Analysis and Modelling of Battery Energy Storage System for Smoothing Wind Power Fluctuation in the Case of Adama-II Wind Power Plant

Fedlu Hassen Koroso

A Thesis Submitted to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of Master's in Electrical Power and Control Engineering (Power Systems Engineering)

Office of Graduate Studies

Adama Science and Technology University

June, 2022

Adama, Ethiopia

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Declaration

I hereby declare that this Master Thesis entitled “Analysis and Modelling of Battery Energy Storage System for Smoothing Wind Power Fluctuation in the Case of Adama-II Wind Power Plant” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

Fedlu Hassen Koroso___	________________	01/05/2022
Name of the student	Signature	Date

Recommendation

I the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "Analysis and Modelling of Battery Energy Storage System for Smoothing Wind Power Fluctuation in the Case of Adama-II Wind Power Plant" prepared under my guidance by Fedlu Hassen Koroso submitted in partial fulfillment of the requirements for the degree of Masters of Science in Power and Control Engineering (Power Systems Engineering).Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Milkias Berhanu	______________	______________
Advisor	Signature	Date

Approval Page

I the advisor of the thesis entitled "Analysis and Modelling of Battery Energy Storage System for Smoothing Wind Power Fluctuation in the Case of Adama-II Wind Power Plant" and developed by Fedlu Hassen Koroso**,** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Milkias Berhanu	______________	______________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Fedlu Hassen Koroso have read and evaluated the thesis entitled "Analysis and Modelling of Battery Energy Storage System for Smoothing Wind Power Fluctuation in the Case of Adama-II Wind Power Plant" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Power and Control Engineering (Power Systems Engineering).

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Next, to that, I would like to express my sincere gratitude to my advisor Dr. Milkias Berhanu for his guidance and constructive comments, encouragement, and suggestions. I am also thankful to Adama wind II power station staffs for their helping optimistically.

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At last but not least, to start and to complete every activity, it is up on him, since my effort is blessed I am lucky, as a result it becomes tangible now and tomorrow it may be a vital ingredient for further implementation to simplify life, for all thanks God!

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ACRONOMYS

AC	Alternative Current
BESS	Battery Energy Storage System
BMS:	Battery Management System
CAES	Compressed Air Energy
DC	Direct Current
DFIG	Doubly Fed Induction Generator
FESS	Flywheel Energy Storage System
FPID	Fuzzy Proportional Integral Derivative Controller
LIB	Lithium-Ion Batteries
MPPT	Maximum Power Point
PCC	Point of Common Coupling
PHS	Pumped Hydro-System
PMSG	Permanent Magnet Synchronous Generator
SMESS	Superconducting Magnetic Energy Storage System
WECS	Wind Energy Conversion System
WF	Wind Farm
WT	Wind Turbine

ABSTRACT

As a result of increasing proportion of renewable energy, more and more flexible options are necessary in order to flexibly compensate for the fluctuations regarding electricity generation through wind turbines power plants, consequently, a reliable power supply is guaranteed. One of the most prevalent forms of renewable energy is wind energy. It is a developing source of electric power generation because of its sustainability and advantages for the environment. When connected to the grid, the wind's sudden and unpredictable changes in speed make it an unpredictable and inconsistent supply of electricity, leading to various technical issues with protection, power quality, and generating dispatch control. Effective intermittent smoothing methods for wind power output are absolutely necessary to reduce these issues as a result of these issues. Battery energy storage system scheme is adopting to smooth wind power fluctuation and compensate power mismatch between wind power and desired power schedule for dispatching wind power on an hourly basis. In doing so BESS is modeled for Adama wind farm II of capacity 153 MW power. For first cluster of having 11 WT with 16.5MW power the battery capacity of 9.7MWh energy is modeled. Similarly for the left seven other clusters of having 13 WT with 19.5MW power each, the BESS capacity of 11.47 MWh is modeled. To track the power reference and MPPT in pitch angle control FPID Controller is implemented in Simulink.

Keywords: *BESS (Battery energy storage system), DFIG WT, frequency variations, Matlab/Simulink, Smooth wind power fluctuation, voltage variations, Wind farm, Wind speed.*

CHAPTER ONE
INTRODUCTION

1.1. Background

The worldwide of the concern about the environmental pollution and a possible energy crisis, there has been a rapid increase in renewable energy sources in the past decade. Among various renewable sources, wind power is the most rapidly growing one. Wind power has become one of the fastest growing renewable energy sources around the world. It is the use of air flow through wind turbines to mechanically power generators for electricity. Wind power, as an alternative to burning fossil fuels, is plentiful, renewable, widely distributed, free, clean, produces no greenhouse gas emissions during operation, consumes no water, inexhaustible energy source and uses little land. The net effects on the environment are better than those of other nonrenewable power sources. However, the intermittent nature of wind is the biggest problem associated with wind power. As the installed capacity of wind increases, the problems associated with wind power become magnified. Thus it need to ensure stability of the wind power system (R. Billinton et al., 2018), (R. Saidur et al., 2016).

Energy Storage systems are regarded as possible solutions to these problems. From different of energy storage systems, BESS can be used to store electricity at time so for high wind and can be discharged in low wind speed, so the electricity is provided when it is needed. BESS may also increase the penetration levels attainable by wind energy into generation systems and reduce the amount of alternative generation required as the stored electricity will be reliable and predictable (C. Eisenhut et al., 2017).

This thesis addresses the issues on a control strategy for a wind farm, which is made up exclusively of the DFIG (doubly fed induction generators), mainly contribute to propose a control strategy of BESS to smooth output power of Adama II 153MW wind power plant. The proposed control strategy is as follows: Firstly, produce the wind speed and obtain the maximum available wind power by analyzing the characteristic curve of the wind power. Next, configure the capacity of battery energy storage system according to wind speed probability distribution and wind speed-power characteristic curve of wind turbine. Finally, Matlab/Simulink simulation is demonstrated to visualize the feasibility of the proposed methodology.

1.2. Brief background of Adama II wind farm

Adama II Wind Farm, located in Oromia region 95KM southwest to the Capital Addis Ababa and in the name of the second biggest city Adama in Ethiopia, is the largest wind farm in Ethiopia and the second in Africa. The wind turbines for Adama II are from a Sunny Electric Co., Ltd. These wind turbines are the DFIG wind turbine with unit capacity of 1.5 MW and total installed capacity of 153 MW and will be able to supply 480GWH/year satisfying about 20% electricity demand of the capital Addis Ababa. There are 102 sets of Sany SE7715 DFIG wind turbines that are installed on the project with total installed capacity of 153 MW. Moreover, installation, equipment commissioning and power grid connection were all provided by Sany Heavy Machinery. The Adama II wind energy made further progress recently with it having awarded Chinese wind turbine maker Sany a contract to supply a hundred-and-two 1.5MW wind turbines in a contract worth US$95 mill.

1.2.1 Introduction of generator

YSK15-04A generator is High-speed double-fed generator horizontal mounting, forced air-to-air cooling structure, its profile is shown as Figure1.1.

Figure 1.1. Wind Power Generator (Sany Electric Co.Ltd, 2013)

The design and manufacture of generator accord with national standard GB755-2000 and international standard IEC60034-2004.
YSK15-04A generator is for wind power. It can be operational well under -40° C.

1.2.1.1 Generator power curve

YSK15-04A generator power curve reflect the power of generator which is under the different rotational speed.

YSK15-04A generator's power curve is shown as Figure 1.2: when the rotational speed reach cut-in speed, the generator begin to generate power; with the increasing of speed, the output power also gradually increase; when the speed reach the rated speed, the output power reach nominal rated 1560KW.

