THESIS REPORT

On

DESIGNING OF STAND ALONE SMALL SCALE WIND TURBINE FOR BATTERY CHARGING APPLICATION

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Disclaimer

I hereby declare that all the work presented in this thesis report of the project is my own, in accordance with the policy of university on Plagiarism.

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June 2021

Executive Summary

The increase in fossil fuel costs and global warming issues lead to the popularity of renewable energies. Wind and solar energy are two main sources of green energy which have been widely used in large and small-scale power plants. In small-scale power plants, consumers are storing the additional generated energy in a battery pack. The battery packages are charged in the constant current or constant voltage charging process where the battery state of charge (SOC) determines the charging type. Therefore, a controller is required when the generated energy is stored in the battery. The charge controller consists of a power converter and its controller system. The permanent magnet synchronous generators (PMSGs) are usually utilized in small-scale wind generators due to their high power density. In this thesis, a 1.1kW wind turbine equipped by PMSG is investigated for the design of the charge controller. The wind turbine which operates independently from the power grid supplies a small load and a battery package. A 12V 30Ah battery package and 150W constant load is assumed as the loads of the system. A charged controller is designed to provide a regulated voltage for the system load in a wide range wind speed. Both the constant load and battery package are supplied through a constant DC-link where a boost converter provides a regulated voltage for the constant load, the main power converter of the charge controller is a buck converter. The elements of the buck and boost converter are designed based on the required power and voltage level. The control loops of these converters are optimally designed to deliver the power with a regulated voltage. The proportional and integral gains of the control loops are determined using the Characteristic equation derived from the transfer function of the overall system consisting of DC-DC buck converter and PI controller. The results demonstrate the designed controller can deliver the required power properly to the load and battery package.

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Chapter 1: Introduction and Background

1.1. Project background and Motivation

In earlier times, the non-renewable energy sources, like fossils fuels (coal, oil, and natural gas), were used for the generation of electricity and have made a larger portion in today's energy market. The scarcity of fossil fuels leads to increase of their production cost. Also, fossil fuels consumption is one of the main reasons of the earth pollution and global warming. The use of the renewable energies becomes popular to generate clean energy from the infinite resources to protect environment. Wind energy has emerged as a major form for green energy generation among its counterparts such as solar and water power plants. Before 21 century, wind energy was only or primarily used for pumping the water from the wells and for grinding the grains. With the advancement in the technology and the reduction in the prices of the wind energy, over the last 20 years, has made this energy source as most affordable one and made it possible to generate the electricity with the help of this energy source that can be further used in the residential areas. This technology can be proved as a boon for those residential places which are in the remote areas and are not connected to the grids. Off grid or stand alone small wind turbine provides a very attractive source of energy for remote communities and small business due to its benefit of reducing the stress on grids by eliminating the pollution, reducing the cost incurred on the fuel used for diesel generators which are not used in standalone systems. Even these generators require a lot of polluting fuel and also require high operating and maintenance cost. Moreover the standalone wind turbines can be installed where the source of wind is enough or the connection to grid is very costly. The concept of operation in both cases either off grid or on-grid wind energy conversion system is same just the absence of the grid in the system adds the hardware and control requirements (PerrySadorsky, 2021).

With the help of the wind turbine system, the wind energy can be used to generate electricity which can be further stored for the usage in the houses. The energy generated from the wind turbines can charge a battery of up to a required voltage which can be further used in houses to provide the power to the household items. The advantage of using the wind energy to generate electricity, for usage in household items, is that it works effectively in any weather condition without any consumption of fossil fuels and the electricity is also available at night time with the help of charged batteries. The batteries also charge automatically without any harmful emissions and drawbacks.

1.2. Method

The main focus of this project/thesis is to design and analyze a 1.1 kW wind turbine to charge a battery package and delivering a power to constant load. For designing a small scale wind turbine which will be used to generate the electricity for battery charging application, a wind turbine with a permanent magnet generator will be used in this project because of their high efficiency. The kinetic energy of the wind turbines will be converted to three-phase electricity with the help of this generator. Now this generated electricity cannot be directly used in the residential houses, so here comes the need for power electronics in terms of power converter that will be used to convert this electricity to appropriate voltage. The power converter of single-stage made with the help of rectifiers and dc/dc converter can be used for the conversation of the power, as they are simple and easy to implement. The dc/dc converters in the wind turbine system can be of any type either buck converter, boost converter or buck-boost converter. However in this project a buck converter after the rectification section was used as the produced value of the voltage at the output was more than the voltage of the battery which was required to charge it. After converting the electricity to the required levels, the batteries can be used to store this power that would be required for the residential use further. The converter output voltage will be kept constant with the help of voltage produced at the output and the reference value of the voltage required via a controller. This controller will be used to control the duty cycle of the Pulse width modulation signal required to turn on the switching devices of the converter based on the values of the error signal generated using the difference of the reference voltage and output voltage of the converter.

For simulating all the sections starting from wind turbine till battery charger Simulink model of MATLAB is used.

1.3. Objectives of project

- The main aims of this project are to get a working knowledge of the wind turbine that is required to convert the kinetic energy of the wind into electricity. The main focus of this goal is to decide upon the type of the wind turbine that will be used for this project along with power requirements that will suit the project.
- Along with this goal, another objective is to design the power electronic circuits that are required to convert the generated electricity to required level of voltage and of required

form which includes designing of link capacitor between the rectification and the converter stage and the designing of the inductor and capacitor of buck converter used.

- Besides this, the main goal is to design a control circuitry that will be required to keep the constant value of the voltage that will be applied to the battery using the PI (proportional integral) controller. The estimated block diagram of the project is given in figure (1-1).

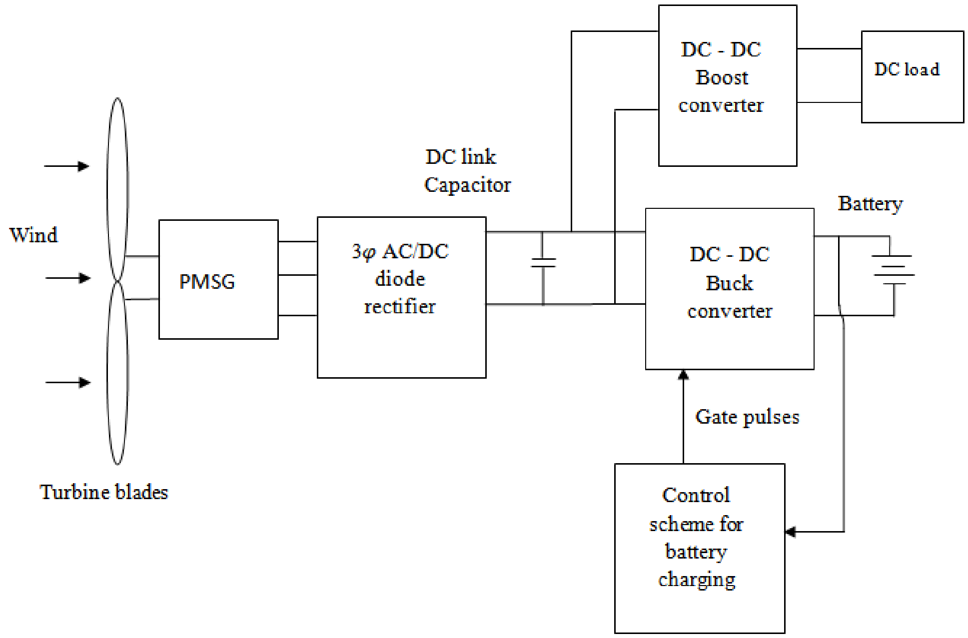

Figure (1-1): - block diagram of wind energy conversion system for this project

1.4. Outline of Thesis

Chapter 1: - Introduction

The first chapter of the thesis gives the brief introduction about the reasons project undertaken. It gives the information about the methods used to implement a model of standalone wind turbine system of 1.1 kW capacity. The aim or objectives of the project along with the outline of the thesis are also included in this chapter.

Chapter 2: - Literature review

The literature review provides an overview of the project background and the other research conducted for the components of the wind energy conversion system.

Chapter 3: Wind Energy Conversion system and its component, Wind turbine and Generators

This chapter first gives the general information about the wind turbine. It also provides the details about the different types of wind turbine along with their advantages and disadvantages. The parameters of the Simulink wind turbine model are also described in the end of the section. This section of the chapter also provides information about the different types of generators and the model used in Simulink.

Chapter 4: Power Electronic Circuits and energy storage system required for wind energy conversion system

This chapter provides the information of different power electronic circuit used for the wind energy conversion system. This section gives information about the rectifier section, DC link capacitor and Buck converter which are required to get a required value of DC voltage. After this the energy storage system were explained mainly indicating the properties and charging methods of the battery.

Chapter 5: Mathematical models of the components required for wind energy conversion system

In this chapter the mathematical model of all components were described used for the wind energy conversion system. The models were also used to determine the values of the components of the power electronic circuits.

Chapter 6: Simulations and Results for wind energy conversion system

In this chapter the simulation of all the sections were presented along with the results obtained.

Chapter7: -Conclusion and Future Work

This chapter provides the conclusion of this project based on the results obtained in previous section. The future work that can be done on this project is also discussed in this chapter

Chapter 2: - Literature review

The utilization of the wind energy has grown rapidly in Europe, North America and Asia. According to the Global wind energy Council (GWEC) report, total capacity of the wind energy has increased to 44 GW worldwide, till 2021. Some countries such has European Union has aimed to achieve a 20% of their demand of the electricity from wind energy in 2020. Same like these cities Canada also plans to have 20 % of demand supplied by the wind energy till 2025. Asia is the largest regional market for the wind energy in which China target is to install 150 GW of wind power capacity till 2020 according to (Zuher Alnasir, 2013).

A large number of research and development has been done on the wind energy conversion system for a Grid connected WECS based on the type of generators and power converters used. In (Zuher Alnasir, 2013) author has mentioned that however there was large number of research on grid connected system but a less focus was put on off-grid WECS. So, he has provided various advantages of using the stand alone system as compared to grid connected system. Due to all these advantages, a standalone system was proposed for this project in which a battery as energy storage element is used to provide the power to remote areas in the absence of the grid.

The main component used to convert the kinetic energy of the wind to the mechanical energy is wind turbine. There is lot of information available for the types of the wind turbines that can be used for this project in literature. Based on the advantages that the horizontal axis wind turbine was providing, it was selected for this project. For the generator selection for stand-alone system a thorough study was done in (Zuher Alnasir, 2013) for types of generators available. Author has conducted the study in paper based on the efficiency, reliability, cost, operation and maintenance requirement, excitation requirements and noise level associated with each type. The Permanent magnet synchronous generator was used for this project based on the advantages described in (Zuher Alnasir, 2013).

For the power converters the circuits mentioned in (S. Eren, 2006) are used to convert the AC electrical energy generated by the generator to the DC. The variable DC voltage was generated using the bridge rectifier discussed in (S. Eren, 2006). To stabilize this variable Dc a buck converter was used in this project. To design the components of the buck converters equations mention in the paper were used. At the output of the Buck converter a DC voltage is available to store in some form which can be further used in households.

For storage of the energy, various energy storage systems were described in (Luanna Maria Silva de Siqueira, March 2021). Based on the advantages of battery energy storage system discussed in paper a battery was used to store the electricity in electrochemical form. To maintain the battery voltage constant various control scheme are described in papers. For control scheme, a Battery charger with a buck converter described in (Her-Terng Yau, 2012) was used for this project in which a proportional integral controller was using a battery voltage and reference voltage to generate an error signal for producing a duty cycle for the buck converter. In (Her-Terng Yau, 2012) transfer function of the closed loop system was first used to calculate the characteristic equation of the system. Then this equation was used in paper to calculate the value of the gains of PI controller using Routh array table.

Chapter 3: Wind Energy Conversion system and its component Wind turbine and Generators

In this chapter of Wind energy conversion system first the concept about the wind turbine is described which leads to generator section which is required to convert the mechanical energy generated by the wind turbine to the electrical energy. The details about these components are given below. Initially a general description is presented about these components then the type of particular section which is used in this project is discussed.

3.1. Wind turbine

Wind turbines are used to generate electricity from wind energy. The first wind turbine that was operated automatically was designed and built by Charles Brush in 1888. It was equipped with 144 cedar blades with a rotating diameter of 17 m. A peak power of around 12 kW was generated from this turbine to power up the batteries to supply DC current to lamps and electric motors.

3.1.1. Characteristics of wind energy

For understanding the working of wind turbine first it is required to understand the characteristics of wind energy. It is a special form of kinetic energy in air as it flows.

a. Wind power:

Power in wind which is moving is a flow rate of the kinetic energy in wind per second in watts where kinetic energy is given as KE= ½ * (m V^2) in which m is the mass of the air and V is the speed.

Mechanical Power coming in upstream wind is given as

P= ½ (mass flow per second) V^2 (3-1)

P= ½ $(\rho AV)V^2$ (3-2)

Where ρ is air density, A is area swept by rotor blades and V is velocity of air

b. Blade swept area

The swept area of the blades also determines the output power of the wind turbines. The wind turbines with larger diameter of their blades are capable of extracting more power from the wind (Anon., 2018) . Blade swept area can be calculated from formula

A= πl (l+2r)

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

c. Air density

Another parameter that affects the wind power is air density. The density of the wind varies with temperature and pressure and is calculated from the following state of equation.

$$\rho = \frac{p}{RT} \tag{3-3}$$

Where p is air pressure, R is the gas constant and T is the temperature of the air.
The temperature and pressure both varies with the height and the following equation depicts the combined effect on air density.

$$\rho = \rho_o \, e^{-\left\{\frac{0.297\,Hm}{3048}\right\}} \tag{3-4}$$

Where Hm is elevation of site in meters

3.1.2. Classification of wind turbine

Wind turbines can be classified according to different parameters such as turbine generator configuration, airflow path relative to turbine rotor, turbine capacity, power supply mode and location of turbine installation. Wind turbine can be classified into two different categories either horizontal-axis and vertical axis wind turbine or upwind and downwind wind turbine. Besides these types another classification of wind turbines are direct drive and geared drive wind drive, on-grid and off grid wind turbine and the last one is onshore and off shore wind turbines. A small description of each type is given below.

a. Horizontal-axis and vertical axis wind turbine:

Most of the commercial wind turbines are of type horizontal-axis in which the rotating axis of the blade are parallel to the stream of the wind. Due to this type of configuration of blades these turbines provide higher efficiency, higher power density, low cut-in speed and low cost per unit power output.

