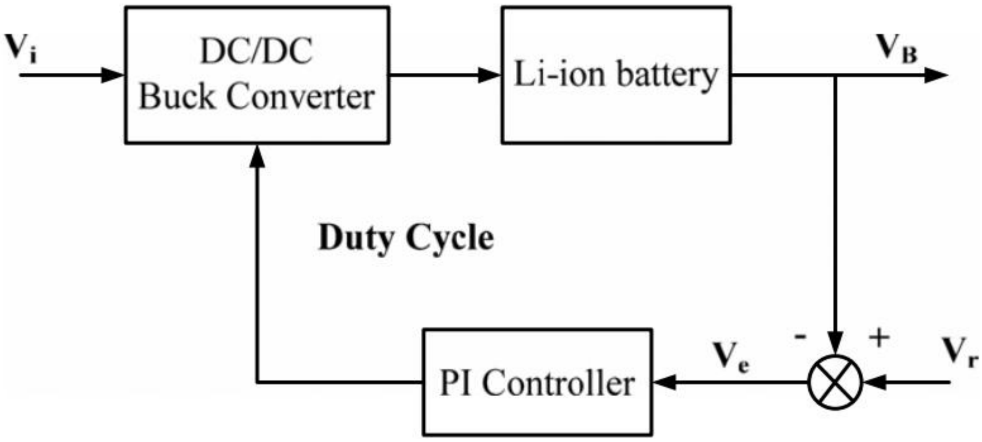


Figure (3.5):- Schematic of charging control

The PI controller ensures that the steady-state error remains at 0 at all times. This ensures that the battery voltage does not go above the control voltage, which ultimately results in the battery voltage remaining constant.

The transfer function is determined from this system, and DC/DC buck converter's equivalent diagram as illustrated in figure (3.6). This system is utilised to get the transfer function of the input and output.

The equation that describes the transfer function of the converter is as follows: (3.24).

$$\frac{V_o}{V_i} = D \times \frac{R(sCR+1)}{s^2RLC + sL + R} = D \times \frac{\frac{R}{L}s + \frac{1}{LC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}} \tag{3.24}$$

Where D is duty cycle of the DC/DC buck converter [24].

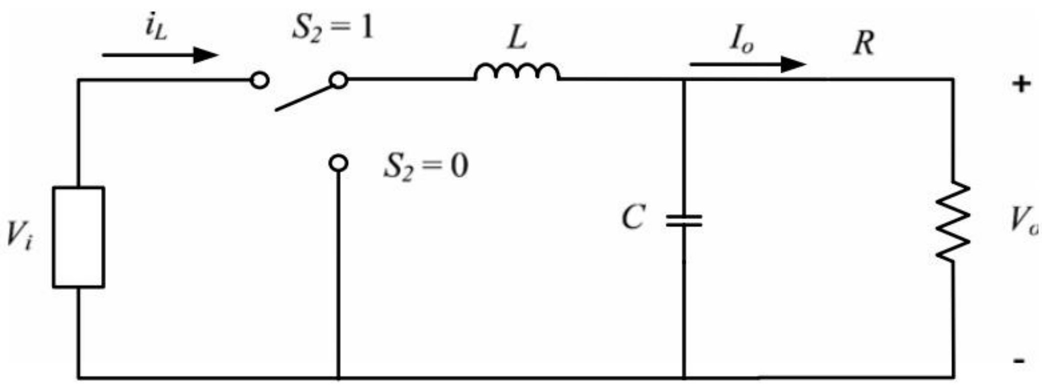


Figure (3.6) :- Diagram Of DC/DC Buck converter

The overall charging system's transfer function can be deduced from the transfer functions of each individual component of the DC/DC buck converter and the PI controller respectively. The equation for the transfer function is as follows: (3.25).

$$T(s) = \frac{V_o}{D} \times PI(s)$$
$$= V_i \times \frac{\frac{R}{L}s + \frac{1}{LC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}} \times \frac{k_P s + k_I}{s}. \tag{3.25}$$

Equation (5-31) is further used to find the function's characteristic equation, and the value of the proportional and integral gains was found by using the results of the Routh table method to solve the characteristic equation..

CHAPTER 4
RESULTS AND DISCUSSION

Figure (4.1) shows the simulated wind speed, and the rated wind speed is 12 m/s. Figures (4.2) - (4.6) show the results of the simulation for the generator's speed, generated power, electromagnetic torque, quadrature axis current, and direct axis current.