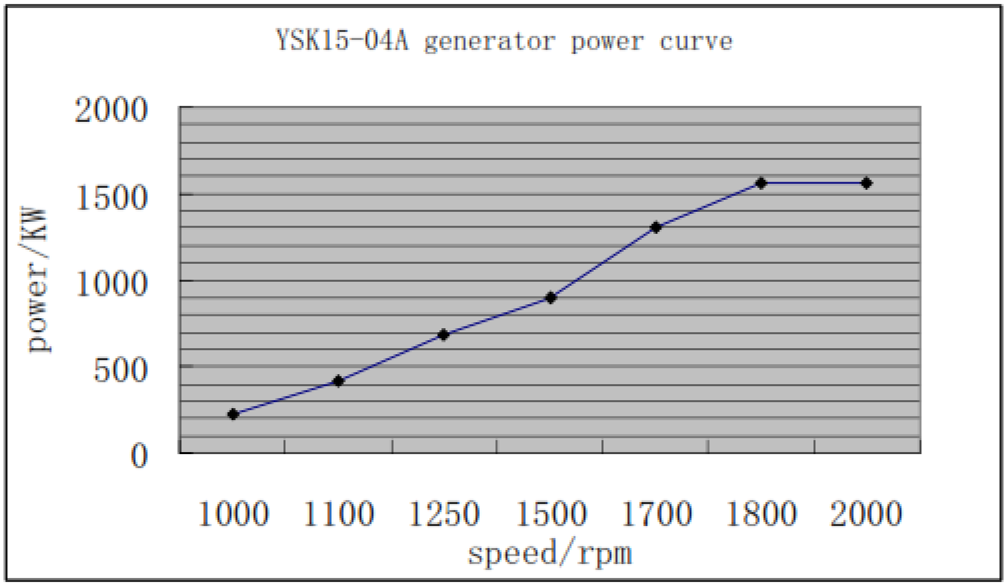


Figure 1.2. YSK15-04A generator power curve (Sany Electric Co.Ltd, 2013)

1.2.1.2 Operational principle

YSK15-04A generator is a doubly-fed induction excitation AC generator; the three-phase windings of stator and rotor connect with two separate three-phase power supply respectively: stator windings directly connect with the grid, the rotor windings connect with grid by convertor which can adjust frequency, amplitude, and phase with the different requirement.

Generator output power consists of two parts, which are directly from the stator output power and the output power from the rotor by convertor. Rotor of doubly-fed generator connects with the grid with two-way convertor, realize two-way flow of power. With the change of speed, the generator achieves output of constant frequency by adjusting frequency of supplied voltage and phase of the rotor.

The principle chart of generator is shown as Figure 1.3:

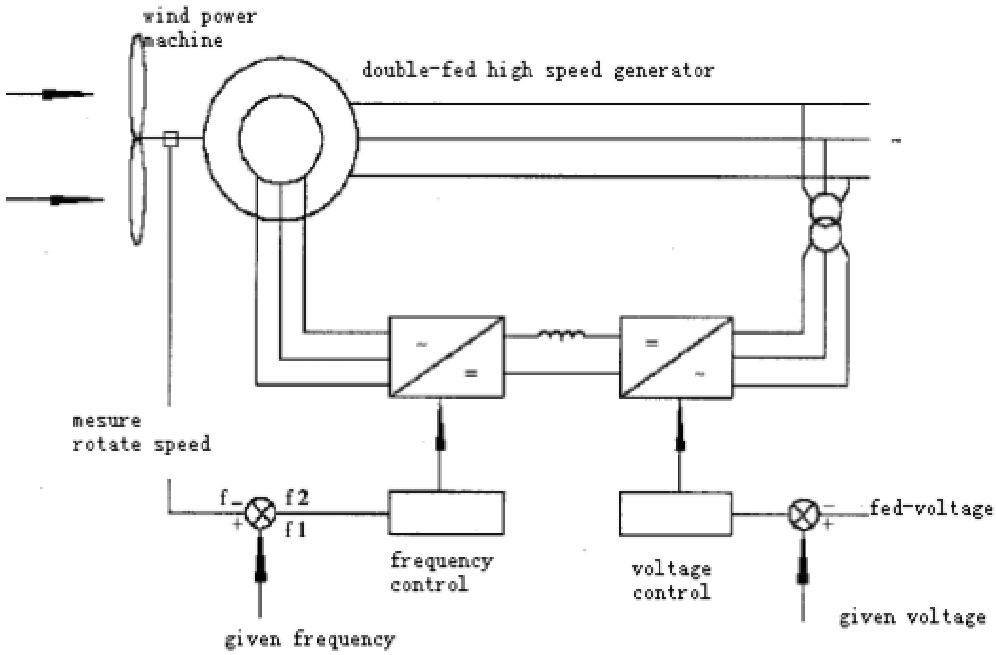


Figure 1.3. Generator principle (Sany Electric Co.Ltd, 2013)

1.3. Statement of the Problem

The national power grid in Ethiopia is heavily reliant on hydropower generation. Wind power generating is Ethiopia's second-largest source of electricity generation, behind hydropower generation. Due to its variable speed operation, in which active and reactive powers are managed individually, the wind turbine in a grid-connected wind farm uses double feed induction generators. Power quality difficulties arise as a result of the integration of wind-based energy sources into the utility grid. Voltage Fluctuation, Reverse Power Flow Due to Voltage Rise, Voltage Flicker, Power Fluctuations in Grid, and Grid Frequency Influence are among the difficulties. During grid outages, it is generally recommended that wind turbines continue to provide energy without being disconnected. However, because DFIG is susceptible to grid disturbances, it may be disconnected from the grid. As a result, the incorporation of a battery energy storage system compensates the power continuity by smoothing the wind power as per the load requirement during grid interruption and wind power rejection. The goal of this study is to model, analyze, and construct a BESS for the Adama wind farm II.

1.4. Significance of the Study

Due to renewable resource, easily available and non-air pollution energy from wind is preferable in the world as well as in our country. As a result of increase of wind power contribution to grid is increase from time to time it needs formulating the different mechanism to mitigate fluctuation of system power caused by wind power. From different energy storage mechanism battery energy storage system if most likely preferable solution for Adama II wind power plant to overcome problem relate with the system fluctuation as well as it is has great advantages for Ethiopia power grid as this wind power of energy source highly expanding.

1.5. OBJECTIVES

1.5.1. General Objective

The general objective of this thesis is to study the application of battery energy storage system in wind power.

1.5.2. Specific Objectives

The specific objectives of this thesis work are to:

- ✓ To analysis and model of BESS for Wind Power fluctuation Smooth
- ✓ To determine capacity, Control and Operational Strategy of the BESS for Adama II Wind power
- ✓ Develop MATLAB Model and simulate it under different conditions
- ✓ Economic analysis for BESS

1.6. Scope of the Study

A major advantage provided by battery energy storage is flexibility in addressing the full range of active and reactive power needs. As the source of energy from wind power is increasing eventually in our country Ethiopia the effect on the grid voltage and power fluctuation become significant so to improve such problem there is need of wind power fluctuation smoothing methods by using energy storage system. Battery energy storage system is the best solution and choice of different energy storage system to smooth fluctuation of wind power occur at Adama II wind power plant. The thesis is limited to simulation of the system using MATLAB Simulink by showing how the different components of the system interact with each other.

This is due to the fact that implementation of the real system is difficult because of the components are not easily available in our country and along with it the additional time and cost incurred in making the actual implementation.

1.7. Thesis Layout

The thesis is organized into five chapters which are briefly summarized below. Chapter one**,** presents the introduction, background, objectives, problem statements, scope, the significance of the study and methodology followed in the thesis work. Additionally, it offers the thesis's outline. Chapter two discusses the theoretical background of different types of wind power energy conversion system, and different types of electrical energy storage technologies including BESS, and a review of the literature on wind power conversion system using DFIG and the modeling and integration of BESS in smoothing wind power. In chapter three of the thesis, the collected data's of about the specifications of each component and other requirement of Adama wind II has been analyzed to model BESS and the proposed system at whole; wind turbine, DFIG, pitch angle controller using FPID and the required BESS capacity is modeled to be integrated at the PCC with wind farm. Chapter four presents the result and discussions of the thesis. Finally, the conclusions, recommendations, and future work for researches are discussed in chapter five.

CHAPTER TWO
THEORETICAL BACKGROUND AND LITERATURE REVIEW

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.

2.1. Wind turbine

Wind turbines are used to change wind power into electricity. Charles Brush invented and built the world's first fully automated wind turbine in 1888. It had 144 cedar blades, each with a spinning diameter of 17 meters. This turbine produced a peak output of roughly 12 kW, which was used to charge the batteries and supply DC current to lamps and electric motors (C. Eisenhut et al., 2017), (O. Tremblay et al., 2009).

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. Some detail 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 (O. Tremblay et al., 2009).