In case of vertical-axis wind turbines the blades rotates w.r.t their vertical axis that are perpendicular to ground. The main benefit of these types of wind turbine is that it can accept wind from any direction which eliminates the use of yaw control. This type of turbine also reduces the cost of the turbine and simplifies the design and the construction of the wind tower as all the components required can be set up on ground. But an external energy source is required to rotate the blades during the initial stage. The maximum practical height is also limited in this type as the axis of the turbine is only supported on one end of the ground.

In comparison to horizontal-axis turbine these type make up a small percentage of wind turbine due to lower wind power efficiency. The figure depicting the horizontal and vertical axis wind turbine is given in figure (3-2).

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Figure (3-2):- View of horizontal and vertical axis wind turbine

b. Upwind and downwind wind turbines:

Generally a horizontal axis wind turbines are classified into these two categories. Most of the used horizontal-axis wind turbines today are of type upwind turbines. In these turbines the rotors face the wind and the main advantage of these types of turbines is to avoid the distortion of the flow field as the wind passes through the wind tower and nacelle.

In case of downwind turbines wind passes first through the nacelle and tower and then through the blades. This also enables blades to be made more flexible. However, the wind power output generated in these turbines fluctuates greatly because of the influence of the distorted unstable waves behind the tower and nacelle. The blades of the downwind turbines also make impulsive or thumping noises sometimes. The two types of wind turbine with upwind and downwind configuration is shown in figure (3-3).

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Figure (3-3): - Schematic of upwind, three-bladed HAWT, and downwind, two-bladed HAWT

c. Direct drive and geared drive wind turbines:

Generally to increase the speed of the rotor of the generator to get a higher output power a multistage gearbox is used. The advantage of using a using a geared generator system includes lower cost, smaller size and weight. Besides this, the usage of gearbox also reduces the reliability of the turbine and increases the mechanical losses and noise levels (Tong, 2010).

When the generator shaft is directly connected to the blade rotor then this type of turbines is known as direct drive turbines. These turbines are more superior to the geared drive turbines in terms of energy efficiency, reliability and design simplicity (Tong, 2010). The figure (3-4) depicts the mechanism and the inside of the two wind turbines.

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Figure (3-4): - Internal structure of direct drive and geared drive wind turbine

d. On grid and off grid wind turbines:

Most of the medium size and large size wind turbines are connected to the grids for the different applications. The main advantage of being connected to grid is that there will be no problem of energy storage.

On the other side, all the small wind turbines are of type off-grid wind turbines which are mostly used for residential homes, farms, telecommunication and other applications. The wind power generated from these types of turbines also changes dramatically over a short period of time even with a little warning. Therefore these turbines are used with batteries, diesel generators and photovoltaic systems to improve the stability of supplied power by the turbine.

e. Onshore and offshore wind turbines:

On shore turbines have a long history of their development which provides the number of advantages which includes easier integration to grid network, lower cost of foundation, tower building and turbine installation.

On the contrary offshore wind turbines can make higher power output and can also operate for more hours each year in comparison to turbine which is installed onshore. Along with these advantages, in case of offshore wind turbines the turbine noise is no longer an issue.

3.1.3. Wind turbine Configuration:

Most of the wind turbines nowadays are of horizontal axis type with three blades typically. The wind turbine is comprised of a nacelle which houses the most of the turbine components inside. It is positioned on the top of the wind tower. The three blades are connected to the rotor hub which is connected via to the gear box with the help of main shaft.

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Figure (3-5):- Configuration of Horizontal axis wind turbine

The rotor of the wind turbine is also connected to the output shaft of the gearbox so that the slow speed if the rotor hub can be increased to required speed of the generator rotor.

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Figure (3-6): - parts and components which are required for vertical axis wind turbine

Figure (3-6) depicts the various parts that are required in vertical axis wind turbines. It generally requires a guide wire which is used to keep the shaft of the rotor in position. It also has a provision of two hubs to which the rotor blades are attached. These rotors blades are generally a part of rotor which takes the kinetic energy of the wind and converts that to the rotation of the hub; where rotor is a heart of wind turbines, responsible for capturing the energy of the wind and transforms that energy to mechanical energy. Then the shaft is rotated with the help of the turning blades which is further connected to the generator sometimes via gearbox. The main function of the gear box is to increase the speed achieved using the shaft to further increase the speed of the generator. The last component is generator which converts the rotational speed to the electricity (Anon., 2013).

3.1.4. Wind power parameters:

a. Power coefficient

Power coefficient deals with the converting efficiency of the energies which are converted from one stage to another in wind energy conversion system. This parameter generally deals with the conversion of the energy in the first stage which involves the conversion of kinetic energy to mechanical energy to run the shaft of wind generator. The power coefficient is given as ratio of mechanical power captured by blades and wind power which is given in (3-5) (Tong, 2010)[2].

$$C \qquad (3\text{-}5)$$

b. Tip speed ratio

Another important factor in the designing of wind turbine is tip speed ratio which is defined as a ratio of tangential speed at blade tip to the actual speed of wind which is given in (3-6).

(3-6)

Where l is the length of blade, r is the radius of blade and ω is the angular speed of blades. If the angular speed of blades is small then the wind passes undisturbed through the blade swept area on the other hand for a larger value of omega may leads to reduction in the power extraction so an optimal value for angular velocity of blades is required which can be approximately determined by (3-7) where L is length of strongly distributed airstream upwind and downwind (Tong, 2010) [2].

(3-7)

c. Wind turbine capacity factor

Due to unpredictable nature of wind, wind turbines are not able to make power all the time. So the capacity factor of the wind turbine is used to determine the measure of the actual power output of the wind turbine in a given period divided by its power output if the turbine has operated the entire time (Tong, 2010). A reasonable capacity factor as described in (Tong, 2010) is in between 0.25 and 0.30

3.1.5. Wind Turbine used in project

In this project already provided wind turbine model in Simulink was used which was implementing a variable pitch wind turbine model. However, it was decided to choose a prototype of horizontal axis wind turbine that will be able to provide a power of 1.1 kW because of its benefits that it was providing in comparison to its counterpart Vertical axis wind turbine. Horizontal Axis wind turbine with direct drive was chosen to test for this project, as higher output power was not required to test this small scale wind turbine. The turbine power characteristics with the set parameters (shown in figure (3-7)) is shown in figure (3-8) which was providing maximum power of 1100 W at base wind speed of 12m/sec.

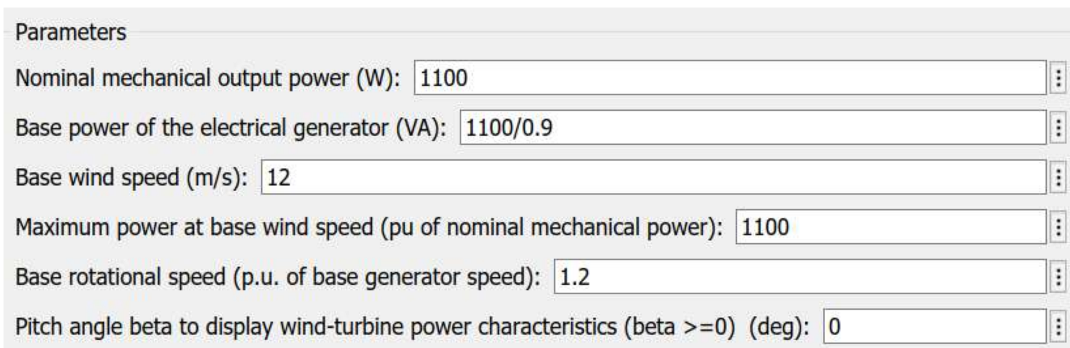

Figure (3-7): - parameters set for wind turbine model in Simulink

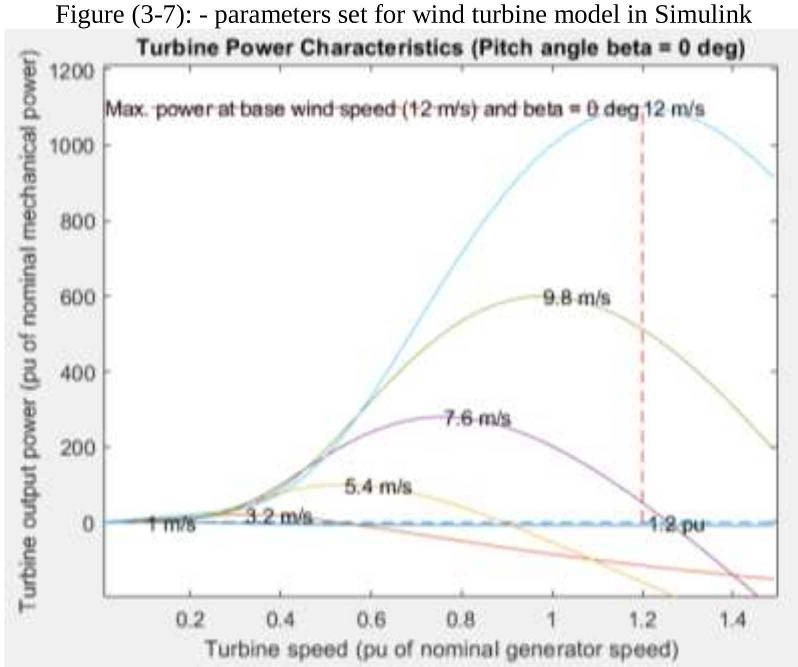

Figure (3-8): -Turbine power characteristics with set parameters of turbine

3.2. Wind turbine Generator: -

A mean is required to convert the mechanical power generated with the help of turbine to electric power which is done with the help of generators which works on the principle of faraday law of electromagnetic induction. Generally, there are three main types of generators that can be used with various wind turbine systems which are AC (alternating current) synchronous, DC (Direct current) and AC asynchronous generators (Wenping Cao, March 2012). These machines, in principle run at fixed and variable speed. It is advantageous to use wind turbine generators at variable speed because of fluctuating nature of wind as it reduces the stress on the blades of turbine improving the system aerodynamic efficiency and torque transient behaviors (Wenping Cao, March 2012). The details about types of generators are discussed in next section which will lead to comparison between each other to decide upon the type of generator used for this project.

a. DC generators

In traditional DC machines, field winding is on stator and armature winding is on the rotor where stator consists of number of poles excited either by permanent magnets or by DC field windings. If machine is excited electrically then it follows the concept of shunt wound DC generators. In DC shunt wound generators, the field current increases with the speed of the operation however the actual speed of the wind turbine is determined by the balance between the two types of torques which are wind turbine drive torque and load torque. The rotor consists of conductor windings on armature which is further connected to the split-slip ring commutator. Brushes connected to the commutator are used to extract the electrical power which is also used to rectify the AC power generated to DC power. These DC generators require regular maintenance and are relatively costly because of the presence of the commutators and brushes (Wenping Cao, March 2012).

Overall, these DC generators are not used much in wind turbine systems in contrast to low power demand applications in which the load is in close proximity to wind turbine for example in heating application or in battery charging.

b. AC Asynchronous Generators

Asynchronous generators are also known as induction generators which presents very mature technology, low maintenance, low cost, simple operation and control and good dynamic response (Zuher Alnasir, 2013). These generators require a continuous source of reactive power for its excitation in order to continuously generate voltage and supply active power. In these generators a gear box is also required to match the low speed of the turbine to high speed required by generators (Zuher Alnasir, 2013). These induction generators or an asynchronous generator falls into two categories based on rotor type which are fixed speed induction generators with squirrel cage rotor (SCIG) and doubly fed induction generators (DFIG) with wound rotors (Wenping Cao, March 2012). The rotor of DFIG contains three phase windings similar to that of stator; however in SCIG rotor consists of shirt-circuited conducting bars shaped like squirrel cage. The diagrams of squirrel cage induction generator and doubly fed induction generators is shown in figure (3-9) and figure (3-10) respectively.

Image removed due to copyright restriction.

Figure (3-9): - Cutaway diagram of Squirrel cage induction generator **(Wenping Cao, March 2012)**

Image removed due to copyright restriction.