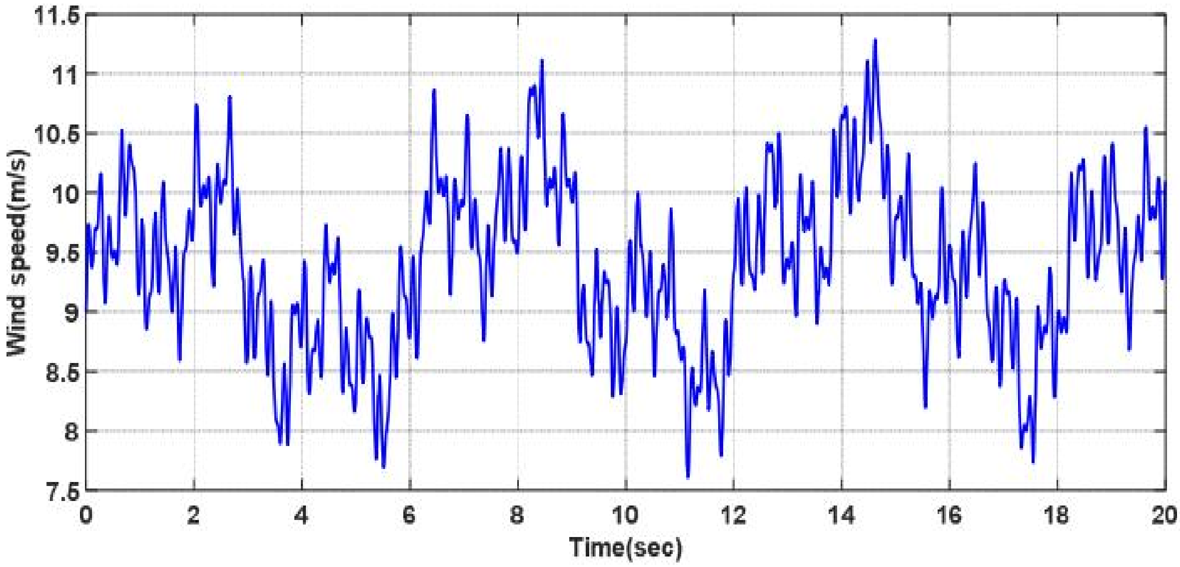


Figure (4.1) :- Wind Speed

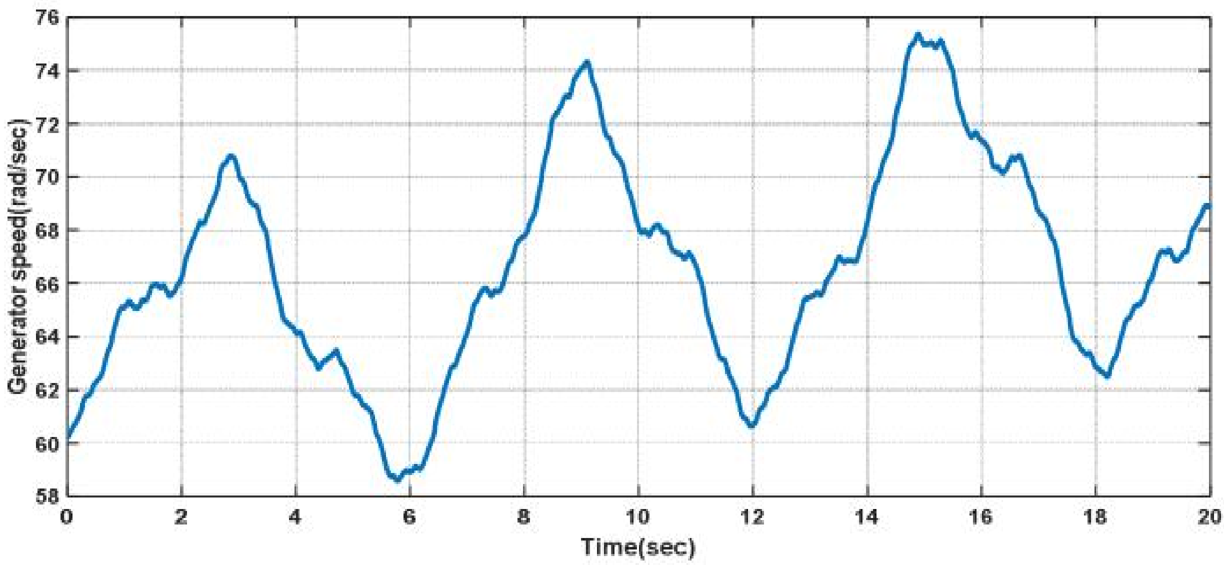


Figure (4.2):- Generator Speed (rad/sec)