Figure 2.1. Horizontal axis wind turbine (Gelma B, 2012)

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

Figure 2.2. Vertical axis wind turbine (Gelma B, 2012)

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 (H. S. Chen et al., 2009).

2.2 Components of a wind turbine converter system.

The components of a wind turbine converter system are shown below.

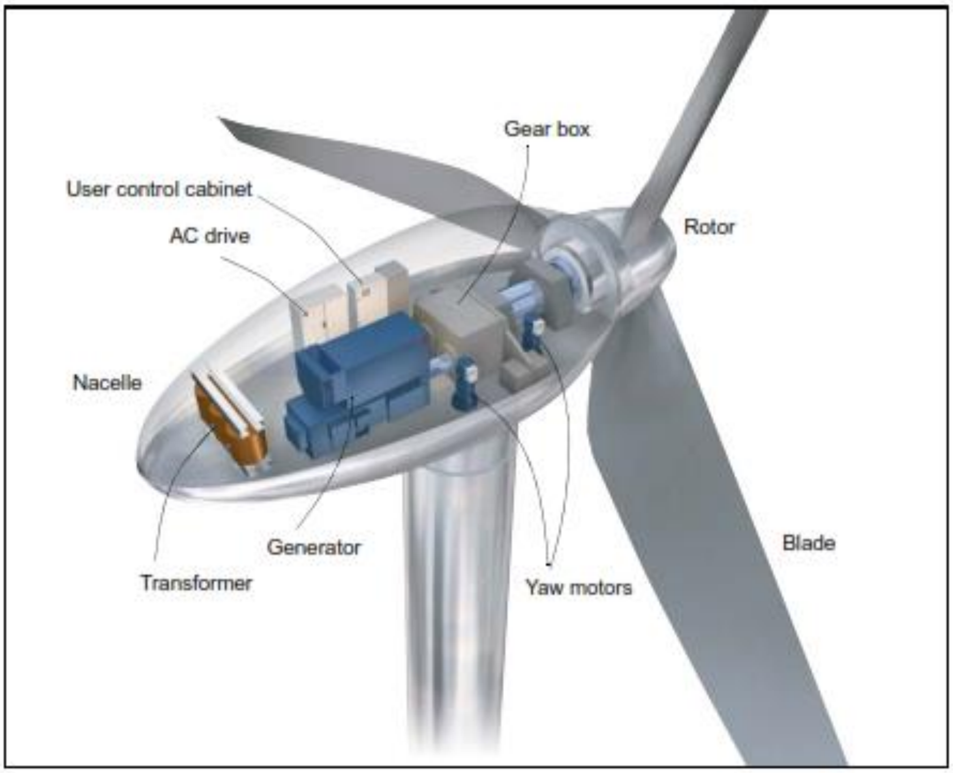


Figure 2.3. Components of wind turbine (ACS800-67LC, 2012)

2.2.1. AC converter for wind turbine applications

The generator rotor and the supply network are connected by the converter. The rotor's speed is proportional to the wind speed. The angle of the rotor blades is adjusted via a pitch drive to keep the speed ideal (i.e. slightly higher than the generator's synchronous speed). Adjusting the pitch, on the other hand, is a slow process.

In order to compensate for faster changes in rotor speed, the AC converter rapidly accelerates or decelerates the rotation speed of the field in the rotor. When the wind speed drops, the converter draws energy from the supply and speeds the rotor field's rotation, allowing the stator to continue feeding electricity to the grid. Similarly, as the wind speed increases, the rotor field rotates slower.

The energy generated above the synchronous speed of the rotor can also be sent into the grid. Before the actual grid connection, the converter is also used to synchronize the stator output with the grid. When the converter is disconnected, the torque is reset to zero. This also reduces the stator current to zero, allowing the generator to be turned off.

In normal functioning, the rotor rotates within a specified speed range due to the wind. The operable speed range is typically 30% around the synchronous speed (Ns), which is defined by the following equation (in rpm).

In normal operation, the rotor is rotating due to the wind within a certain speed range. Typical value for the operational speed range is ±30% around the synchronous speed (N_s), which (in rpm) is given by the following equation.

$$N_s = \frac{120 * f_n}{p} \tag{2.1}$$

Where

P = number of generator poles

f = nominal frequency of the grid

If the mechanical speed of the rotor is lower than the synchronous speed, the torque controlled rotor-side converter supplies power to the rotor windings. If the mechanical speed of the rotor is higher than the synchronous speed, the rotor windings supply power to the rotor-side converter. Therefore, it is necessary to have a grid-side converter between the grid and the DC link of the converter. The grid-side converter is capable of handling the bidirectional power flow between the grid and the rotor-side converter.

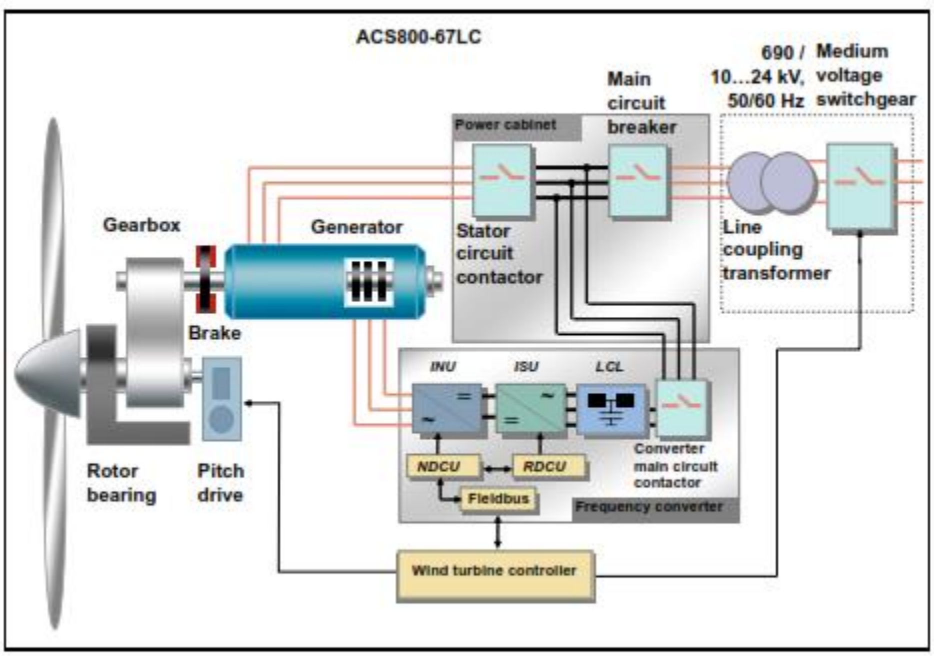


Figure 2.4. A block diagram of the converter system (ACS800-67LC, 2012)

The grid-side converter is controlled with the grid-side control program. The rotor-side converter is controlled with the doubly-fed induction generator control program.

2.2.2. Control of Generator Power

The generator power can be controlled by adjusting torque or speed:

$$P = T \cdot \omega = T \cdot \frac{2\pi \cdot n}{60} \tag{2.2}$$

Where

P = generator power (W)

T = generator torque (N·m)

ω = angular speed of the generator

N = generator speed (rpm)

The converter regulates the generator torque in normal operation. The converter receives a torque reference from the overriding turbine controller, which generates a particular torque on the generator shaft. Wind turns the turbine at the same time as it generates a counter-torque on the generator shaft. The converter's rotation speed is determined by the wind power. The needed torque reference is determined by the overriding turbine controller based on wind speed and turbine characteristics. Below is an example of a power-speed-curve. It depicts the turbine's operational speed range between the cut-in and cut-out speeds. The minimum wind speed at which power generation is feasible is known as the cut-in speed. The maximum operational speed is known as the cut-out speed.