Figure (3-10): - Cutaway diagram of doubly fed induction generator **(Wenping Cao, March 2012)**

In DFIG based standalone WECS, stator is directly connected to the load bus whereas rotor is connected through a power converters. Power flows in stator in unidirectional ways however the direction of the power flow in rotor totally depends on the modes of operations of generator. When the generator operates below the synchronous speed or as sub-synchronously then rotor acts as receiver means it receives the power. If generator operates above the synchronous speed or super-synchronously then rotor delivers the power. These DFIG generators are a best choice for high power grid connected wind energy conversion system because of reduced size of power converters and filters used which leads to huge economic gain. However, these DFIG cannot be considered in a low power standalone wind turbine system. Another benefit of these generators is that for the excitation of the stator there is no need of external VAR compensators as they can get power from rotor circuit through power converters. Beside these advantages DFIG has a drawback of reduction of reliability and increased maintenance requirements due the use of brushes and slip rings (Zuher Alnasir, 2013)

SCIG has a rotor made of longitudinal conductive bars set into groves and short circuited by bars. SCIG overcomes the problem of DFIG which are problem of brushes and slip rings, and complexity problem. They are also smallest in size, lowest in cost and robust in structure; however, SCIG based wind energy conversion system requires a full capacity power converters to get maximum power available from wind to achieve full control of reactive and active power. This machine has also been in interest of many research project s including simulator design, emulator set-up, novel power converters and control schemes and self-excitation and voltage build up techniques in stand-alone and hybrid micro-grids (Zuher Alnasir, 2013).

c. AC Synchronous Generators

Design of stator of the synchronous generator is same as that of the induction generators whereas the rotor of the synchronous generator can be either cylindrical or salient. Cylindrical rotor has a distributed winding with uniform air gap and salient rotor has concentrated windings on the pole and non uniform air gap. With short axial length, large diameter and high number of poles, salient-pole rotor synchronous generators are used for low speed applications. The possibility of eliminating the need of the gearbox which further reduces the maintenance requirements and increases the system reliability and efficiency are major advantages of synchronous generators over induction or asynchronous generators. Due to the elimination of the gearbox, wind turbines utilizing synchronous generators are also sometimes known by the name of gearless or direct drive wind turbine (Zuher Alnasir, 2013). The elimination of the gear box saves the money but with this advantage there comes some drawbacks which are that direct drive generators without gearbox become heavier, larger in size and more costly due to the need of the larger number of poles required in rotor. The reason behind the larger number of poles is to lower the speed requirements required for generator and to match the speed of the turbine with the absence of gearbox. AC synchronous wind turbine generators generally fall in two categories which are wound rotor synchronous generators (WRSG) and permanent-magnet synchronous generator (PMSG) which are explained next along with their application in wind energy conversion system. A cutaway diagram of traditionally used synchronous generator is shown in figure (3-11) (Wenping Cao, March 2012).

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Figure (3-11): - Cutaway diagram of synchronous generator

For rotor field winding of the wound rotor type synchronous generator DC excitation is required, which can be either provided by DC source through slip rings and brushes or brushless exciter. Providing an excitation using the help of brushes is a simple method but requires regular maintenance of the brushes and slip rings whereas in another method less maintenance is required but this method is more complex and expensive due to the involvement of power electronics and also needs an auxiliary AC generator. These WRSG are also known as electrically excited synchronous generator due to the excitation by DC current (Zuher Alnasir, 2013). The rotor field winding is usually excited with the help of auxiliary DC source with the help of DC/Dc converters. These converters are controlled in such a way that a constant voltage can be maintained at stator terminal. For these purposes an automatic voltage regulator can be used. Wound rotor type synchronous generator based stand alone WECS can be used for serving the remote load demands but the use of external DC source for excitation of the rotor windings via brushes and slip rings leading to higher complexity and cost are the main obstacles for adopting these generators for wind turbines especially for off-grid applications (Zuher Alnasir, 2013).

Another type of Synchronous generator, permanent magnet synchronous generator, requires a brushless self excitation for rotor which is produced by the permanent magnets. The structure of the PMSG is relatively simple is shown in figure (3-12) in which the rugged permanent magnets are installed on rotor to produce magnetic field constantly and the produced electricity is gathered through the stator (armature) with the help of commutator, slip rings or brushes. To reduce the cost sometimes the permanent magnets can be integrated into a cylindrical cast aluminum rotor (Wenping Cao, March 2012). The operation of the permanent magnet generator is same as that of synchronous generator except that PM can be operated asynchronously. These permanent magnet synchronous generators are rugged, reliable and simple because of the elimination of brushes, slip rings and commutator. The power losses associated with the field windings are also not present in permanent magnet generators as the field windings are replaced by magnets in these generators. However, this makes impossible to control the required field and the cost the magnets used in these generators will be higher for larger machines (Wenping Cao, March 2012).

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Figure (3-12): - Cutaway diagram of permanent magnet synchronous generator **(Wenping Cao, March 2012)**

Depending upon the installation of permanent magnets on the rotor, these generators can be divided into two types first is surface-mounted permanent magnet synchronous generators and the other one is inset-magnet permanent magnet synchronous generators. In the former type the magnets are placed on the rotor surface in which the mechanical integrity of the structure is compromised with the risk of detachment of the magnets from the rotor at higher speed. Owing to this reason and other reasons associated with the efficiency and the power density of the machine, surface mounted permanent magnet synchronous generators are preferred for low speed applications of wind turbine (Zuher Alnasir, 2013). In the later type, the magnets are placed inside the rotor body which makes this configuration suitable for high speed applications. These inset magnet permanent magnet synchronous generators offers high efficiency drive by using the both reluctance and magnetic torque.

In recent years, permanent magnet synchronous generators has been seen as a dominating solution in direct-drive small scale wind turbine systems in both applications of turbines connected to grid and the stand alone wind turbines. The inset permanent magnet synchronous generators for large scale wind turbines, provides higher efficiency for different types of rotor structures. However these permanent magnet synchronous generators may not be preferable for large scale wind turbines because of the involvement of the heavy and the large magnets in size. To resolve this problem, a light weight structure for permanent magnet synchronous generators has been proposed in many papers, as a solution for direct drive wind turbines for large scale applications (Zuher Alnasir, 2013).

The comparison of the two different types of generators for wind turbines namely geared or indirect-drive squirrel cage induction generator and direct drive permanent magnet synchronous generator in terms of their advantages and disadvantages is given in table 1 (Zuher Alnasir, 2013).

Table 1: Advantages and disadvantages 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

In addition to advantages and disadvantages of these generators their performance comparison is given in 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

Fault Response	Slow	Slow	High
Cost	Low	Low	High
Suitability	Low power, residential applications	Small wind turbines	Direct drive small-medium wind turbines

3.2.1. Model of generator used in project

After going through all the generators and studying their advantages that they were providing, permanent magnet synchronous generator was decided to opt for this small scale wind turbine project. This was the generator which was capable of proving the benefits required for this project. Already provided model of permanent magnet synchronous generator in Matlab Simulink was used. In matlab a three phase permanent magnet synchronous machine was implemented with a sinusoidal back EMF and a rotor with round shape was selected. The selection of these configurations for permanent magnet synchronous machine is shown in figure (3-13).

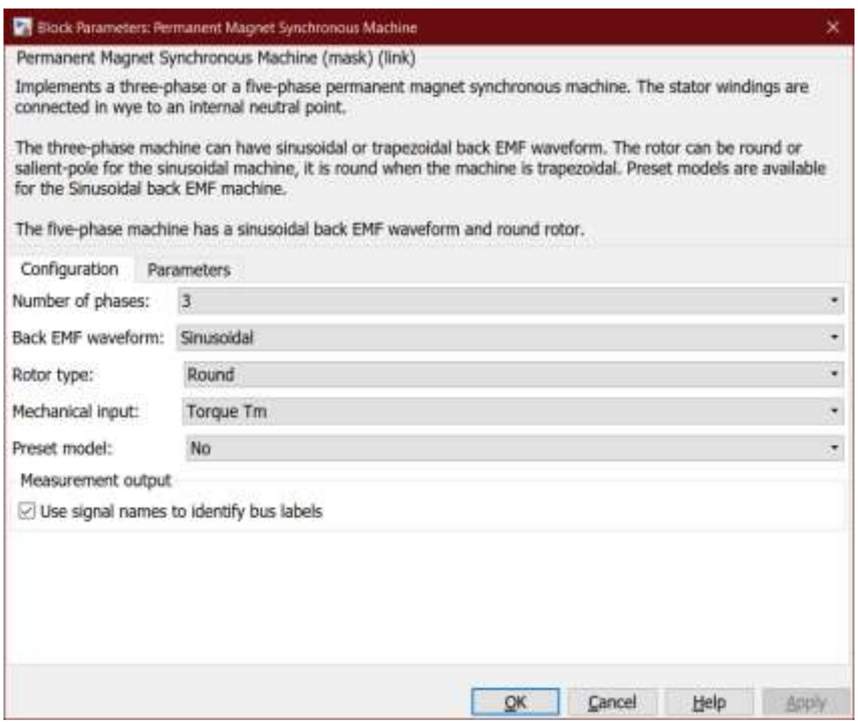

Figure (3-13): - Configuration of permanent magnet synchronous machine in Matlab for project

The parameters for this machine are shown in figure (3-14).

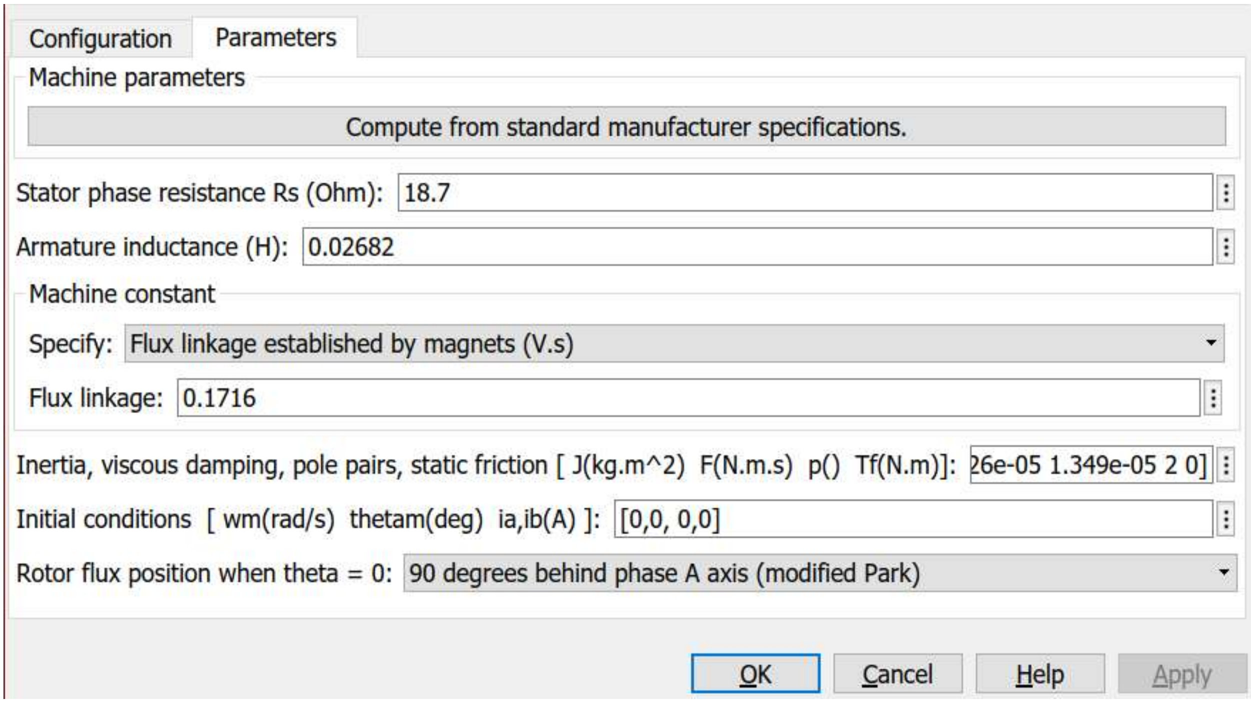

Figure (3-14): - Parameters of permanent magnet synchronous machine in Matlab for project

Chapter 4: Power Electronic Circuits and energy storage system required for wind energy conversion system

4.1. Power Electronic for project

After generating the electrical energy from the kinetic energy of the wind using the wind turbine and the generator then there come the need for the power electronics. During the last 30 years, power electronics has changed rapidly and an increase in the number of the applications using the power electronics have been seen due to the advancement in the microprocessor technologies and development of semiconductor devices (Zhe Chen, August 2009). Due to development and advancement in technology, the performance is steadily increasing and the prices of the devices are reducing continuously (Zhe Chen, August 2009). Power electronics is a combination of power, electronics and control. Control part of the power electronics looks for steady-state and dynamic characteristics of closed-loop system. The requirements for the generation, transmission and distribution of the electric energy are dealt by Power. In addition to this, electronic part deals with solid-state devices for the processing of the signals to meet the desired control objectives (Rashid, 2014).

Power electronic converters are made by semiconductor devices to perform an operation of the conversion and the control of voltage magnitude and conversion. Depending upon the properties of circuits and applications converter can allow the flow of power in both directions. There are two types of systems in which power converters can be divided mainly grid commuted converter systems and self commuted converter systems. In grid commuted converter systems the semiconductor device that is used is thyristor with a high power capacity of 6 or 12 or even more pulses. A thyristor converter is not able to control reactive power as it consumes inductive reactive power. Hence, thyristor converters are mainly used for the very high voltage and power applications such as traditional HVDC systems (Zhe Chen, August 2009).

Self commuted converter systems generally use a control method of pulse width modulation (PWM) in which mostly semiconductor device having a turn-off ability are used, such as IGBTs. These types of converters are able to transfer both active and reactive power in both directions (ac-dc or dc-ac). This means that the demand of the reactive power can be delivered by PWM converter. PWM converters can produce harmonics and interharmonics because of the high frequency switching, generally in the range of kilohertz. Hence it is easy to remove the harmonics relatively with the help of small-size filters because of high frequencies (Zhe Chen, August 2009). In this project for a small scale wind turbine, converters with a control method of pulse width modulation method were used after the generator section.