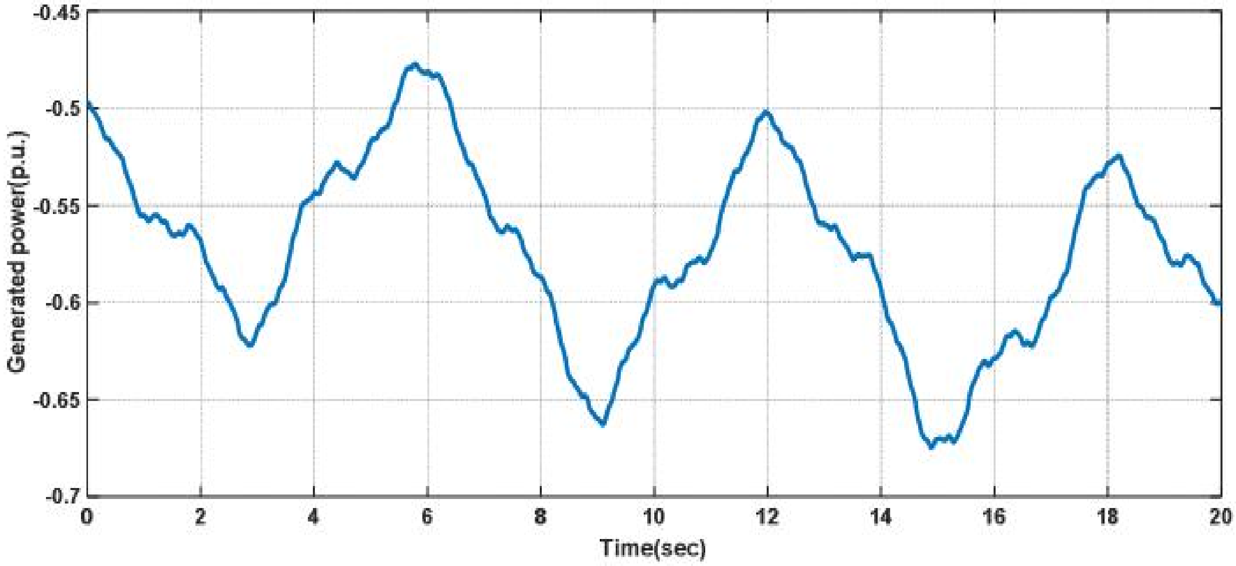


Figure (4.3) :- Generator Power (per unit)

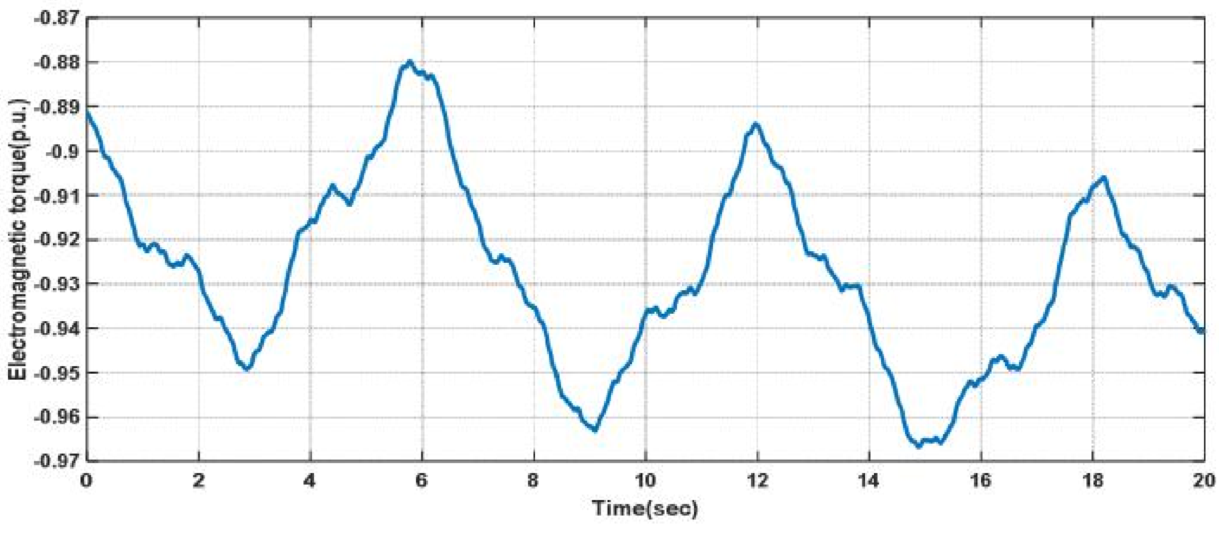


Figure (4.4) :- Electromagnetic Torque (per unit)

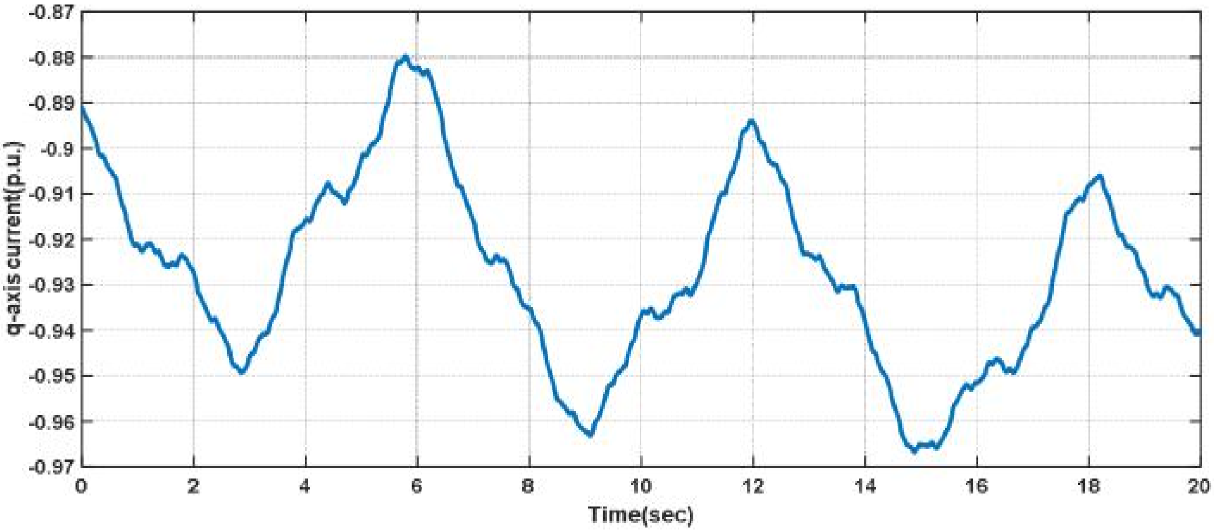


Figure (4.5) :- Quadrature Axis Current (per unit)