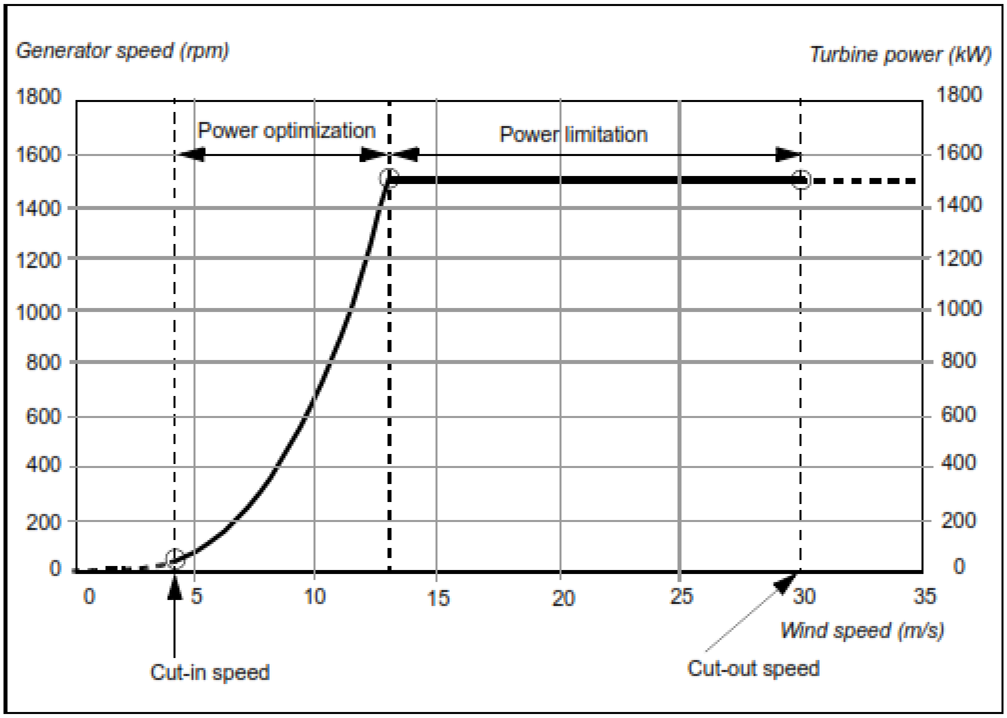


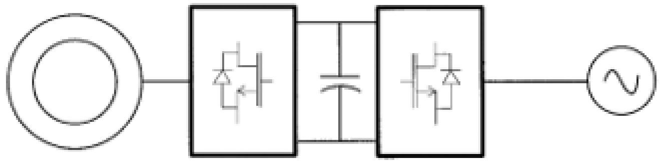
Figure 2.5. Generator Power Control Scheme (ACS800-67LC, 2012)

For example, to run the rotor to a specific position for maintenance, a speed reference is required. This control mechanism is ineffective for generating continuous electricity. By providing an internal torque reference that matches the intended shaft speed, the converter speed control achieves the desired speed.

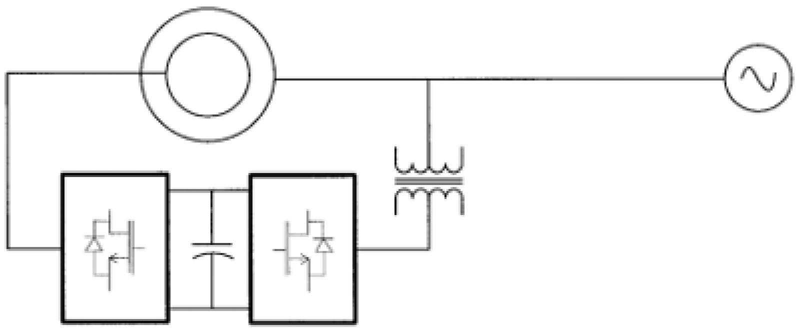
2.3 Wind Turbine Technologies

Figure 2.5 depicts the many types of wind turbines. Variable speed generators are more widely utilized in wind generators than traditional generators, as optimum power capture is obtained at varying rotor speeds for different wind speeds. Furthermore, variable speed operation reduces mechanical loads on the blades caused by wind gusts. As a result, synchronous generators are rarely employed when directly connected since they require a mechanical means of speed regulation and lack the benefits of variable speed wind generators. Synchronous generators are sometimes used, and when the generator is connected to the system via a back-to-back voltage source converter (VSC), variable speed operation is conceivable. The most frequent option is permanent magnet synchronous machines (PMSM), which are typically used in stand-alone systems. PMSMs are popular because they don't require field winding control and don't require a gearbox, making them low-maintenance and appropriate for usage in distant places.

a) Directly coupled Synchronous of Asynchronous Machine



b) Back-to-back VSC connected generator



c) DFIG

Figure 2.6. Different wind generator topologies (Chad Abbey, 2004)

The back-to-back VSC topology has the advantage of allowing the generator side converter to manage the generator speed while the line side converter can adjust the reactive power delivered to the system. At the PCC, the wind generating system so simulates a synchronous machine, with the exception that the output power is not fully adjustable. Because the wind generator does not need to be synced with the system when it is directly coupled, it is usually a squirrel cage induction machine. However, because generators use VARs in all modes of operation and hence affect the voltage at the PCC, especially during transients, the addition of reactive power sources is frequently required.

2.3.1. Doubly-Fed Induction Generator

For wind power applications, the DFIG is now the most prevalent machine structure. DFIGs make up the majority of big capacity machines (>1 MW) offered from companies like Vestas and General Electric-Wind (although some producers such as Entercon are favoring PMSM). The power electronic converters allow control of generator operational properties like speed and reactive power, which are unavailable or constrained in squirrel cage induction machines. This enables variable-speed operation for tracking peak power points or regulating output power. In addition, when compared to a stator-connected converter system, the converter rating is much lower.

Table 2.1. Comparison of wind generator design characteristics and costs

WECS	*Converter*	*VAR control*	*Speed control*	*Overall Cost*
Directly Connected	None	None	None/limited control using pitch angle	Inexpensive
DFIG	30-50% machine rating	Two reactive power sources	Pitch control and converter control	Low converter cost, machine expensive
VSC Connected	Full machine rating	Reactive power control	Pitch control and converter control	Machine inexpensive, converter cost high

2.3.2. Wind Farm Layout

Several wind turbines make up the wind farm. Figure 2.7 depicts the network's layout. The wind farm management system functions as a single centralized unit (M. R. Aghaebrahimi and V. A. Shandiz, 2012). It takes the system operator's input demand and measures the PCC's output (point of common coupling). The system's performance varies depending on the current state of the network.

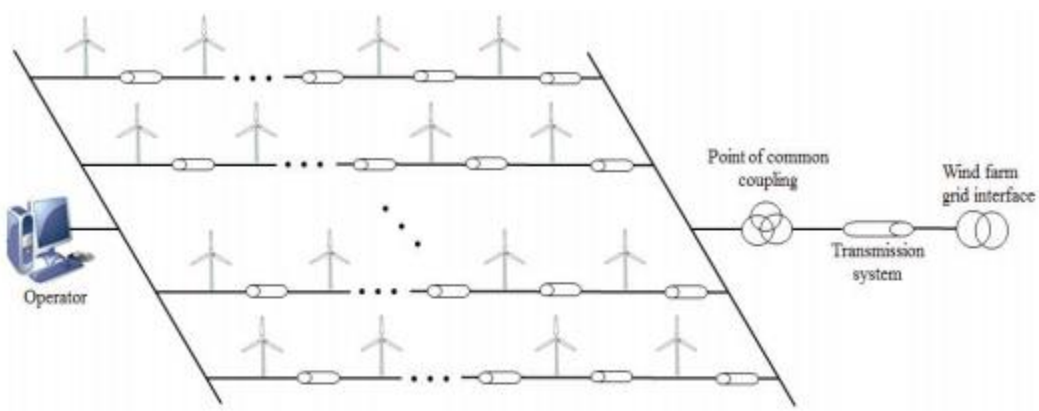


Figure 2.7. The network layout of the wind farm (Zhang Wei* et al., 2014)

2.3.3 Wind Power Challenges

The complex and highly linked processes that span numerous physical and temporal scales relevant to wind energy and the larger power system are what create the research challenges that are essential to reaching the full potential of wind energy. It is crucial to consider everything from global weather phenomena to regional weather activity to complex local flows and, ultimately, to the responses of the turbines within the power plant in order to maximize value at the lowest possible cost while maintaining the reliability and resiliency of the power system. The wind resource also operates differently offshore, across plains, and over mountains, and this behavior changes substantially depending on the region. A fleet of wind energy facilities must also be synchronized with the needs of power system operators and, eventually, of consumers at time scales ranging from a fraction of a second to a decade. Although the European Academy of Wind Energy had a detailed agenda for the research challenges in wind energy for 2016 (G. van Kuik and J. Peinke, Eds., 2016), the pace of future technological development and the difficulty of relying on wind energy for at least one-third of the world's electricity demand required a closer look at research requirements. Through this additional effort, the wind energy research community's focus was intended to be narrowed. It also aimed to identify crucial abilities and skills from the larger scientific and research community that will be required to support the very high levels of wind energy use. In order to address this need, a group of international wind power experts met in a series of meetings that started in October 2017 to explore and articulate innovation pathways and related research challenges that, if addressed, would position wind energy as the world's primary supplier of electricity at levels of one-third to one-half or even more (K. Dykes et al., 2019). The three big challenges that resulted from the synthesis of these issues span a wide range of scientific fields and demand an extensive and integrated research program.