The main function of the Power electronic circuits or the converts is to convert alternating current (AC) to Direct current (DC); to convert DC to AC; to control voltage and frequency and to convert DC to DC. After generating electricity from generator in three phase AC form some kind of circuit is required which can convert the alternating current generated from generator to direct current for the storage in battery. For this purpose a three phase bridge rectifier was used after the generator section. Beside the rectifier circuit in power electronic circuits, Power converters mainly either buck or boost converters were used to achieve a required level of DC voltage at the load side. In between a Rectifier and buck or boost converter a DC link capacitor was also required to limit the value of the ripples that are allowed at the output section. The basic block diagram of the power electronics used for the project is shown in Figure (4-15).

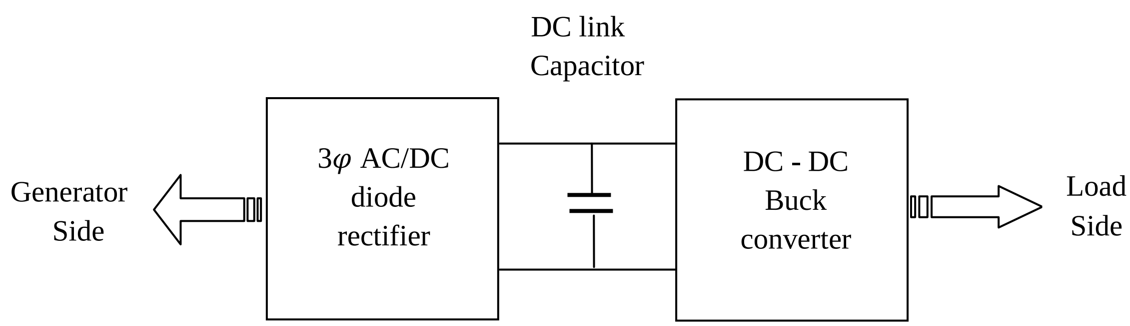

Figure (4-15): - block diagram of the power electronics sections of the Wind energy conversion system

The information about these blocks, in details, is given below one by one.

a. Three Phase Bridge rectifier

A rectifier is a circuit which is used to convert an ac signal into a dc signal or unidirectional signal with the help of Diode semiconductor device. A rectifier due to its operation is also known as ac-dc converter. The waveform of the output voltage of the rectifier is same as that of the input voltage except that the negative part of the waveform appears as positive value at the output. Depending upon the type of the input signal applied to the rectifier it can be categorized into two different types which are single phase and three phase. Further these types can be either half wave or full wave single / three rectifiers. Generally in half wave, output is present only for positive cycle of the input voltage whereas in full wave, output is available for both positive and negative cycle (Rashid, 2014).

In this project a three phase full wave rectifier was used, as the input voltage applied to the rectifier from the output of generator was in three phase form. A three phase full wave rectifier is also known as three phase bridge rectifier which is commonly used in high power applications. The model of the project was considered to be loss less system so the source inductance for the bridge rectifier was considered to be negligible. The circuit diagram of three phase bridge rectifier is shown in figure (4-16) with pure resistive load.

Image removed due to copyright restriction.

Figure (4-16): - Circuit diagram of three phase bridge rectifier **(Rashid, 2014)**

It is clear from the circuit diagram that the three phase bridge rectifier consists of 6 diodes which can operate either with transformer or without it, giving six pulse ripples in the output voltage. The numbering of the diodes in the circuit diagram is same as that of the conduction sequence in which diodes are turned on. Each diode conducts for the duration of 120 degree angle and the conduction sequence in which diodes are turned on is D1 - D2, D3 - D2, D3 - D4, D5 - D4 , D5 - D6 and D1 - D6. The pairs of the diodes which are connected between the supply lines having a highest amount of the instantaneous line to line voltage generally conducts. The line voltage is generally represented as a multiplication of the single phase with $\sqrt{3}$ (Rashid, 2014). The waveform of the input voltage and the output voltage of the three phase bridge is shown in Figure (4-17) also indicating the diodes which will be on.

Image removed due to copyright restriction.

Figure (4-17): - Waveform of input and output voltage of three phase bridge rectifier **(Rashid, 2014)**

Using the peak value of the phase voltage, represented as V_m, the output voltage can be calculated. The average output voltage at the end rectifier means at load side is shown in equation (4-8).

(4-8)

The RMS value of the output voltage is given as (Rashid, 2014)

(4-9)

In case of purely resistive load, the diode current can be found out using the value of load and the input voltage as R, through which the value of the RMS diode is given as and the RMS value of the transformer secondary current is given as I where I_m is the peak value of the secondary line current (Rashid, 2014).

At the output of the rectifier some harmonics are also present due to non linear nature of the diodes leading to the increase in total harmonic distortion of input current. To reduce these harmonics or ripples in the output voltage, a DC link capacitor is employed between the output section of the rectifier and input of the inverter section of the power electronic circuit for this project.

b. Designing of DC link Capacitor for rectifier and converter section

DC link capacitor is mainly employed between the rectifier and inverter section. The main purpose of the DC link capacitor is to maintain a DC voltage with small ripples in output at steady state and to serve as storage element for energy for supplying real power difference during the transients between load and source (Jain, 2018).

In steady state it is assumed that the real power supplied by the source must match with the demand of the power at the load side along with some small power to compensate for the active filter losses. So, a reference value can be set for a DC link voltage (Jain, 2018).

However, the condition of the load changes then the balance of the real power will be disturbed between the source and the load. DC link capacitor is used to compensate this difference in the power. This difference also changes the value of the DC link voltage which is different than the reference voltage. For the satisfactory operation of the active filters, the peak value of the reference current must be adjusted in such a way that it changes with the real power drawn from source proportionally. The charging / discharging of the real power with the help of the DC link capacitor is used to compensate the power that load has consumed. When the DC link voltage is recovered and attains the value same that of reference voltage then it is supposed that real power supplied by source matches with the load power consumed again (Jain, 2018). Hence by regulating the average voltage value of the DC link capacitor, peak value of the reference source current can be obtained.

If the value of the DC link voltage is less than reference voltage than this means that the real power of the supply is not enough to meet the power demands of the load. To meet the demands of the load, source current means the real power drawn from the source needs to be increased. Whereas the larger value of the DC link voltage as compared to reference voltage tries to decrease the reference source current (Jain, 2018).

Beside these purposes, DC link capacitor also has another responsibility of providing a low impedance path for the high frequency current. As the frequency of the signal goes up then the DC voltage at the input of the capacitor along with the cable inductance causes the increase in the impedance. As the impedance of the DC link capacitor decreases then it automatically become the preferable path for the AC current to pass which is known as Ripple current. DC link capacitor is also used to stiffen the DC bus. It is important to have a stiff DC bus because the Voltage ripples on the DC bus are shown in a phase current in form of ripples which is undesirable. The specification of required ripple voltage on the DC bus is used to determine the value of the capacitance required (Sylvestre, 2019).

Generally ripples in the DC-link voltage is observed more in case of unbalanced load as compared to balanced load. Ripples are also introduced in the reference compensating currents due to voltage ripples. Hence the RMS value and the third harmonic distortion (THD) of the three phase compensated currents are not same. Therefore to limit the ripples in the DC link voltage, a higher value of the capacitor is required which results in generation of a ripple free reference current. Further this ripple free reference current improves a compensated source current (Jain, 2018).

For minimizing the ripples in the voltage the selection of the value of the capacitor can be done while considering the maximum value of the peak to peak switching ripple Δv_{pp}^{max} or the RMS value of the switching ripple ΔV_{rms}.

Hence the DC link capacitor value can be calculated using the equation (4-10) which is given below also considering the maximum value of the output current I_o^{max} (Marija Vujacic, 2017)

(4-10)

Using the RMS value of the switching ripple, the value of the DC link capacitor can be calculated using equation (4-11) (Marija Vujacic, 2017).

(4-11)

c. Buck Converter/ DC-DC (step down) converter

A DC – DC converter is used mainly to convert voltage directly from dc to dc and is also known as dc converters. It can be considered as an dc equivalent to an ac transformer with a turn ratio that varies continuously. It can be used as an ac transformer to step up or step down a dc voltage. In case of DC converter both the input and output are dc and they are able to generate a fixed or variable dc output voltage from a fixed or variable dc voltage. Ideally the output voltage and input current of the dc-dc converter should be pure dc but practically it contains harmonics and ripples in output voltage and input current (Rashid, 2014).

DC Converters are used as switching mode regulators to convert the unregulated DC voltage to regulated one. This regulation is achieved with the help of switching devices such as MOSFET, BJT or IGBT using the method of pulse width modulation. Buck converter in this project was used to reduce the value of the voltage produced after the rectifier section (Rashid, 2014).

In buck converter, the average output voltage V_a is less than the input voltage V_s. It consists of one active switch which is controlled by the duty cycle of the pulses provided to it to turn it on or off, a diode and a filter. The circuit diagram of the buck converter is shown in figure (4-18).

Image removed due to copyright restriction.

Figure (4-18):- Circuit diagram for buck converter **(Rashid, 2014)**

In this circuit the transistor Q_1 acts as controlled switch and diode D_m is an uncontrolled switch. They operate as a two single pole single through (SPST) bidirectional switch (Rashid, 2014).

Due to input exposed to the transistor, the input current is highly dynamic in nature which is undesirable as it introduces noise in the system. That is why the capacitor at the input of the converter is required and this purpose is served by the DC link capacitor.

This buck converter can operate in two different modes Continues conduction mode (CCM) with fixed frequency and high current and discontinuous conduction mode (DCM).

In mode 1 transistor Q_1 is switched on at time t = 0. The input current rises in values and flows through filter inductor L, filter capacitor C and a load resistor R. The equivalent circuit diagram of the buck converter in mode 1 is shown in figure (4-19).

Image removed due to copyright restriction.

Figure (4-19): - Equivalent circuit diagram of buck converter for mode 1 **(Rashid, 2014)**

Mode 2 begins when the transistor is switched off at time t = t_1. Due to the energy stored in the inductor, the freewheeling diode conducts and the current of the inductor starts to flows through filter inductor L, filter capacitor C, a load resistor R and diode . The inductor current falls again when the transistor is turned on again in the next cycle. The equivalent circuit diagram of the mode 2 operation of the buck converter is shown in figure (4-20) (Rashid, 2014).

Image removed due to copyright restriction.

Figure (4-20):- Equivalent circuit diagram of buck converter for mode 2 operation **(Rashid, 2014)**

The waveform of the input and output voltages and currents for the continuous flow of a current in filter inductor L is shown in figure (4-21). In the figure of waveforms it is assumed that the current rises and falls linearly. However in practical circuits, switch has a finite amount of nonlinear resistance. In most of the applications the effect of the nonlinear resistance of the switch is negligible. Depending upon the values of the switching frequency, value of the filter inductance and capacitance, inductor current can be discontinuous in nature.

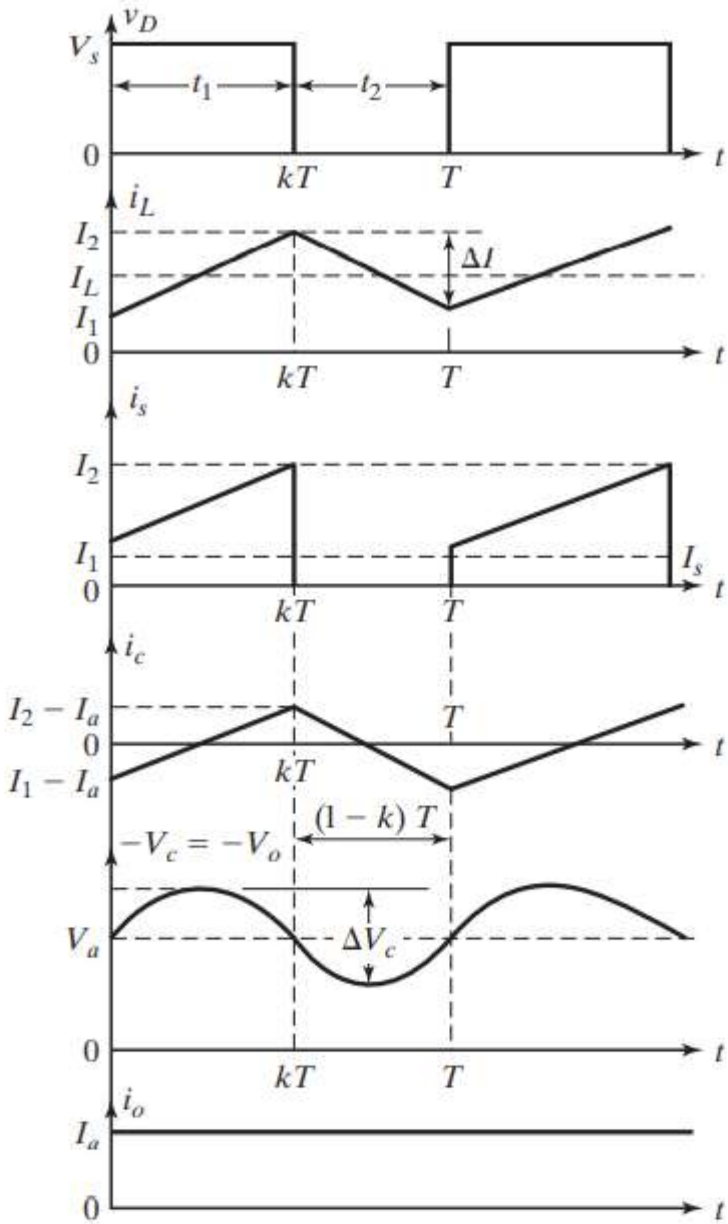

Figure (4-21):- Waveforms of the input and output voltage and current of buck converter for the continuous flow of inductor current

4.2. Energy Storage System

Energy storage units are systems that can receive and store energy from renewable energy sources or directly from grid.