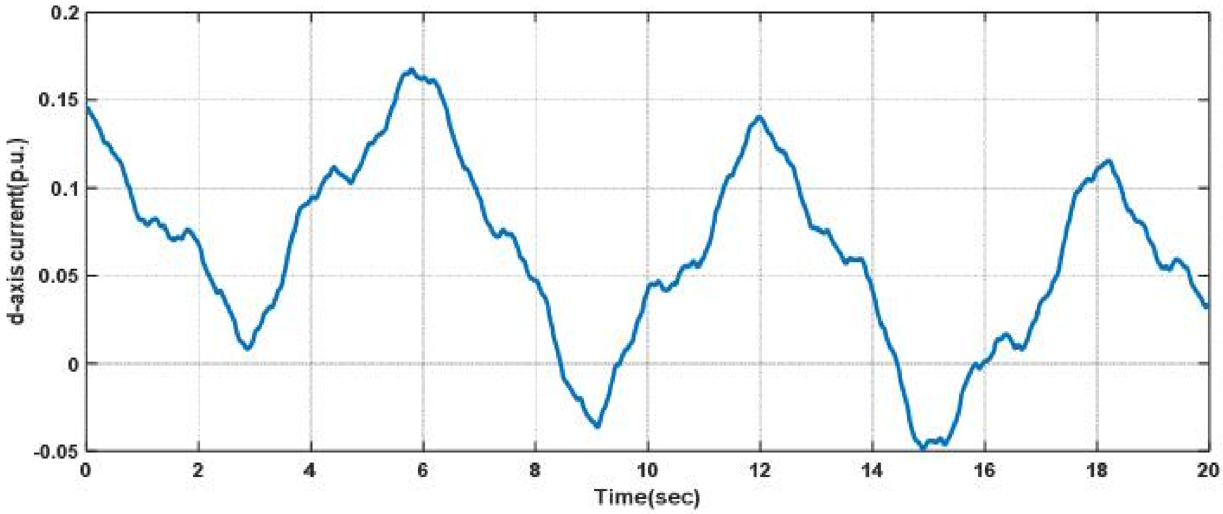


Figure (4.6) :- Direct Axis Current (per unit)

Since the PMSG model described in Chapter 3 is based on the motor convention, the numbers in Figures (4.3) - (4.6) are all negative.

Figures (4.1) - (4.3) show that as the wind speed changes, so do the speed of the generator and the amount of power it makes. The simulation results are found when $\beta = 0$ and the coefficient of friction (B) is not taken into account. The variation of coefficient of wind turbine is shown in figure (4.7).

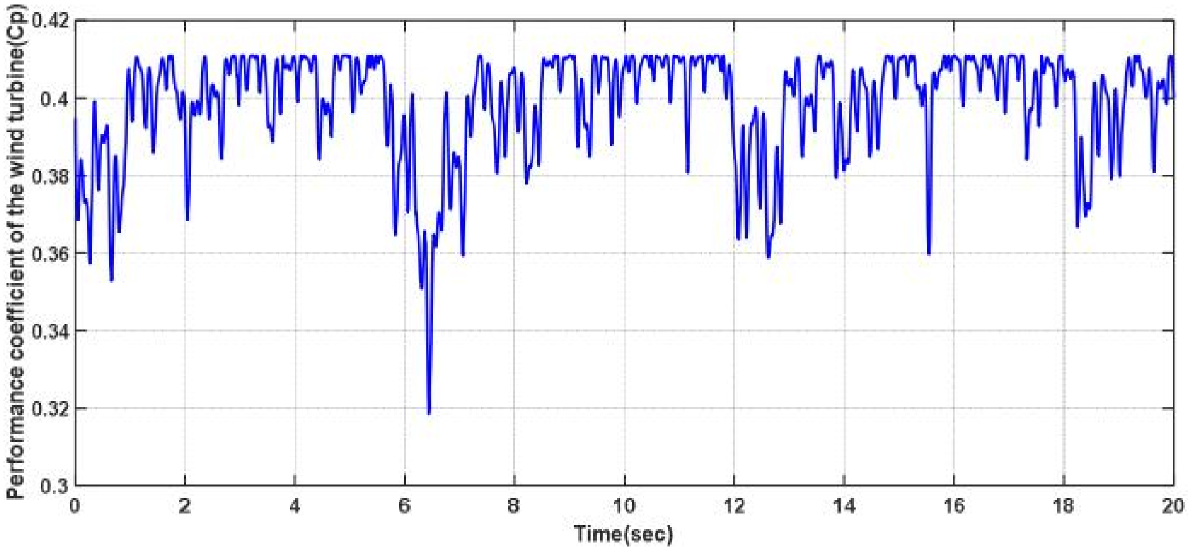


Figure (4.7) :- Performance Coefficient of the wind turbine (C_p)