1. Improved understanding of atmospheric and wind power plant flow physics
2. Aerodynamics, structural dynamics, and offshore wind hydrodynamics of enlarged wind turbines
3. Systems science for integration of wind power plants into the future electricity grid

2.4. Wind Energy Conversion system

In general, fixed-speed or variable-speed turbines are used in wind power generating. The fundamental differences between these wind turbine models are the methods in which the rotor's aerodynamic efficiency is limited at various wind speeds.

2.4.1. Fixed Speed Wind Turbine WECS

WECS with a fixed speed run at a constant speed. This means that the wind turbine rotor speed is fixed and determined by the grid frequency, independent of wind speed. Squirrel-cage induction generators are commonly used in fixed-speed WECS (SCIG). When the wind speed exceeds the cut-in speed (3-4 m/s), the fixed speed WECS begins to generate power. The power captured by the turbine is limited by active/passive stall or pitch control of the rotor blades when the wind speed exceeds the authorized wind speed (13 to 15 m/s). The turbine is stopped at a speed greater than the cutout speed (about 25 m/s) by either full stall or full pitch of the blades to protect the turbine and generator from damage (R. C. Kroeze, and R. T. Krein, 2016), (Francisco Díaz-Gonzáleza et al., 2012). Large fixed-speed turbines have a rotational speed of 6 to 15 rpm, whereas an induction generator has a rotational speed of much greater rpm (750 rpm to 1800 rpm). The number of poles and grid frequency define the generator's operating speed (Francisco Díaz-Gonzáleza et al., 2012).

Fixed-speed wind turbines provide the following advantages (Bent Sorensen, 2013):

- Simple electrical system;
- High dependability;
- Moderate cost.

The following are their primary drawbacks:

- The power extracted hasn't been optimized: We don't have the ability to modify the power provided by this sort of wind turbine.
- Induction generator lacks reactive power management. The addition of capacitor banks to a direct connection of an induction generator to the grid reduces the amount of reactive power required by the grid.

2.4.2. Variable-Speed WECS

The most common WECS are variable-speed wind turbines. Because of the power electronic converters' interface, variable speed operation is possible, allowing for full (or partial) grid decoupling. In order to maximize the power produced from the wind, a variable-speed operation will be required. However, due to the stator voltage frequency variations, a direct connection to the grid is not possible in this case. Between the generator and the grid, a power electronic (PE) interface is required. It is made up of two converters (a rectifier and an inverter) that are linked together by a DC voltage bus.

Variable-speed wind turbines have the following advantages (Bent Sorensen, 2013):

- It can supply power at a constant frequency and voltage, even if the rotor speed varies;
- Active and reactive power can be controlled separately;
- It can use a Maximum Power Point Tracking (MPPT) strategy when the wind speed is less than rated, allowing the turbine to absorb the maximum amount of wind energy.

However, this type of turbine has significant drawbacks, such as the generation of changeable frequencies, which necessitates the use of sophisticated power electronics converters.

Table 2.2. Comparisons between Fixed Speed and Variable Speed Wind Turbines.

WECs wind turbine types	Fixed Speed	Variable speed
Advantages	• Low cost • Low maintenance • Simple and Robust construction	• Independent control of active and reactive power • Higher efficiency
Disadvantages	• No control over the active or reactive power • Less efficiency • Less power factor • Higher stress on turbine	• Higher cost of power electronics • Limited fault management Capability

2.5 Energy Storage Systems

Although energy storage is widely employed in low-power applications, effective, low-cost energy storage technologies do not yet exist. In a traditional utility, power is generated at one site in the system and consumed at another, with the transmission network connecting the two points. However, despite their consistently elevated costs, many benefits can be gained through the use of a short-term energy storage device, and energy storage systems (ESS) have been used in a variety of applications

2.5.1. Benefits of ESS

Transportation, flexible ac transmission systems (FACTS), and uninterruptible power supplies are just a few of the possibilities for energy storage (UPS). The key advantages can be described as follows:

(i) Using a power electronic interface, instantaneous exchange of rea1 power with the system.

(ii) Enables both energy storage and supply

(iii) Short-term supply eliminates multiple switching of backup generators

(iv) Integration of ESS with FACTS has been demonstrated to increase transient stability

(v) Smoothing of non-dispatch able energy source output power

The final two principles can be utilized in wind energy applications. The ability to dispatch the wind generator can be improved by integrating energy storage into the wind energy conversion system (WECS). Also the transient stability of the wind park is improved while the associated transmission system benefits from this design choice.

2.6. Energy Storage Technology

There are many different types of energy storage systems, such as BESS, PHS (pumped hydro-system), FESS (flywheel energy storage system), SMESS (superconducting magnetic energy storage system), CAES (compressed air energy storage), and so on (M. Stanley Whittingham, 2012), (M.Jabir and Safdar Raza, 2017). PHS necessitates a large-scale installation that will have a significant negative influence on the environment. In terms of pumped hydro, CAES and FESS are smaller, but not in terms of batteries.

2.6.1. Compressed Air Energy Storage System

CAES is an energy storage technology that is both efficient and low-emitting. This method works by compressing air and storing it in a suitable tank during off-peak hours. The charging process is the name given to this period. When users want power during peak hours, compressed air is injected into a gas turbine's combustor and mixed with the fuel. As a result, a gas turbine is used to create electricity. The discharge interval is the name given to this period. This arrangement resembles a gas turbine power plant more closely. It's worth noting that the fuel usage in this example is less than 40% of what a traditional gas turbine power plant would use to create the same quantity of electrical energy.

Natural underground holes, caverns, and dummy cavities are examples of storage tanks that can be employed in the CAES system (Abdorreza Rabiee et al., 2013). Water tanks and depleted gas fields are often more cost-effective for storing compressed air in big quantities. This system has a low energy loss and can store energy for a long time. The requirement to store compressed air in a bulk tank is the system's primary disadvantage. Typically, it is not cost-effective to construct a new huge reservoir for energy storage. The concept for compressed air energy storage is shown in Figure 2.8.