As the electricity is a highly ordered form of energy as it can be converted from one form to another very efficiently so it is more versatile than types of power. For instance electricity can be converted back to mechanical and heat form very efficiently. However, the heat energy cannot be converted back to electrical form with that efficiency because of its disordered form.

The main disadvantage of the wind energy is that it is not same all the time and cannot fulfil the demand of the load all the times. So an energy storage system is required to full fill the demands of the load means it can provide a solution for fluctuations in the output power of the wind while compensating the power when it is below the target value and by storing power when it is above that vale. There are various technologies for the storage of energy such as Compressed air energy storage; Hydrogen based energy storage system (also known as fuel cell), Flywheel energy storage system, super conducting magnetic energy storage system, super capacitors and battery energy storage system (Luanna Maria Silva de Siqueira, March 2021).

The most popular energy storage system out of the types mentioned above is Battery energy storage system where the energy is stored in a form of charges in electrochemical cells. To achieve a desired value of the output voltage required, in power system application multiple cells are usually connected together. Each cell consists of electrolyte and an electrode (positive electrode is known as cathode and negative electrode is known as anode). The movement of the ions inside of electrolyte causes electrons to move providing or accumulating electrical energy upon the electrochemical reaction in cells (Luanna Maria Silva de Siqueira, March 2021).

4.2.1. Types of electrochemical batteries

Generally there are two types of electrochemical batteries. One is primary battery in which chemical energy is converted into electrical energy and this reaction in primary batteries is non reversible and it is discarded after a full discharge. They are generally used in standalone applications where the charging is impossible. An example of devices in which these batteries can be used are military grade devices, battery powered devices, pace maker, animal tracker, wrist watches and many more (Odunlade, 2018).

Another type is secondary battery also known as researchable batteries. The electrochemical reaction in these batteries is reversible. This reaction can be reversed by applying a certain amount of voltage in reverse direction. In discharging mode these batteries convert chemical energy to electrical energy and in charging mode reverse action of these energies is happened. Secondary batteries with a small capacity are generally used to power up some portable electronic devices such as mobile phones whereas heavy duty batteries are used in powering electric vehicles and sometimes in high drain applications such a levelling of load in generation of electricity. Secondary batteries can be further divided in different categories based on chemistry involved (Odunlade, 2018).

The rating of the batteries is stated in terms of the average voltage during discharge and the ampere-hour capacity it can deliver before the voltage drops below the specified limit. The product of these two quantities means voltage and ampere-hour capacity, forms the watt-hour (Wh) energy rating the battery can deliver to load under fully charged condition.

4.2.2. Battery condition

a. *State of charge (SOC) %: -*

The state of the charge (SOC) of a cell is defined as the capacity that is already available as a function of the rated capacity. The value of the SOC varies between 0% and 100%. The cell is known as fully charged when the value of SOC is 100% whereas a SOC of 0% means that the cell is completely discharged. In practical applications, the state of the charge is not allowed to go beyond 50% and therefore the cell is recharged when the SOC reaches 50%. Similarly when the cell starts aging then the maximum value of SOC starts reducing which means that the 100% SOC for an aged cell would be equivalent to 75% to 80% SOC of new cell (Hamdi Abdi, 2017).

In general, SOC is defined as a ratio of its current capacity [Q (t)] to the nominal capacity [Q_n]. The nominal capacity is generally provided by the manufacturer and represents the maximum amount of charge that can be stored in the battery. The formula for SOC is given in equation (4-12) (Matúš Dankoa, 2019).

$$— \tag{4-12}$$

b. Self-Discharge rate: -

Self discharge of a cell is defined as a leakage of a current between the anode and the cathode because of various chemical reactions that take place within a cell. Even if the cell is not used, due to some internal reactions the cell can still get discharged to a certain level. The rate of the self discharging of the cell depends upon the cell chemistry as well as on the temperature at which it is being operated. Self-discharging generally increases with the increase in temperature (Hamdi Abdi, 2017).

c. Discharge rate: -

The rate of the discharge of cell is also a vital factor in determining the performance of the battery. In practical experiments it has been proven that for a large discharge time the capacity to store the charge of the cell decreases.

d. Charge/Discharge ratio (C/D ratio): -

The ratio of C/D is defined as the ampere hour input over the output ampere hour with no net change in SOC. This ratio also depends upon the temperature along with charging and discharging rates.

4.2.3. Control strategies for keeping voltage of battery constant

Generally there are two types of control strategies that can be used to keep the voltage of the battery constant in a hybrid wind energy conversion system with an application of battery charging. The two most basic and simple methods of the control are constant voltage and constant current charging systems. There are also some charging methods that combine these two control methods. The brief details about these methods are given below.

a. Constant Voltage:-

This method of control uses a constant voltage to charge a battery. In this algorithm a DC output voltage of the battery is compared with a reference voltage which is further used to obtain an error signal. This error signal is then fed to a comparator along with a triangular waveform. The main function of the comparator is to obtain a pulse width modulation signal which is further used to control the output voltage. The function of the comparator can also be performed by PI controller. Generally this controller is also used to control a duty cycle. The circuit diagram depicting this control is shown in figure (4-22) (S. Eren, 2006)

Image removed due to copyright restriction.

Figure (4-22): - Image depicting the constant voltage control

At the beginning of the cycle, this strategy can be damaging to battery because at the large currents can be produced at the initial charging stage which must be limited to protect the circuit and battery. This charging method also sometimes rises temperature in the battery which can lead to shorten the life of the battery (S. Eren, 2006).

b. Constant Current:-

This control algorithm uses a constant current to charge the battery until the voltage of the battery reaches a specified value. In this constant current method of charging a battery, DC output voltage is compared with a reference voltage to get an error signal. This obtained error signal is then compared with the current of the battery to obtain another error signal which is shown in figure (4-23). This error signal then can be fed to comparator along with a triangular waveform or a controller to obtain a pulse width modulation signal that is used to control the output current (S. Eren, 2006) .

This algorithm is more damaging to battery at the end of the cycle. The amount of the current available for constant current charging method, in case of wind energy battery charging system mainly depends upon the wind. The disadvantage of this charging method is that it may results in large currents which can overcharge the battery, degrading the life of the battery (S. Eren, 2006).

Image removed due to copyright restriction.

Figure (4-23): - Image depicting the constant current control

c. Constant Current-constant voltage:-

This method combines both methods of constant voltage and constant current controls to keep the battery voltage constant. The constant current charging method is used at the first part of the charge cycle until the set value of the battery voltage is not achieved. During the second part of the charging cycle, constant voltage charging method is used. This type of algorithm is generally designed while keeping the individual disadvantages of both charging methods in mind. Both constant current and voltage charging generally occurs during those parts of cycles when they are least damaging to battery.

This method of charging also have its own disadvantages as it does not take into account the state of charge of the battery which can make this method slow and inefficient, and may produce gassing (S. Eren, 2006).

d. Pulse charging:

Pulse charging is another method which is also used to charge the battery. In this strategy current pulse is used to charge the battery. Pulses with a larger width are used to increase the charging time. This method is more effective than the others as it does not result in gassing, thus increasing the efficiency and lengthening the life cycle of the battery. Gassing is avoided in this method because if the current pulses are short than then most of the current will be used for charging the battery rather than producing gas (S. Eren, 2006).

4.2.4. Battery and control scheme used for project

Battery used in the model of the project was already available in Simulink model. This model was implementing a generic battery model for most popular battery types. The type of the battery with Lithium-Ion technology was used. The nominal voltage was set to 12 V in this case and the rated capacity was set to 30 Ah to deliver 360 Watt energy to deliver to a load. The parameters set for battery are shown in figure (4-24).

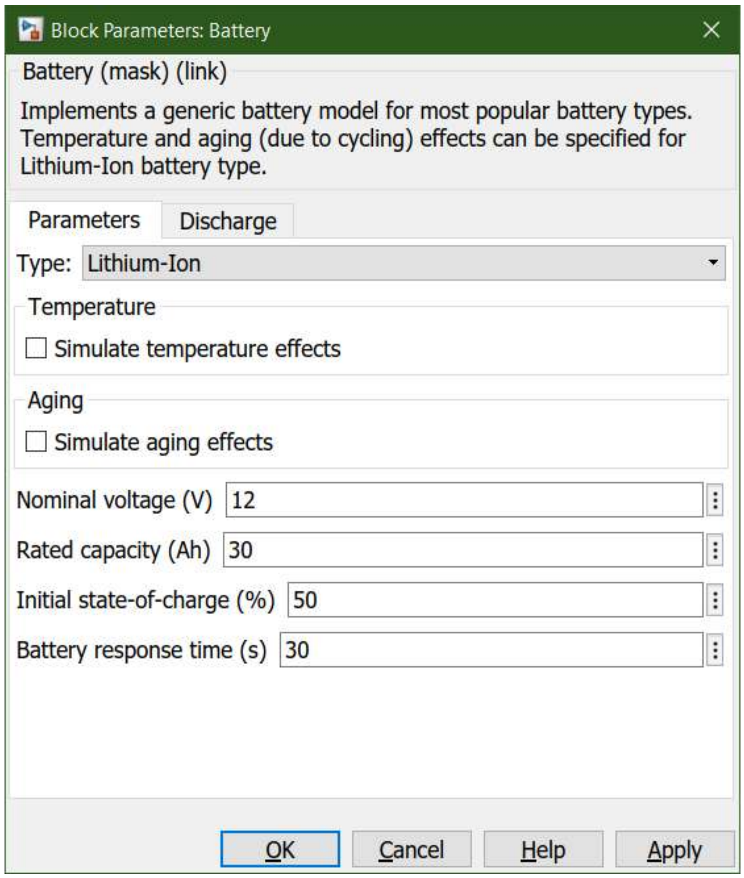

Figure (4-24):- Parameters set for battery for wind energy conversion system

The Battery discharge characteristics are displayed in figure (4-25) for the set parameters of the battery. From the figure it was clear that with the large value of the discharging current the battery voltage was reducing early as compared to smaller value of discharging current.

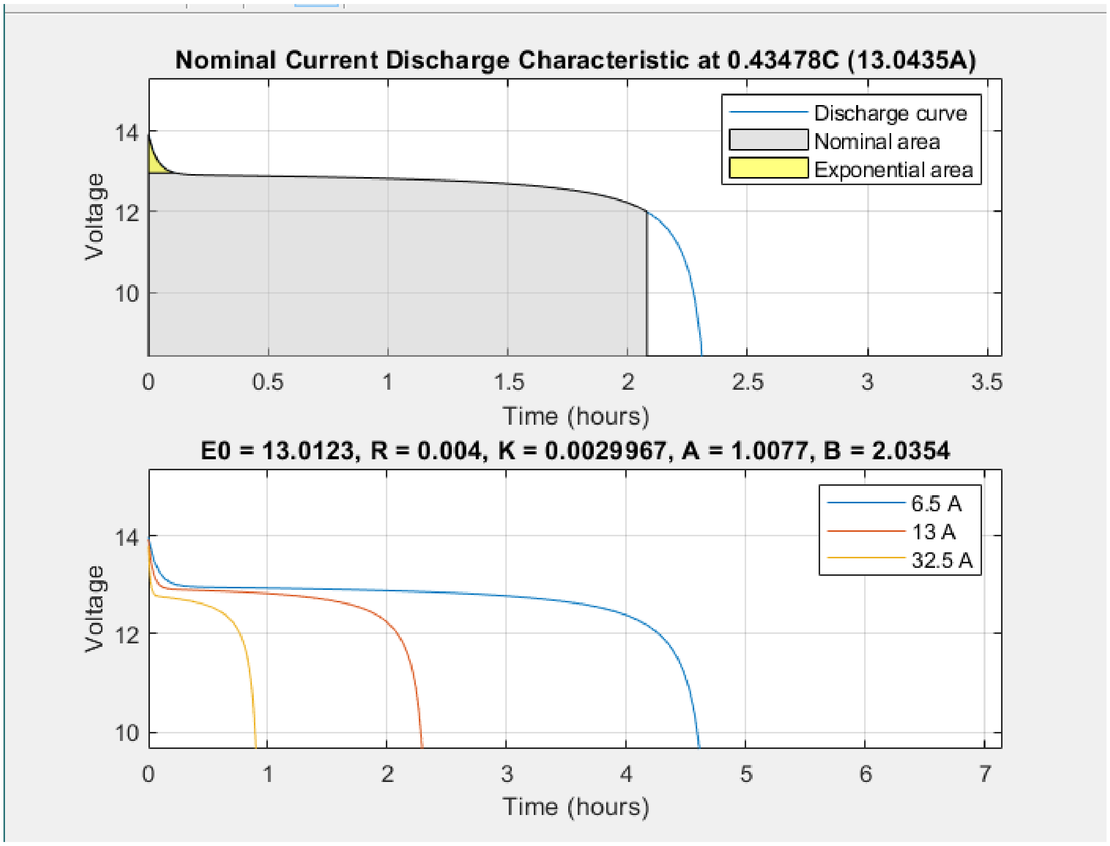

Figure (4-25):- Nominal current discharge characteristics of Battery

A typical discharge curve consists of three sections. First section is the exponential voltage drop when the battery is charged. Type of the battery determines the width of the drop. The second section is the nominal area of the battery which represents the charge which can be extracted from the battery until the nominal voltage hasn't achieved. Lastly, the third section represents the total discharge of the battery, when the battery voltage drops rapidly.

To apply a control scheme for battery charging in this project constant voltage charging method was used. In this the output of the buck converter was applied to battery which was further used with reference voltage to obtain an error signal. This error signal was then applied to PI (proportional integral) controller to obtain the duty cycle to operate the switch of the buck converter.