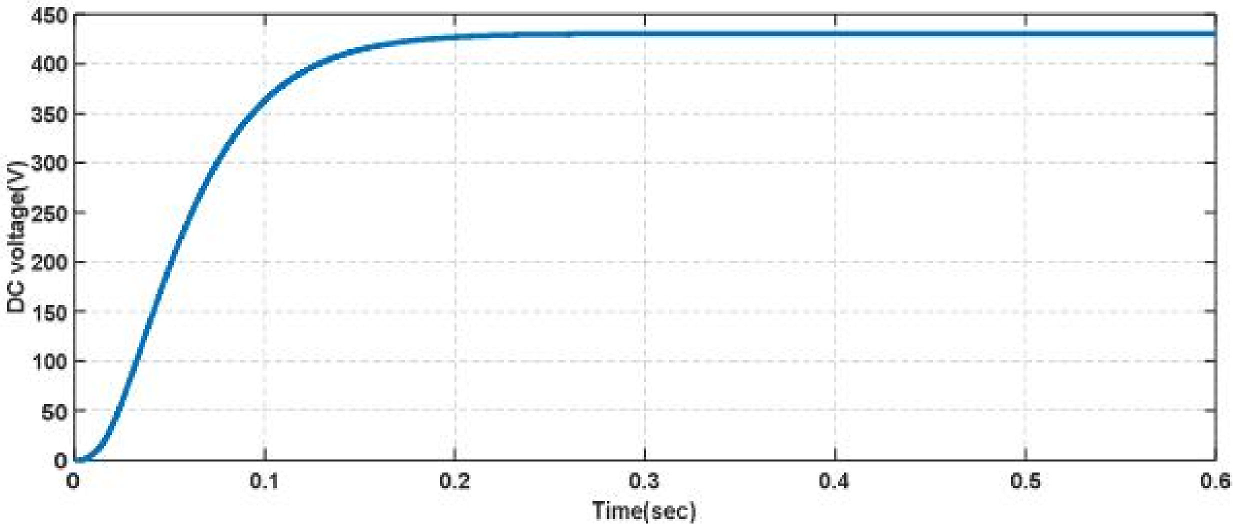
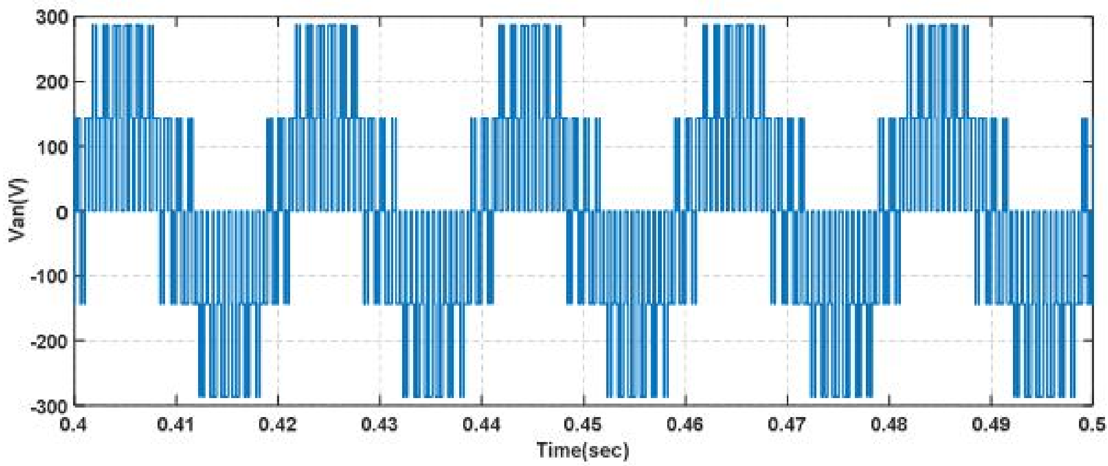


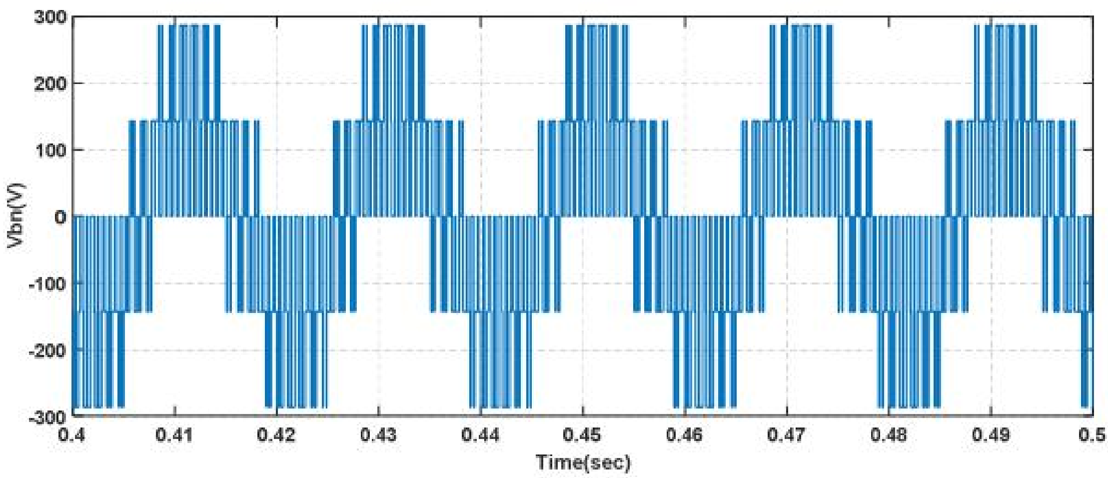
Figure (4.8) :- DC Output Voltage

For the simulation of an ac-to-dc converter, an ac input is three-phase balanced sinusoidal voltages with a frequency of 50 Hz and a peak amplitude of 300 V.