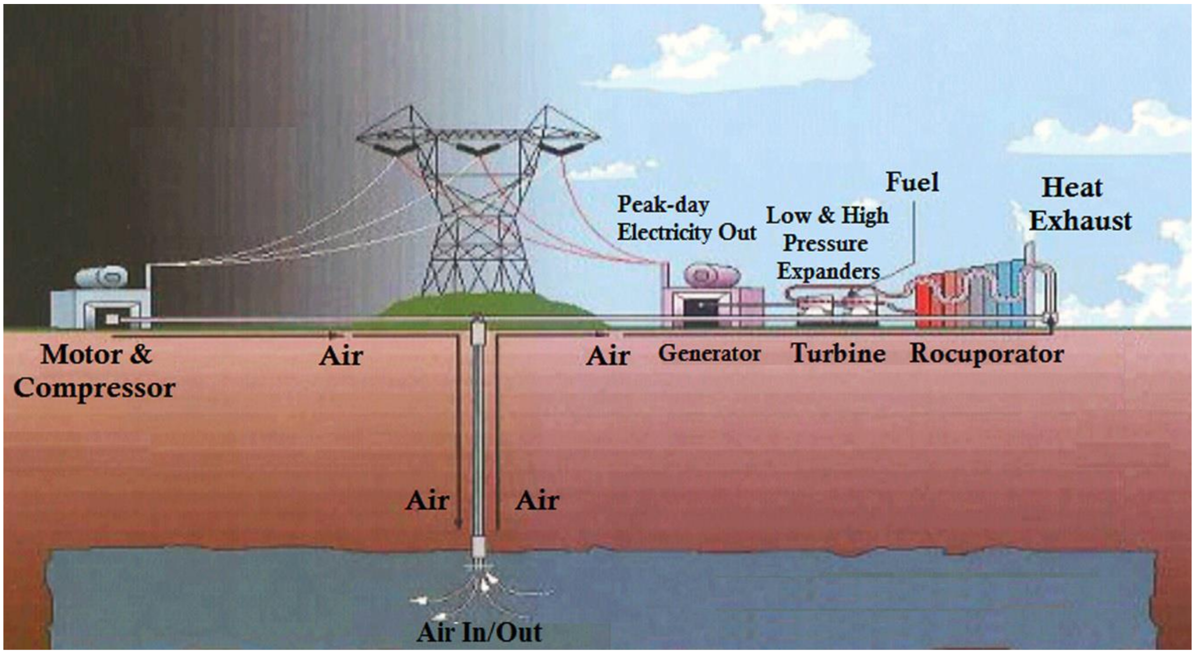


Figure 2.8. The process of energy storage using a compressed air system (Abdorreza Rabiee et al., 2013)

2.6.2. Superconducting Magnetic Energy Storage

The only storage devices now in use that can store electrical energy without converting it to another form of energy are the super magnetic energy storage (SMES) system and the capacitor. The SMES system offers a high power density in contrast to other storage systems and a very quick response time—a few milliseconds at most. With the ability to adjust reactive and actual power separately using distributed SMES (DSMES), it also has a longer cycling time and life expectancy (Zimmermann et al., 2017). However, the SMES system is not without its inherent disadvantages. Low volumetric and gravimetric energy density, material fatigue due to introduction of mechanical stress, and high cost factors are the main limitations of the SMES system. Nevertheless, due to the high efficiency and very low response time, the SMES system has high potentiality in its load levelling, intermittency reduction, and peak shaving applications.

The SMES system stores electrical energy in a magnetic field without requiring to convert it into chemical or mechanical form (Kalaiselvam, and S.Parameshwaran, 2014). In this system, direct current (DC) is induced into superconducting coils, which exhibit zero resistance to the current flow (Zimmermann et al., 2017). These niobium-titane (NbTi) filament-based superconducting coils need to be kept below the critical temperature of 2700°C (Zimmermann et al., 2017), (Kalaiselvam, and S.Parameshwaran, 2014), which is accomplished by integrating a cryogenic system with the SMES. In order to keep the cryogen's temperature below the critical level, a refrigeration system must use a large amount of energy, which lowers the system's overall efficiency. A refrigeration system maintains the temperature of the cryogen below the critical temperature, which requires consuming a prolific amount of energy, therefore, reducing the overall efficiency of the system. However, as the superconducting coil has no resistance, it does not have any ohmic loss, which results in SMES having an overall efficiency of over 95% (Zimmermann et al., 2017).

2.6.3. Flywheel Energy Storage System

Flywheels can be used to store the wind energy in the form of kinetic energy that depends on the form, mass and rotational speed (M.Jabir and Safdar Raza, 2017). In charging mode, rotational motion is increased to store the energy as kinetic energy while in discharging mode, it discharges its kinetic energy. A Flywheel Energy Storage System comprises of a machine, bearing and Power Electronic Interface as shown in Figure 2.9

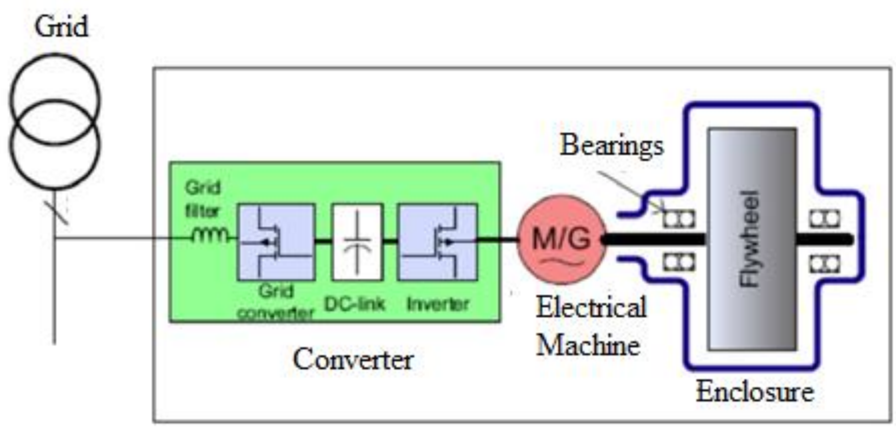


Figure 2.9. Flywheel Energy Storage System (Abdorreza Rabiee et al., 2013)

2.6.4. Battery Energy Storage System

All of the electrochemical storage systems available on the market, batteries are the most popular. Batteries are highly efficient, may be containerized, and are simple to install in both distributed and centralized applications. BESS technology is also quite advanced. As a result, the operating expenses and life cycle have significantly improved. As a result, for a wind farm, pick BESS to smooth out fluctuating wind energy. Experimental model, electrochemical model, and comparable circuit model are the three types of battery models. The comparable circuit model (M.Jabir and Safdar Raza, 2017), (Abdorreza Rabiee et al., 2013) is the most suitable for dynamic simulation among them.

Their applications cover a wide area from power applications to hybrid electric vehicles. They are mostly found in multiple cells connected in series or stacks to get the desired voltage. Each cell is composed of an electrolyte together with positive and negative electrodes. Electrochemical conversions occur at the electrodes and hence, the chemistry of electrodes determines the nature of the reaction and thereby the nature of energy generated. The movement of ions inside the electrolyte causes electrons to move in the external circuit thus providing electrical energy (Hamdi Abdi* et al., 2017).

Battery Characteristics: A battery bank is an electrochemical device that stores electricity in the form of potential chemical energy through electrochemical reactions. It is described by the following parameters:

Battery Capacity: This is a measurement of the battery's ability to store energy. Temperature, rate of discharge, battery age, and battery type all influence how much energy can be retrieved from a fully charged battery (Lai, J et al., 2017).

Ampere-hour (Ah): The maximum current that a battery may discharge at a consistent rate during a set time interval.

Reserve capacity: The amount of time (in minutes) that a battery can discharge to a specific level.

KWh capacity: The amount of energy needed to fully charge a discharged battery. A totally exhausted battery is not always a depleted battery.

Battery Voltage: The battery voltage is the same as when it is completely charged. The number of cells and the voltage per cell are factors. When a battery begins to discharge, the voltage of the battery drops.

Cycle depth: Fully draining batteries can speed up the deterioration of the battery's life or completely eliminate it. Deep cycle batteries have the ability to discharge between 15% and 20% of their capacity. This results in a discharge depth of 85 percent to 80 percent (Hamdi Abdi* et al., 2017).

Energy density: The energy density of a battery is a measurement of how much energy can be retrieved per unit of weight or volume. Deep-cycle batteries, by default, have a higher energy density than non-deep-cycle batteries because more of the energy stored in the battery can be recovered.

Power density: The power density of a battery is a measurement of how much power can be extracted per unit of weight or volume.

Durability (cycling capacity): An energy storage device is designed to release the stored energy after each recharge at a predetermined time interval. Durability or cycling capacity refers to the number of times an energy storage device can discharge the energy level it was designed for after each recharge. It is measured in cycles, and the cycling capacity is mostly determined by the depth of discharge. There are various varieties of batteries, but the following are the most often used rechargeable batteries (Hamdi Abdi* et al., 2017), (Lai, J et al., 2017).

i) Lead-Acid: Lead acid batteries invented in 1859 have been the most mature and commonly used batteries. They have a positive electrode made of lead dioxide (PbO_2) and a negative sponge lead (Pb) electrode immersed in an acidic electrolyte mostly diluted sulfuric acid (H_2SO_4). When the battery is charging these electrodes are converted to lead sulphate ($PbSO_4$) and while discharging they are restored back to their initial state. More recently valve-regulated batteries are also being researched on where the electrolyte is immobilized within an absorbent material called separator

(Daniel Akinyele et al., 2017). The redox reactions deteriorate the battery electrodes and reduce the efficiency of the battery. The performance and lifetime of a battery depend on its operating temperatures. Also known as the ultra-battery, it's used in both vehicle and grid power. Further improvements will need significant development in the materials used within (Anju PK and Zarina PP, 2018).