Chapter 5: Mathematical models of the components required for wind energy conversion system

5.1. Wind turbine Mathematical model: -

The mathematical relation for the mechanical power extraction from the wind can be expressed by using the equation (5-13).

(5-13)

Where P_w is the extracted power from the wind, is the air density [kg/m], is the wind speed, A is the area swept by the rotor blades of the wind turbine and is the power coefficient which is a function of both blade pitch angle β and tip speed ratio λ.
The tip speed ratio of the wind turbine is given in equation (5-13a)

(5-13a)

In above equation R is the radius of the radius of the blades and is the angular speed of the turbine rotor.
The power coefficient , a non-linear function, using a generic equation is expressed in equation (5-14).

(5-14)

Where

and = 0.5176, = 116, =0.4, C_4= 5, =21 and =0.0068.

The torque of the wind turbine can be expressed as shown in equation (5-15) (BOUZID Mohamed Amine, jan 2014)

(5-15)

The $C_p - \lambda$ characteristics of a wind turbine for different values of pitch angle β are shown in figure (5-26). It is clear from the figure that for fixed pitch angle or $\beta = 0°$, a maximum value of can be achieved, provided that the tip speed ratio must be at its nominal value λ_{nom} of 8.1.

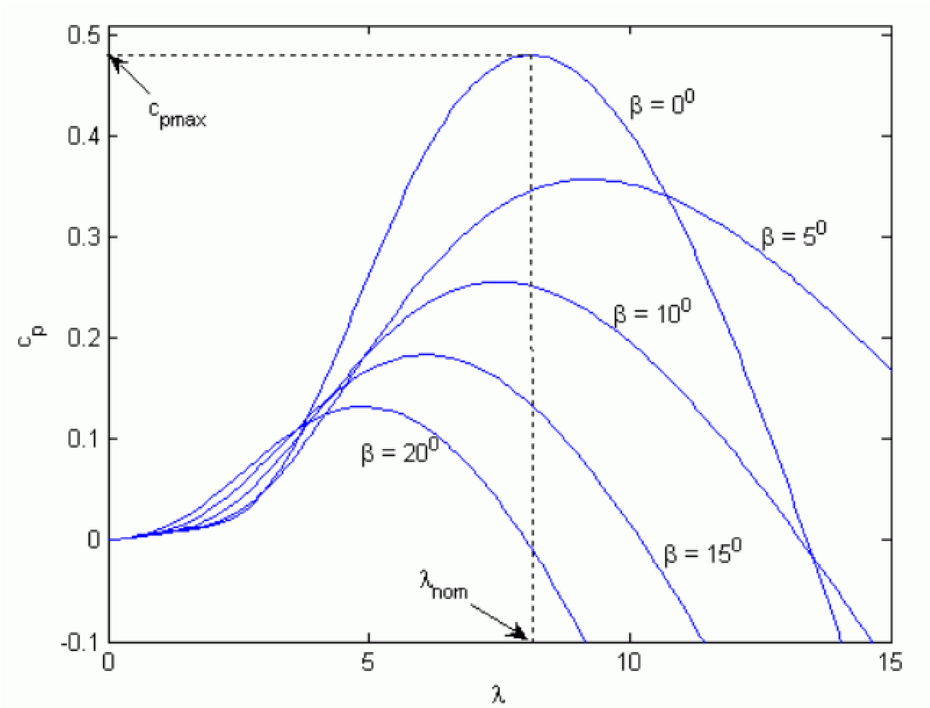

Figure (5-26):- characteristics of a wind turbine for different values of pitch angle

5.2. Permanent Magnet synchronous generator Mathematical model: -

The model of the generator used in the project was three phase sinusoidal permanent magnet synchronous generator. Following equations were used to model the generator. These equations are expressed in rotor reference frame (qd frame). Stator is used to refer all the quantities in rotor reference frame.

— — — — (5-16)

— — — — —— (5-17)

(5-18)

Where,

L are d-axis and q-axis inductances

R is resistance of stator windings

are d and q axis currents

are d and q axis voltages

is angular velocity of rotor

is Amplitude of the flux induced by the permanent magnet of the rotor in the stator phases

p is the number pole pairs

is Electromagnetic torque

The L_q and L_d inductances represent the relation between the phase inductance and the rotor position due to the saliency of the rotor. For example, the inductance measured between phase A and B (when phase C is left open) is given by equation (5-19).

– (5-19)

where θ_e is electrical angle.

The variation of the phase to phase inductance w.r.t. electrical angle of rotor is shown in figure (5-27).

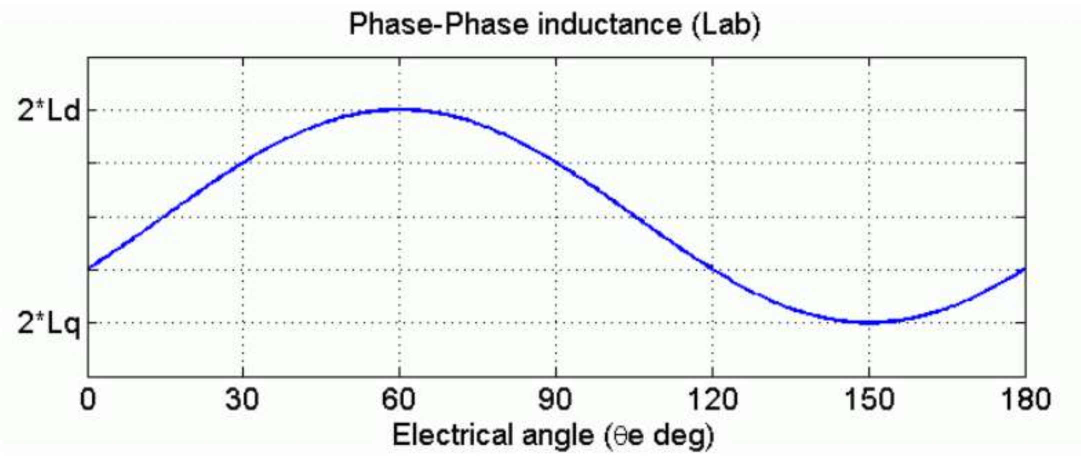

Figure (5-27): - variation of the phase to phase inductance w.r.t. electrical angle of rotor

For rotor of round type the phase inductances for both d and axis is same which is given in equation (5-20).

— (5-20)

For salient pole rotor the phase inductances for both d and q axis are different which is given in equation (5-21) and (5-22).

(5-21)

(5-22)

5.3. Buck converter Mathematical model: -

The variable DC voltage generated from the rectifier section is generally variable in nature, with small number of ripples, which is unsuitable for battery charging. As the power provided may be too high and volatile which can cause a damage to battery, so remedy for this issue is the use of buck converter, in continuous conduction mode. The main purpose of the buck converter is to step down this variable dc voltage and to stabilize it while allowing the application of the control strategy used for charging the battery. The equivalent circuit of the buck converter is shown in figure (5-28).

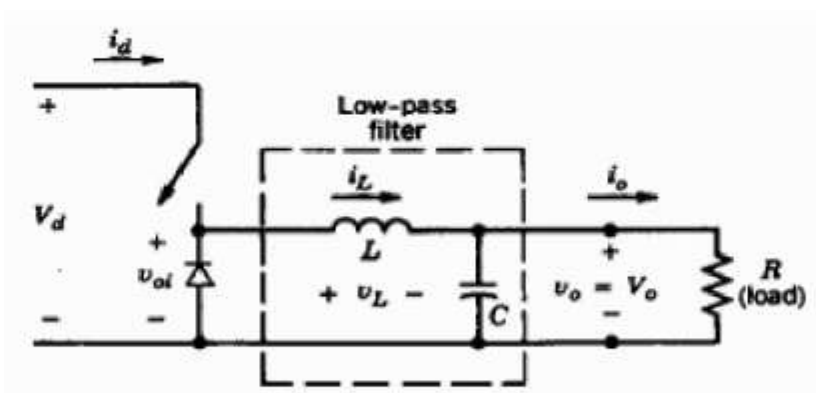

Figure (5-28): - Equivalent circuit of buck converter

The output voltage of the buck converter is equal to the input voltage times the duty cycle and the value of the duty cycle varies between 0 and 1.

The duty cycle of the buck converter, used to control switch of the converter, is modified to control the output current and output voltage of the buck. The duty cycle is also important for determining the values of components required in the converter. To get the value of the duty cycle equation (5-23) was used.

(5-23)

Where

is output current

is input current

is input voltage

V is output voltage

For calculating the minimum value of the inductor following two equations were used

(5-24)

(5-25)

In above two equations I_{LB} is inductor boundary current and T_s is switching period

For calculating the value of the capacitor the equations (5-26) and (5-27) were used and the voltage ripple for the output of the dc - dc converter is desired to be less than 5%.

(5-26)

(5-27)

In above equations C is the value of the capacitor required and is the output voltage ripple.

As the values of the capacitor and inductor are inversely proportional to switching frequency of the buck converter, so a higher frequency is required for minimizing the cost (S. Eren, 2006).

5.4. Battery Mathematical model and controller for battery charging: -

The Simulink model used for the battery in the project is of Lithium-ion type. The equations (5-28) and (5-29) are used to describe the discharge and charge voltage of the battery.

(5-28)

(5-29)

Where E_o is constant voltage

K is polarization constant (in V/Ah) or polarization resistance in ohms

Q is the maximum capacity of battery in Ah (ampere-hour)

A is the exponential voltage, in V

B is exponential capacity in, 1/Ah

is low frequency current dynamics in A and

is extracted capacity in Ah

For charging method constant voltage method of charging was used by using a DC/DC buck converter that is connected to first order output so the voltage of the first order system controls the voltage of Lithium-ion battery. In constant voltage structure, feedback output voltage of the battery uses a PI controller for controlling a duty cycle. The battery output reaches stable voltage as the PI controller is used to suppress the high frequent noise to improve the system and to eliminate the steady-state error (Her-Terng Yau, 2012). The schematic diagram of the second order battery-charging system is shown in figure (5-29).

Image removed due to copyright restriction.

Figure (5-29): - Schematic diagram of charging control **(Her-Terng Yau, 2012)**

The PI controller controls the error signal (steady-state error signal) to be set at 0, so that the batter voltage does exceed control or reference voltage V_r, achieving constant voltage.

The equivalent circuit of the DC/DC buck converter is shown in figure (5-30) which is used to get the transfer function of input and output is deduced from this system. The transfer function of the converter is given in equation (5-30).

(5-30)

Where D is duty cycle of the DC/DC buck converter (Her-Terng Yau, 2012).

Image removed due to copyright restriction.

Figure (5-30): - Equivalent circuit of Buck converter

For the whole charging system the transfer function is deduced from the transfer function of DC/DC buck converter and PI controller. The transfer function is given in equation (5-31).

(5-31)

Further equation (5-31) is used to determine the characteristic equation of the function and the results of the characteristics equation calculated using the Routh table method was used to find value of the proportional k_P and integral k_I gain.

Chapter 6: Simulations and Results for wind energy conversion system

This project uses Simulink of MATLAB simulation software to implement a mathematical model of the overall system. Some components of the wind energy conversion system that are used in model were already available in MATLAB. Models for wind turbine and generator were used that were already available in Simulink. The model of the wind turbine used was implementing a fix pitch wind turbine model. The generator model used was implementing a three-phase permanent magnet synchronous generator. The Simulink model of the project is given in figure (6-31).

Image removed due to copyright restriction.

Figure (6-31): - the Simulink model of Wind energy conversion model for charging a battery in MATLAB

The parameters set for wind turbine model and the generator is given in appendix. The Simulink model of the three phase bridge rectifier, along with generator, used for converting the AC voltage to DC voltage is given in Figure (6-32). The set values for the components of the rectifier are also given in appendix. Before applying a controller for the battery, the rectifier was producing an output of around 56 V so a buck converter was employed after it to step down this voltage to around 12 V.

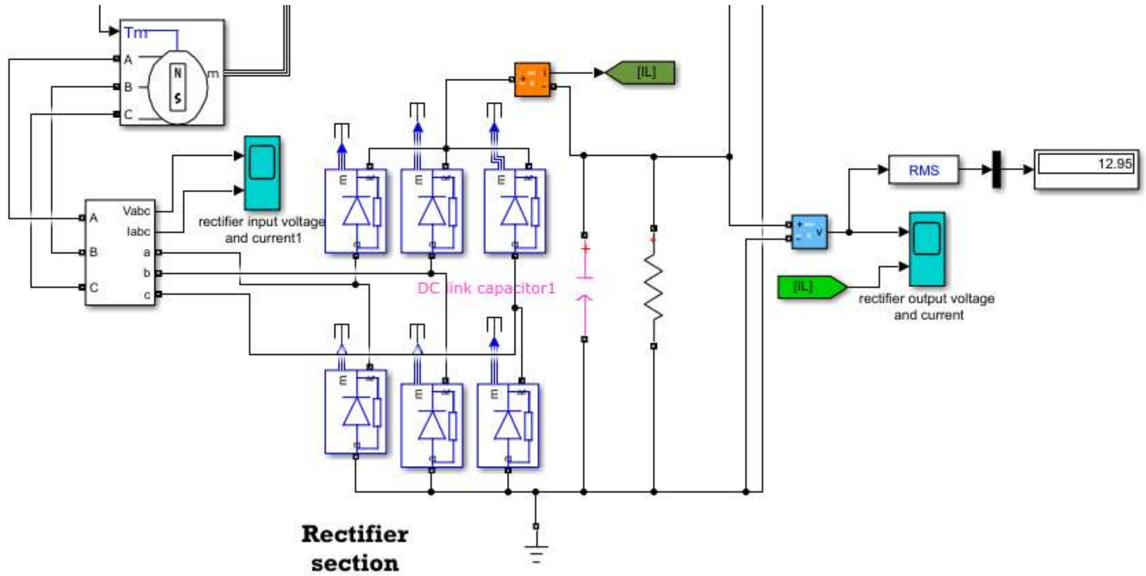

Figure (6-32): - Simulink model of Rectifier section

The waveforms of the voltage and the current at the output of the rectifier are shown in figure (6-33).