Figure (4.8) shows the ac-to-dc converter's smooth, filtered dc output voltage, which is fed into the VSI. In the SPWM method, the modulation index is 0.8, the carrier signal frequency is 900 Hz, and the control signal frequency is 50 Hz.

Figures (4.9) and (4.10) show the voltages of the inverter's three phases (V_{an}, V_{bn}, V_{cn}) and the inverter line voltages (V_{ab}, V_{bc}, V_{ca}) respectively.





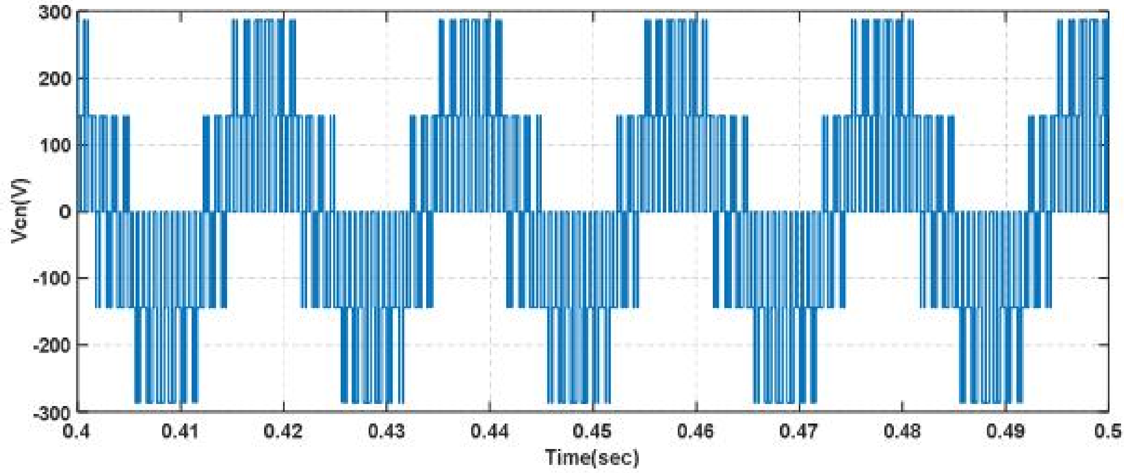
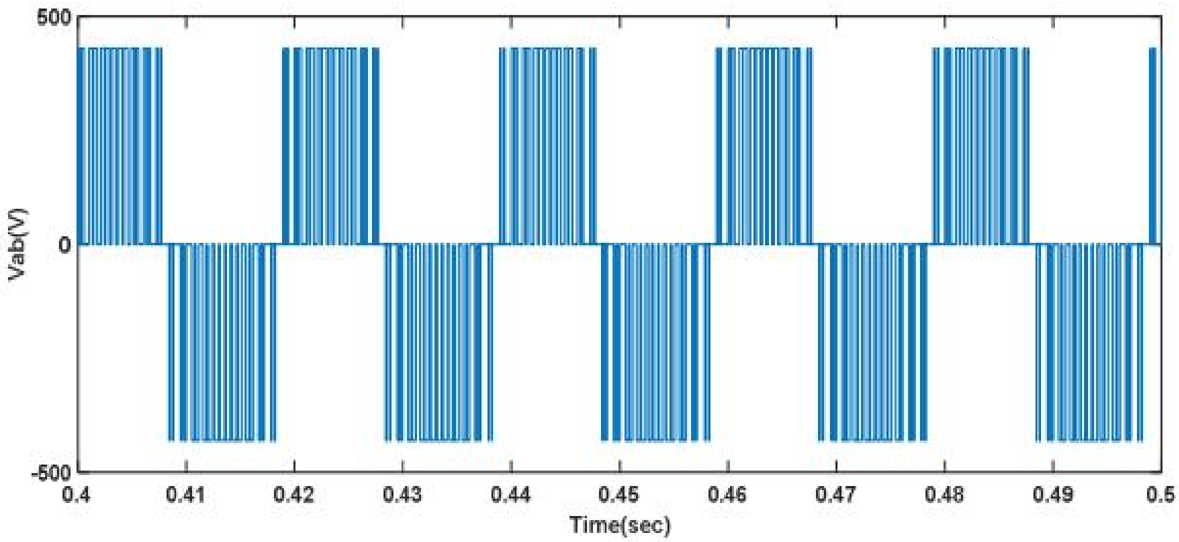
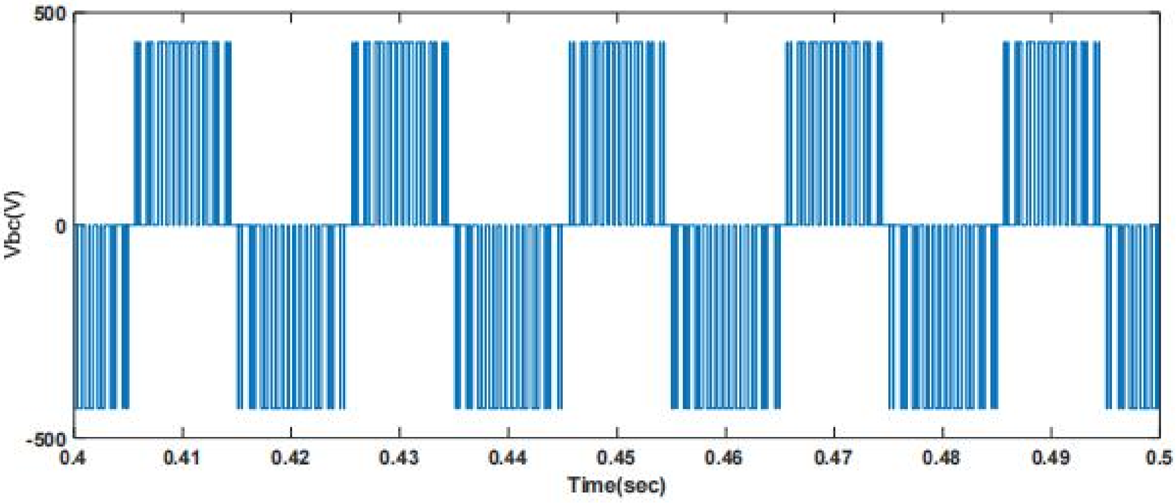