Adv: Easy to install, high η, low investment cost. Due to their low self-discharge they are capable of storing energy for longer duration of times (Cao M et al., 2019).

Disadv: poor performance at low and ambient temperatures needing a temperature management system, short life time, periodic maintenance, low specific power, difficulties in frequent power cycling and partial discharging leads to premature failure. Environmentally unfriendly and transportation hazards exist.

ii) Nickel-based batteries: Ni-Cd batteries invented in 1860's have seen rapid development after the 1950's. The positive electrodes are made from the nickel species and the negative electrodes from cadmium electrolyte solution. Ni (OH)2 is the active material of the positive electrode in Ni Cd cells while they are discharging, and Cd(OH)2 is the active material of the negative electrode. But during the charge cycle, NiOOH is the active material of the positive electrode, and metallic Cd the active material of the negative electrode (Cao M et al., 2019). Other nickel-based cells with negative electrodes made of metal alloys (as in Ni-MH) and zinc hydroxides (as in NiZn) have also been developed.

Adv: Low internal resistance with faster discharge cycles (can be completely discharged within 2h). Longer life cycle and low maintenance requirements. Good low temperature performance. Available in a wide range of sizes and performance options, economically priced – the NiCd is the lowest cost battery in terms of cost per cycle. They also find usage in long term storage integrated with renewable energy sources.

Disadv: Costs at more than 10 times of Lead-Acid while the energy η is lower and self-discharge rate much higher than lead-acid batteries. Ni–Cd batteries are highly toxic and suffer from the memory effect where in the battery doesn't take full charge after series of full discharges (Cao M et al., 2019). Ni and Cd can cause a health risk in humans.

iii) Sodium-Sulphur Batteries: These are more recent compared to lead acid and alkaline batteries but have evolved as a promising technology for high-power storages due to their significant characteristics. The anodes are made of sodium (Na) and cathodes are of Sulphur(S). The Ceramic Beta Al2O3 can be used as an electrolyte and also as a separator Electrons are liberated during the process at anode which circulate through the external circuit. During the discharge process, the opposite reaction occurs as NaSx is decomposed to form sodium and Sulphur. The electrolyte is usually solid, however this limits the mobility of ions, lowering the battery's efficiency. They are packed in a tall cylindrical structure contained by a fixed metallic cover Conventional batteries are operated at 350ºC to maintain electrodes and electrolytes in molten liquid state for reactions to occur. As these reactions are again exothermic it reduces the efficiency further and also aggravates safety concerns. As they possess excellent high energy density, power density and energy efficiencies they are able to deliver multiple times their rated power (Y. Trawler et al., 2013).

Adv: high life cycle, good power density, high energy capacity, high energy efficiency, insensitive to ambient conditions.

Disadv: Thermal management; safety; seal and freeze–thaw durability.

iv) Lithium Metal Batteries: Primary or disposable batteries classified as lithium metal use metallic lithium as the anode. The lithium metal batteries were invented by M. Stanley Whittingham, a chemist at Exxon in the 1970s. Li is a highly reactive metal that easily releases an electron to produce a Li ion, making it an excellent material for an anode. Titanium disulfide was employed as the cathode in the original concept. Since this design led to explosions at the time, it was a difficult notion to put into practice. The researchers then chose the intercalation design, which involves sandwiching layers of an alternative substance between layers of the host material, in this case lithium. Lithium's reactivity could be decreased by intercalating graphite into it. Followed by research from several researchers, the developments to the lithium metal battery gradually gave birth to the Nobel-prize-winning discovery of the lithium ion batteries (The Nobel Prize in Chemistry, 2019), which is described in the next section. Whittingham had the original Li anode TiS_2 cathode 2.5 V battery patented (Pioneers of Innovation, 2020), (Reddy et al., 2020), but it required the combined efforts of John B. Goodenough, Whittingham, and Akira Yoshino to create the lithium-ion battery that we are familiar with today.

Since lithium is one of the lightest metals, Li metal batteries are extremely lightweight. They have a lot of charge density as well. They have an output voltage range of 1.5 to 3.7 V. Consumer electronics and electric cars could both benefit from the use of lithium metal batteries. They might be solid competitors for many popular battery types used today. The popularity of Li ion batteries overtook lithium metal batteries. But now, some 50 years later, they may make a comeback because Li metal batteries may have a chance to displace Li ion batteries (P. 02 J., 2020), (Grossman, D., 2016) according to researchers. Due to their propensity for explosion and dendrite growth, Li metal batteries had two main drawbacks. Small spike-like protrusions known as dendrites are formed at the anode of Li metal batteries. These can cause a short circuit inside the battery by rupturing the separator separating the anode from the cathode. By creating novel cathode materials and architectures, intercalation designs, and anode surface coatings, researchers are attempting to alleviate these problems. References (MIT News, 2020), (Li, S et al., 2018), (Hwang,

J. et al., 2019), (Tang, W et al., 2018), (Yang, Q, 2018), (Chen, L et al., 2019) provide some noteworthy developments in the revived study of Li metal batteries. Li metal batteries may eventually be produced on a large scale and outperform other current battery technologies.

v) Lithium Ion Batteries: Due to its extended lifespan, high working voltage, lower self-discharge rate, etc., Lion batteries have become immensely popular in recent years (Mu, D et al., 2013). The commercial Li-ion batteries were first introduced in 1990 (Koohi-Kamali, 2013). This battery possesses higher charge density than the other rechargeable batteries and in terms of battery capacity, it also has a lighter weight. Therefore, the Li-ion battery has a higher power capacity without being too bulky. Furthermore, this battery has a low self-discharge rate, which is about 1.5% per month. In addition, repeatedly charging the Li-ion batteries after being partially discharged does not have a negative impact on the maximum capacity of the batteries, therefore the aforementioned battery has a negligible memory effect. Li-ion battery has a chemistry that results in higher open-circuit voltage than other aqueous batteries such as lead acid, nickel-metal hydride, and nickel-cadmium. Li-ion battery can typically handle hundreds of charge–discharge cycles. Some lithium ion batteries lose 30% of their capacity after 1000 cycles while more advanced lithium ion batteries still have better capacity only after 5000 cycles (Chung, S.-Y et al., 2002).

The Li-ion battery is made up of two current collectors, an electrolyte, a separator, a positive electrode (anode), and a negative electrode (cathode) (Okou, R et al., 2011). The cathode is made of graphitic carbon with a layering structure, whereas the anode is made of lithiated metal oxide (LiCoO2, LiMO2, LiNiO2, etc.). Lithium salt (LiPF6), which is dissolved in organic carbonates, makes up the electrolyte (Chen, H. et al., 2009). Due to the slight change in electrolyte concentration during the discharging phase, lithium atoms in the anode ionize and disperse. These ions are transported by the electrolyte to the cathode, where they combine with an outside electron to form lithium atoms that are then deposited. As the lithium ions move, the anode produces free electrons that travel via the external circuit and into the cathode, where they rejoin the lithium ions. The separator prevents anode to cathode direct electron flow. During the charging phase, the opposite reaction occurs. Figure 2.10 depicts the basic operation of Li-ion batteries. The following are the chemical processes that occur in lithium-ion batteries (May, G.J, 2018).