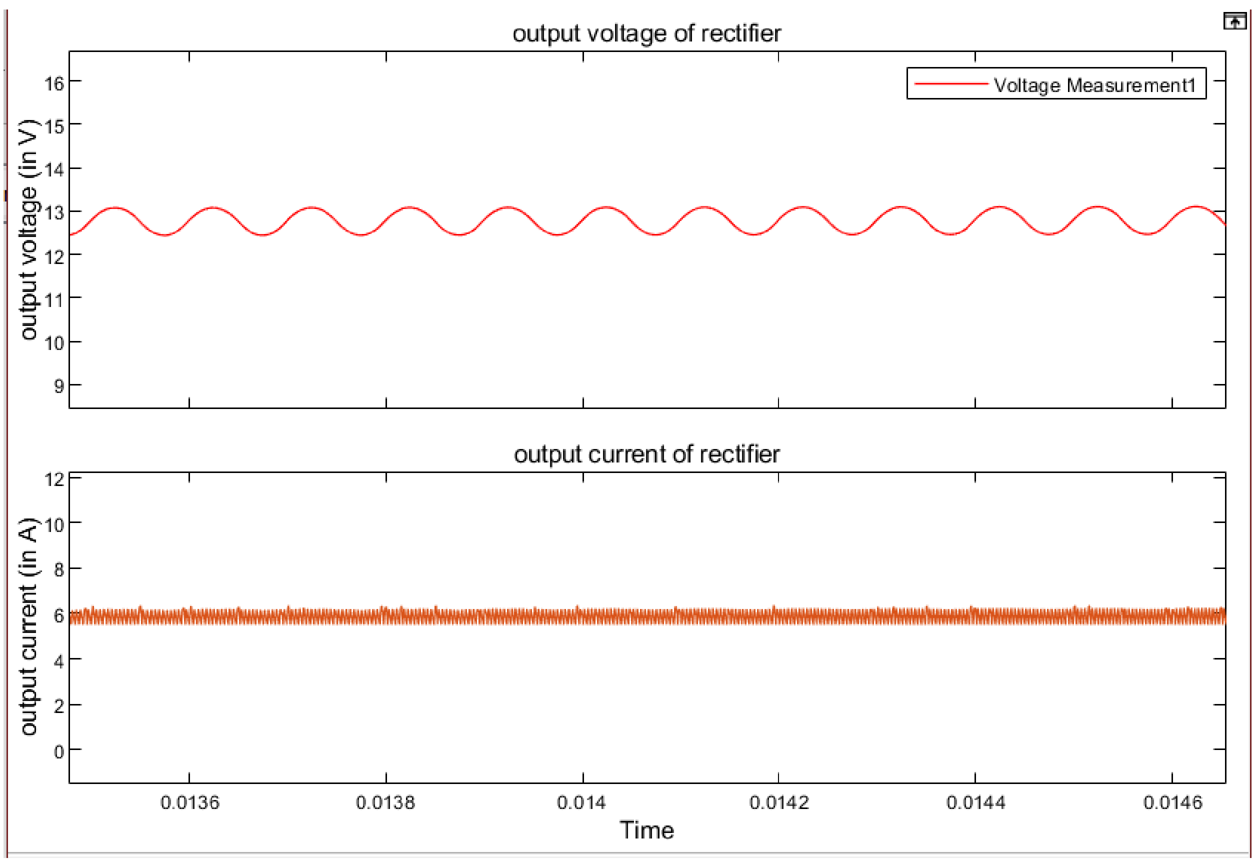

Figure (6-33): - Waveform of variable DC voltage of around 12.8 V obtained at the output of the rectifier

The variable DC voltage generated from rectifier was then sent to buck converter for generating a stable DC voltage. This same buck converter is also used for controlling the battery voltage which is connected at the output of the buck converter. The PI controller is also modeled in Simulink to control the constant voltage of the battery. For implementing controller, a reference voltage was subtracted from the battery output to obtain a duty cycle. Then this error was fed to the proportional and integral part (mainly integrator in Simulink) along with their gain components which was added afterwards to obtain a Duty cycle signal. The Simulink model of buck converter section with a battery charger is shown in figure (6-34).

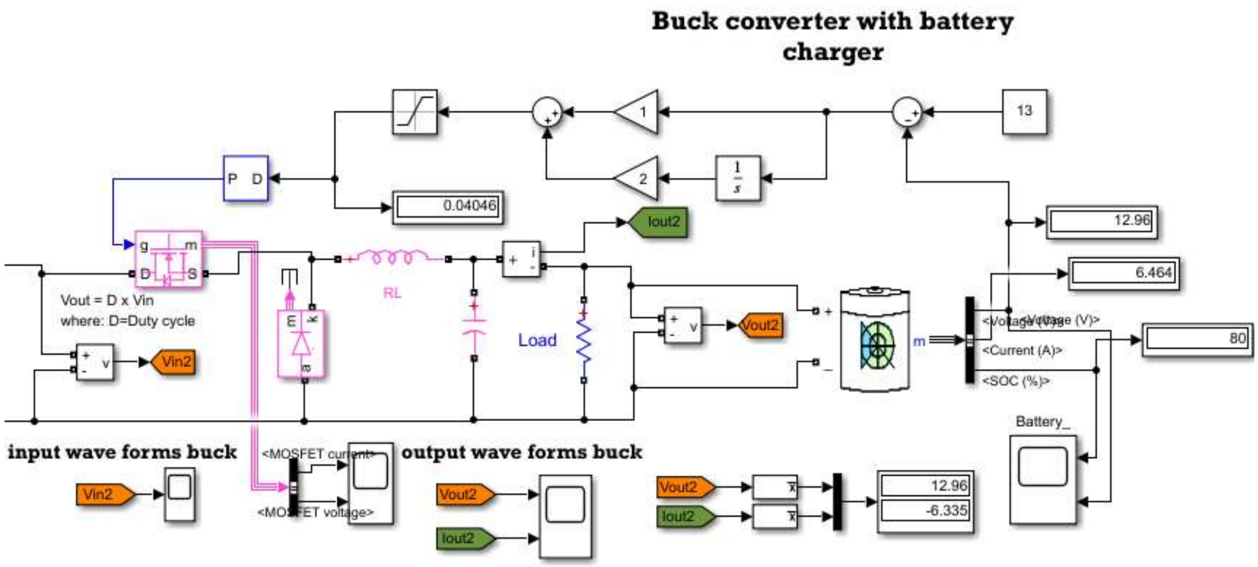

Figure (6-34): - Simulink model of Buck converter with battery charger

The waveform of the battery voltage and the state of the charge of the battery is shown in figure (6-35).

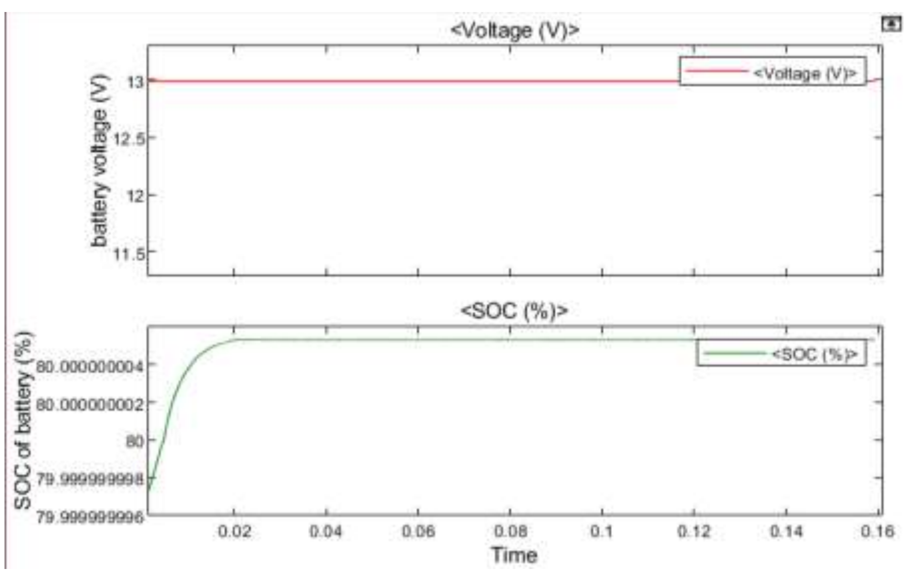

Figure (6-35): - Output voltage and SOC of the battery

It's clear from the waveform that the controller was able keep the voltage of the battery constant to a required level and the SOC curve was also remaining constant indicating the charging phase of the battery.

Besides charging a battery with the help of wind energy, another scenario of providing that energy to a particular load is also presented. For this a Boost converter was used to provide a double voltage, with a duty cycle of 50%, than the input voltage to the load. The Simulink model of Boost converter employing a constant load is shown in figure (6-36) along with results.

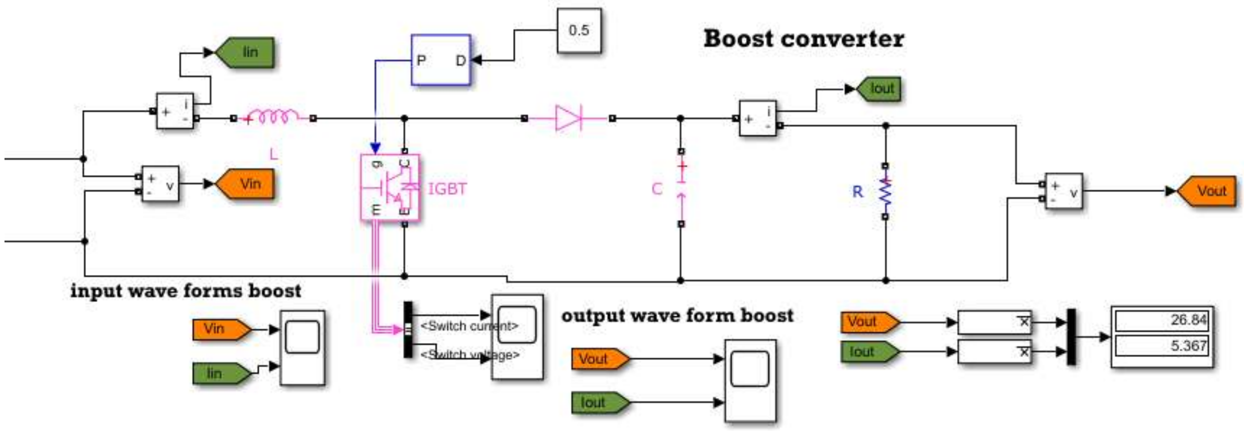

Figure (6-36):- Boost converter for applying a double voltage than the input voltage to a constant load

All these values obtained were for the constant speed of the wind which was set to 12 m/sec. the pitch angle of the blade was also set to 0 degree indicating that the blades of this wind turbine model are able to capture all of the energy of the wind.

This model of wind turbine was also tested for some different value of wind speed which was higher and greater than 12m/s. For the wind speed of around 8m/s (less than the 12 m/s) the battery charger was again able to charge a battery with 12 V even for a small value of the wind speed. For higher values of the wind such as 15 m/s again the battery voltage was kept constant with the help of controller used for battery. Hence this model of wind energy conversion system was able to provide a constant voltage to the battery with a variation in the wind speed.

The results for wind speed 8m/s and 15m/s are given in figures (6-37) and (6-38) respectively. It's clear from both figures that the value of battery voltage was coming out to constant for different values of wind speed because of the PI controller which keeping the voltage constant every time.