Figure (4.9) :- Phase Voltage (V_{an}, V_{bn}, V_{cn})





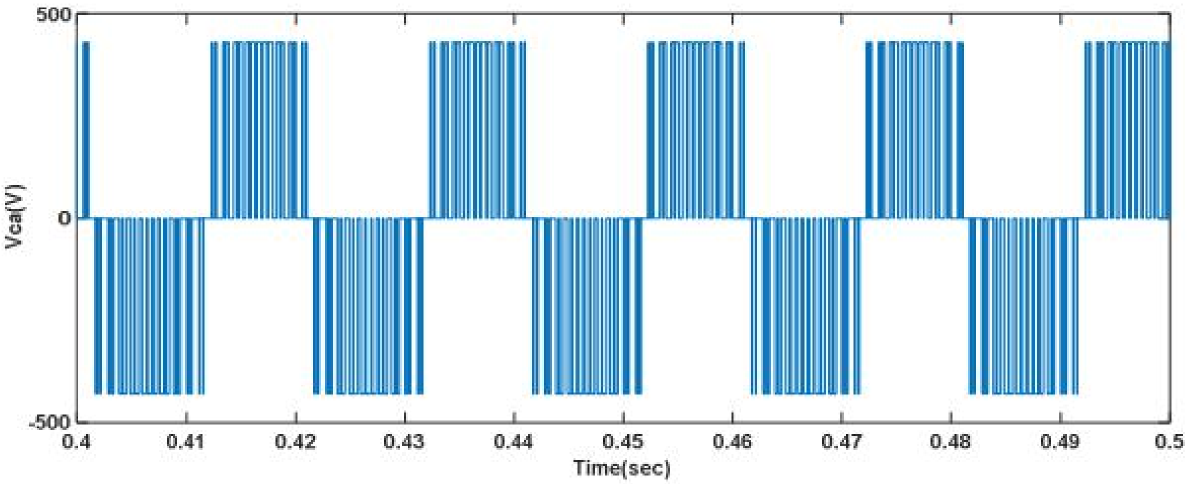


Figure (4.10) :- Line voltages (V_{ab}, V_{bc}, V_{ca})

The load currents (I_a, I_b, I_c) are as shown in figure (4.11) As we can see from the figure the load currents are balanced.

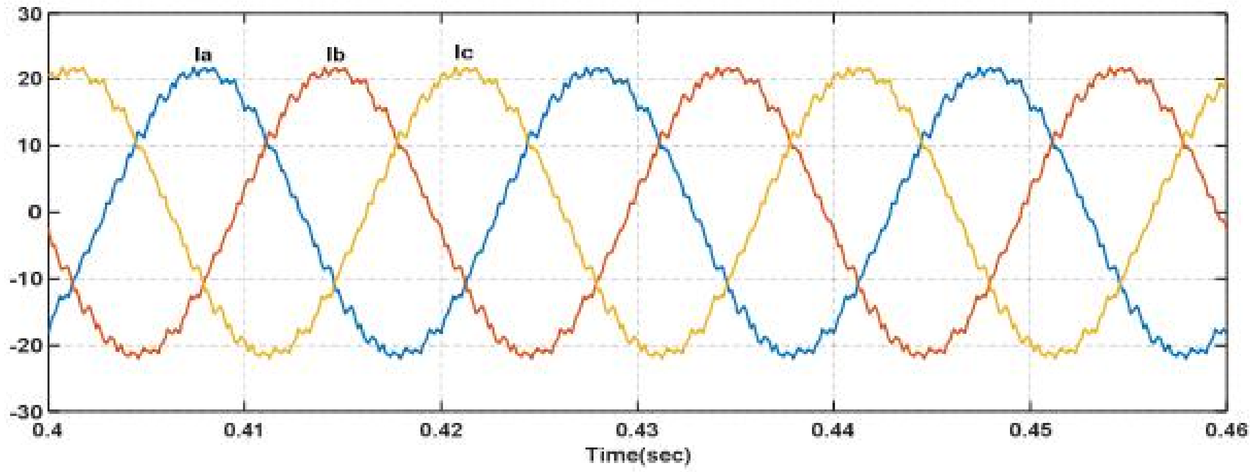


Figure (4.11) :- Load Current (I_a, I_b, I_c)