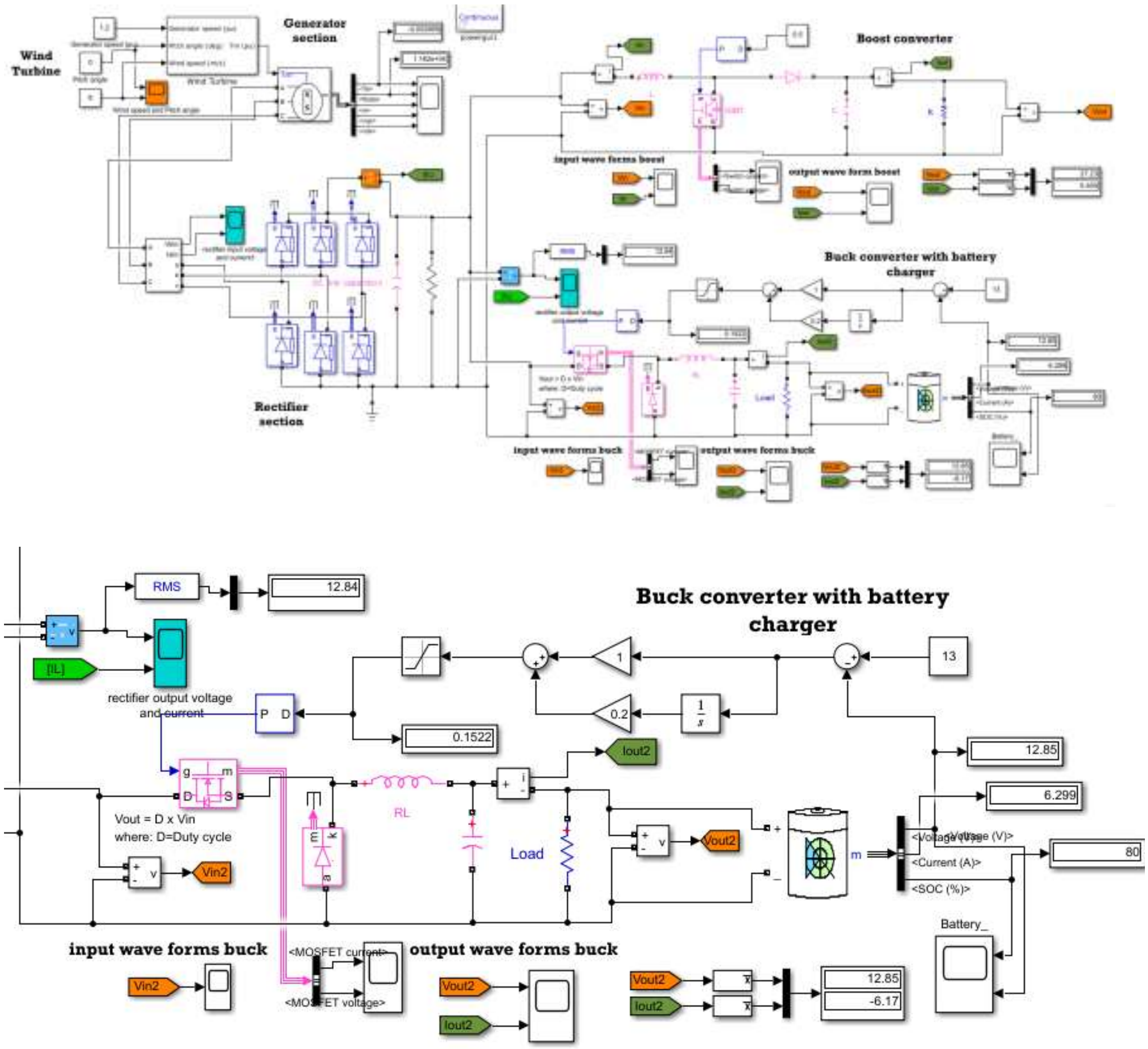

Figure (6-37): - Result of battery voltage for wind speed of 8m/s and a constant load of 5 ohm supplied with the help of boost converter

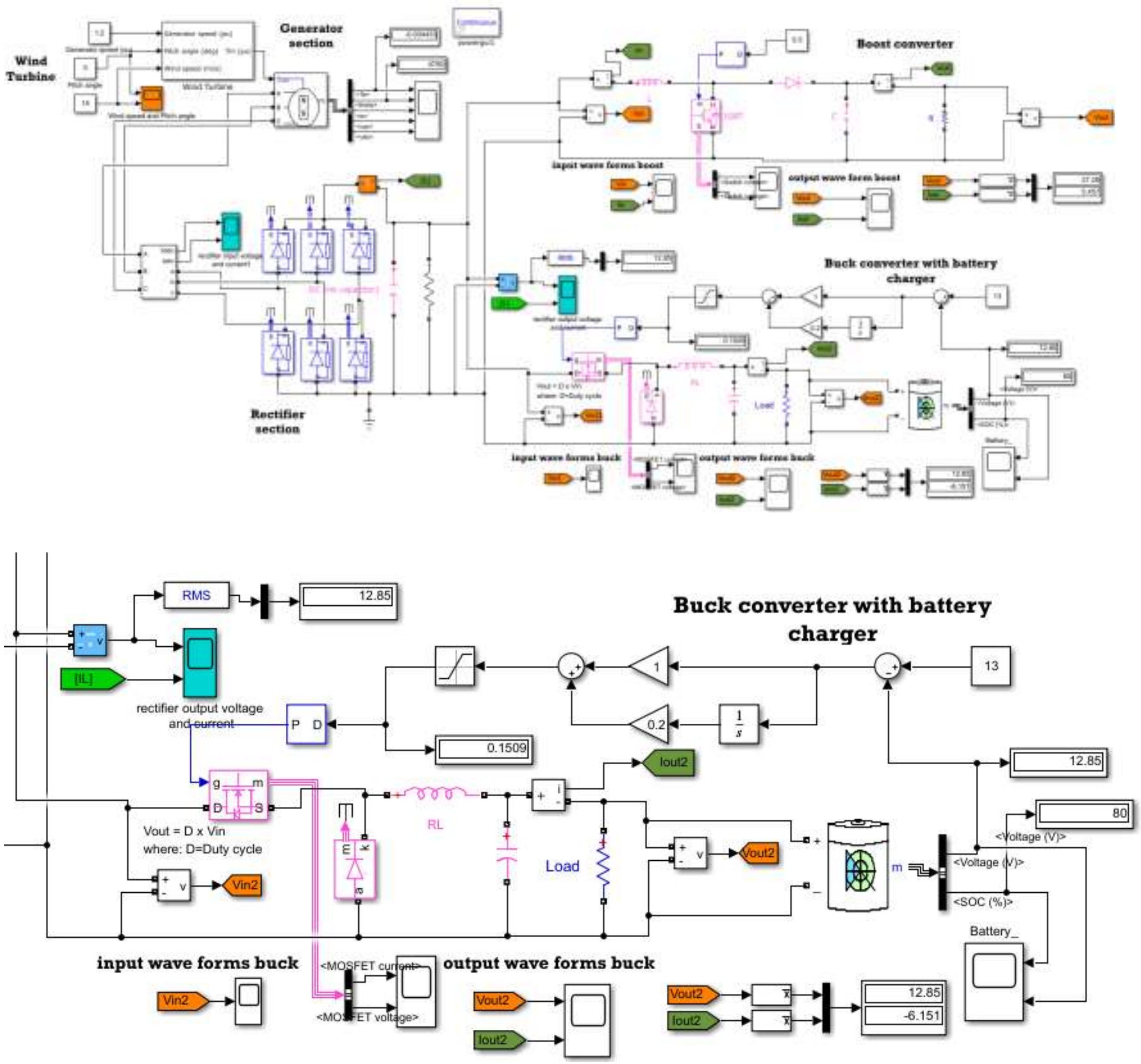

Figure (6-38): - Result of battery voltage for wind speed of 15m/s and a constant load of 5 ohm supplied with the help of boost converter

When the value of the constant load of resistance 5 ohm, at the output of the boost converter, was made variable then the output voltage was also changed. By increasing the resistance of the load the output voltage was also increasing. Figure (6-39) shows the output voltage of the boost converter when the load resistance was changed to 10 ohms from 5 ohms. However there was no effect on the battery voltage with this change in load and the value of battery voltage was again 12.89 V. Hence the controller with DC_DC buck converter is working properly in keeping the battery voltage constant indicating its good reliability.

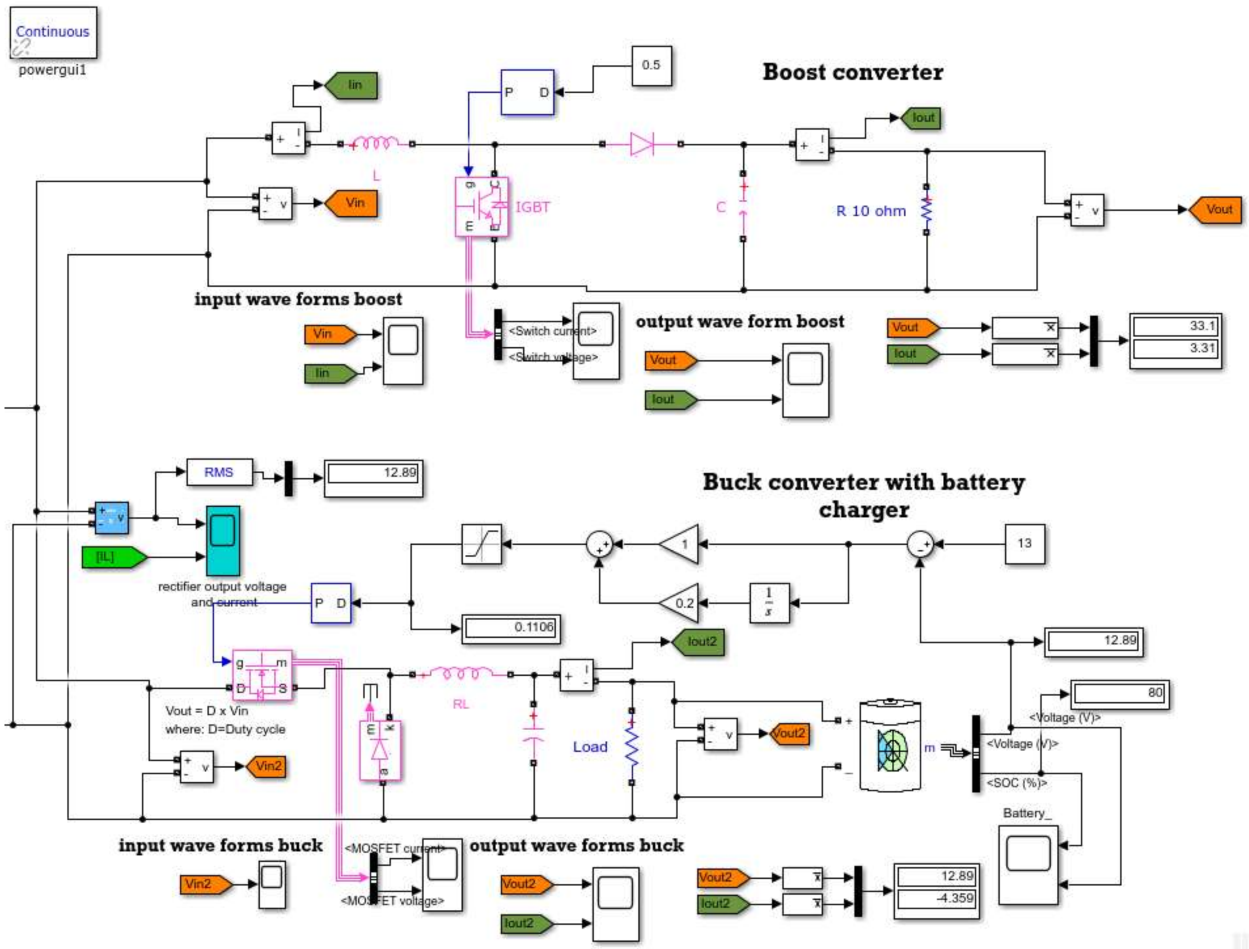

Figure (6-39): - change in the output voltage of boost converter with the change in load resistance

Chapter7: -Conclusion and Future Work

This thesis has designed the small scale stand alone wind turbine model for application of battery charging mainly for the remote areas or residential areas and for small businesses where the connection to grid is not possible. In this thesis a prototype of the wind turbine model in MATLAB Simulink was designed successfully. A wind turbine with a power of 1.1 kW was able to charge a battery package of 12 V with a capacity of 30 Ah. The power electronics required for converting the voltage level to a required value and a nature was also designed properly by studying the models properly. The charge controller for the battery using a charging method of constant voltage was also designed properly using buck converter which was able to deliver a constant voltage to the battery even with the variations in the wind speed. Hence the proposed model in this thesis is able to provide a constant voltage to the battery with different wind speeds. It was also found that controller was able to outperform in case of variable load for the boost converter. Hence controller designed for charging a battery with the help of Buck converter was reliable for charging the battery.

Wind energy does not remain constant all the time means it is fluctuating in nature. It can come from any direction or any side of the wind turbine. So blades of the turbine must be able to capture all of the energy of the wind that it is encountering. For capturing such fluctuating energy some controls can be applied on the Wind turbine section for further work which can be implemented on this thesis. This control generally includes a Maximum Power Point tracking control which takes into an account of the pitch angle of the blade, Tip speed ratio. By applying these controls to the wind turbine, a constant energy even with the fluctuations in the wind can be provided to the next sections of the wind turbine in this conversion system. The constant voltage is also needed to be applied to battery package or a variable load at the end mainly to ensure the reliability and the robustness of the controller used in the model and the healthy life of the battery and loads connected.

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APPENDIX

a) Wind turbine system specification

Rated power - 1.1 kW
Rated wind speed – 12 m/s
Pitch angle – 0 degree

b) Permanent magnet synchronous generator

Number of phase – 3
Mechanical Input – Torque
Rotor type - Round
Stator resistance – 18.7 (ohms)
Armature inductance – 0.0268 H

c) Rectifier specifications

Type – three phase bridge rectifier
Diode resistance – 0.001 ohms
Forward voltage – 0.8 V
Snubber resistance Rs – 500 ohms
Snubber capacitance Cs - 250e-9 F
Load resistance – 10 Ohms
DC link Capacitor - 470e-6 F

d) Buck converter specifications

Switch Resistance - 1e-3 Ohms
Switch internal diode resistance Rd - 1e-3 ohms
Snubber resistance Rs – 1e5 ohms
Snubber capacitance Cs - inf F
Diode resistance – 1e-3ohms
Diode Forward voltage – 0 V
Diode Snubber resistance Rs – inf
Diode Snubber capacitance Cs – inf
Inductance - 3e-3 H
Capacitance - 30e-6 F
Load Resistance – 100 Ohm

e) Battery specifications

Rated capacity – 30 Ah
Nominal voltage – 12 v
Full charged voltage -13.96 v
Soc – 80 %

f) Boost converter specifications for constant load of 5 ohm

Switch Resistance - 1e-3 Ohms
Snubber resistance Rs – 1e5 ohms
Snubber capacitance Cs - inf F
Duty cycle for switch – 50% (kept constant in this case)
Diode resistance – 1e-3ohms
Diode Forward voltage – 0.8 V
Diode Snubber resistance Rs – inf
Diode Snubber capacitance Cs – 0
Inductance – 2.875e-5 H
Capacitance – 0.00011 F
Load Resistance – 5 Ohm