CHAPTER 5
CONCLUSION AND FUTURE WORK

This thesis has made a model of a small, stand-alone wind turbine that can be used to charge batteries, mostly in remote areas, residential areas, and small businesses that can't connect to the grid. In this thesis, a working prototype of a model of a wind turbine was made in MATLAB Simulink. A 1.1 kW wind turbine was able to charge a 12 V battery package with 30 Ah rating. By analysing the models, we were able to develop the power electronics needed to modify the voltage level to a desired level and nature.. The charge controller for the battery, which was charged with a constant voltage method, was also well-made. It used a buck converter, which was able to give the battery a constant voltage even when the wind speed changed. So, the model proposed in this thesis is able to keep the battery's voltage the same even when the wind speed changes. It was also found that the controller could do better when the load on the boost converter changed. So, the controller made to charge a battery using a Buck converter worked well to charge the battery.

The fact that wind energy fluctuates means that it is inherently unstable. It can emanate from any part of the wind turbine, regardless of which way it's facing. That is why it is essential that the turbine's blades capture as much wind energy as possible. There are several controls that can be put to the wind turbine component of this thesis for future study in order to capture this variable energy. The pitch angle of the blade and the Tip Speed Ratio are taken into consideration in this tracking control, which often incorporates a MPPT control. The next parts of the WECS can get continuous energy even when the wind speed changes due to the use of these controls on the wind turbine. Final application of constant voltage is required for battery packages or changeable loads in order to assure controller dependability and robustness, as well as a long battery life and healthy connected loads.

Compared to other renewable technologies in India, grid-connected wind power generation has gained a lot of attention and acceptance. As of March 31, 2008, about 8698 MW of wind energy had been installed in the country, and about 458.27 million units of electricity had been sent to the state grids. India was fifth in the world in terms of how much it used wind energy that came from natural sources.

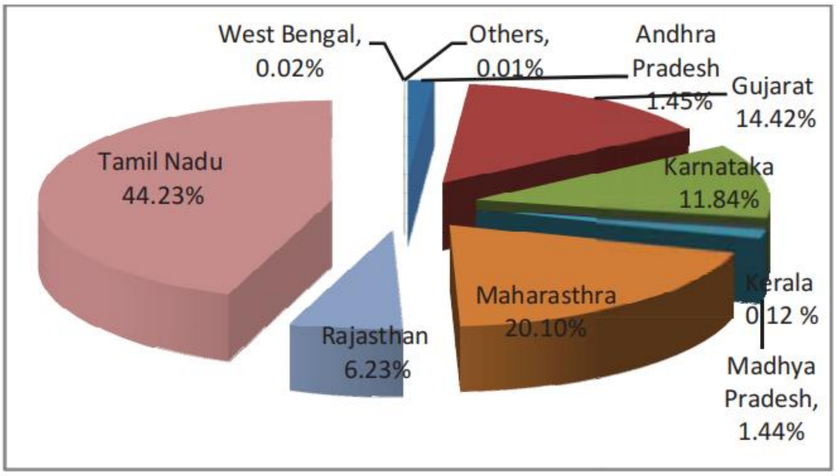


Figure 5.1

Commercial wind power projects with a total capacity of 8698 MW have been set up. With a total installed capacity of about 3847.715MW, the Muppandal and Perungudi area near Kanyakumari in Tamil Nadu has the most wind turbines in the country. The Union Government has written a renewable energy law to enhance the goal to generate electric power from renewable energy to 20 % by 2020 of the country's total power production, which is only 7.5% right now. In the 11th plan, the Ministry of New and Renewable Energy (MNRE) wants to use 17,500 MW of wind power by 2012. Figure (5.1) shows how much wind power is installed in each state.

India is a place of limitless potential, but it is not being utilised in an effective manner. Wind power is an excellent way to meet India's energy demands while also contributing to the country's economic growth. Many elements play a role in India's long-term future, but one of them is the country's ability to meet its own energy needs on its own. In this way, India will no longer be reliant on nuclear power from foreign countries. Although the government's intentions may appear grandiose at first glance, they are definitely aimed at self-sufficiency." In terms of renewable energy, wind is the most important source (generation and distribution). However, the deployment of this technology has several restrictions that must be taken into account. Because wind turbines need a large capital investment, they cannot be installed in many vacant sites. As a result, wind turbines should be less expensive, allowing them to be installed in more places. The growth of wind power should be boosted by the opening of numerous research and development centres. Students should be educated in wind power technology and other renewable energy technologies, which could have a major impact on the future of the industry. There are a number of advantages to wind power generating in India's metro system, including the fact that it will require less heavy equipment than traditional turbines. Governments in some cities have already started operating metro rails, while in others, they are considering doing so in the near future. It is therefore possible to build smaller wind turbines near the metro lines so that wind energy can be generated at a lower cost.

At the moment, India's is moving in the direction of a growing graph, but one with a flatter slope than in the past. If it wants to reach the goals it has set for itself in the energy industry, it will need to maintain a growth rate that is far higher.

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