At anode: $Li_{1-x}CoO_2 + xL^+ + xe^- \leftrightarrow LiCoO_2$

At cathode: $Li_xC_6 \leftrightarrow xLi^+ + xe^- + C_6$

Overall chemical reaction: $LiC_6 + CoO_2 \leftrightarrow C_6 + LiCoO_2$

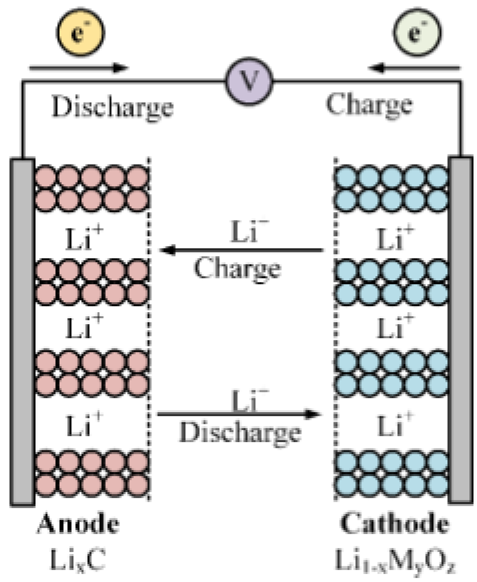


Figure 2.10. Charge and discharge cycles of a typical Li-ion battery; the anode consists of lithiated metal oxide and the cathode consists of graphitic carbon with a layering structure (Barnes, F.S, 2011)

Figure 2.11 illustrates the comparable circuit model for lithium-ion batteries according to (Mu, D et al., 2013). Temperature and SOC have an impact on the parameters R, R, and C. SOC and temperature are regarded as time invariant over a short period of time, or quasi-stationary, due to the fact that the change in SOC and temperature with respect to time is relatively tiny. The voltage equations of Li-ion battery can be expressed by Equations (2.3) and (2.4) (Mu, D et al., 2013). Here, $v_b(t)$ and $i_b(t)$ are the terminal voltage and current, respectively, whereas, $v_c(t)$ is the voltage across the Resistor Capacitor (RC) network.

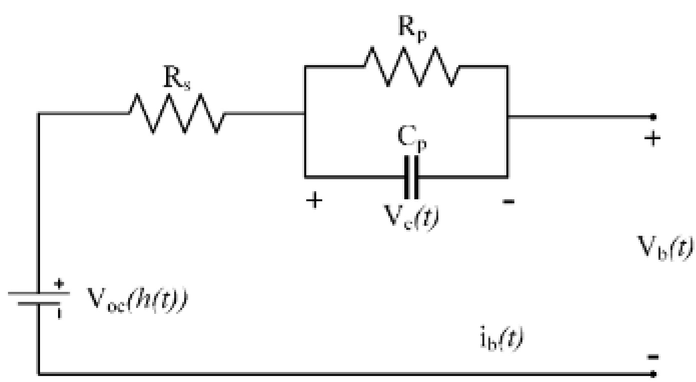


Figure 2.11 Equivalent circuit model of the Li-ion battery, consisting of a resistor in series with an RC parallel branch and a voltage source (Mu, D et al., 2013)

$$v_b(t) = v_{oc}\big(h(t)\big) - R_s i_b(t) - v_c(t) \tag{2.3}$$

$$\frac{dv_c(t)}{dt} = -\frac{1}{C_p R_P} v_c(t) + \frac{1}{C_p} i_b(t) \tag{2.4}$$

vi) Lithium Polymer Batteries: Due to their close resemblance to lithium ion batteries, lithium polymer (LiPo) batteries also fall within this category. However, what sets these cells apart from regular batteries is the sort of electrolyte that is employed in them. The Li-Po batteries were created in 1978 and employed a dry solid polymer electrolyte. Li-Po is much easier to fabricate using the dry polymer electrolyte, but it has low conductivity due to high internal resistance, making it unsuitable for high current applications (Battery University, 2020). Modern Li-Po batteries incorporate gelled electrolyte in addition to dry polymer electrolyte to address the aforementioned issues with low conductivity and make them suitable for high current and rapid discharge applications. Compared to conventional batteries, Li-Po batteries have a low self-discharge rate and a long life cycle. In addition, Li-Po batteries are more compact and lighter than Li-ion batteries of equivalent capacity (Esfahanian, M et al., 2013).

A positive electrode, a negative electrode, electrolyte, and a separator make up a standard Li-Po battery. Figure 2.12 shows a Li-Po cell that looks like a sandwich.

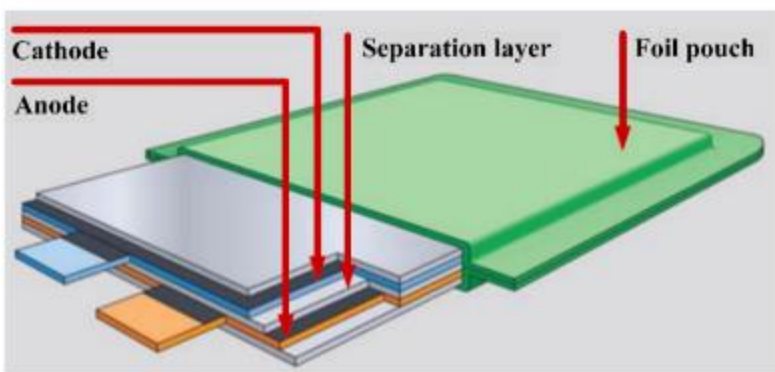


Figure 2.12. Basic construction of sandwich like Li-polymer cells. A typical Li-Po battery consists of a positive electrode, negative electrode, electrolyte, and a separator (Fattal, J. and Dib Nabil Karami, P.B et al., 2015)

Figure 2.13 illustrates the temperature-dependent, I-V characteristics of Li-Po batteries. SOC, current, and temperature all affect the I/V characteristics. The minor impact of the subordinate parameter has been disregarded to reduce complexity. Figure 2.13 depicts the equivalent circuit modeling of a Li-Po battery, per (Esfahanian, M et al., 2013). The IV characteristics are used to estimate the parameters of the various circuit components. Two parallel RC networks are connected in series with a resistor R1 in the analogous circuit. The immediate voltage drop is represented for step response by the series resistor R 1. The short and long time constants of the step response are controlled by the two parallel RC networks (R 2C2 and R 3C3).

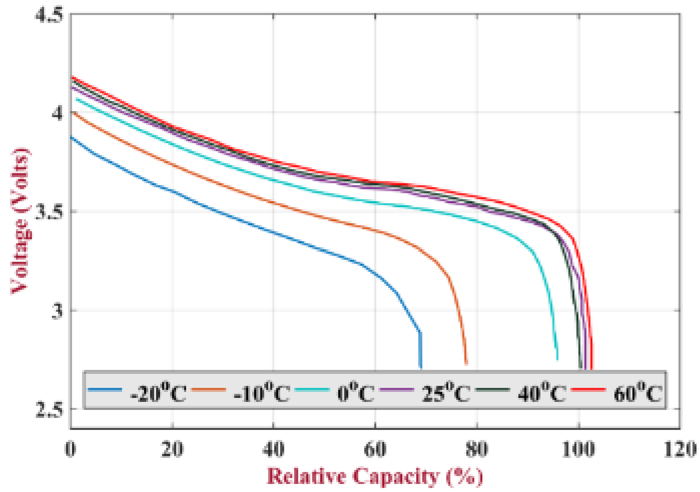


Figure 2.13. Graphical demonstration of voltage versus relative capacity of a typical Li-Po cell at different temperatures (Esfahanian, M et al., 2013).

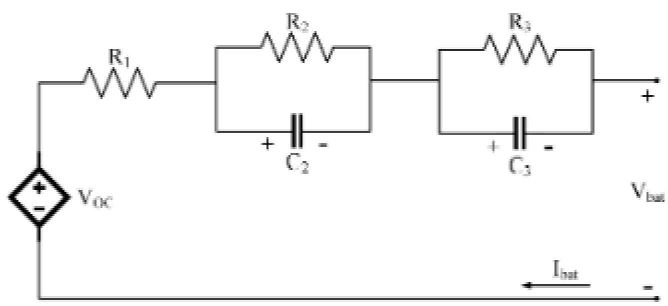


Figure 2.14. Equivalent circuit used for the simulation of the Li-polymer battery consisting of a resistor in series with two RC parallel branches (Esfahanian, M et al., 2013).

vii) Flow battery energy storage systems: A flow battery is a sophisticated aqueous electrolytic battery that can be compared to a hybrid of batteries and traditional fuel cells (Nadeem, F et al., 2019), (BU-210b, 2020). In that one or more electroactive species are dissolved in the electrolyte in this form of battery, the energy is stored in the electrolyte as opposed to the typical secondary batteries (Chen, H et al., 2009), (Nadeem, F et al., 2019). Via the movement of this electroactive species through the power core, chemical energy is transformed into electrical energy. The flow batteries don't self-discharge because they are made of active electrolytes (Nadeem, F et al., 2019). The additional electrolyte, which is kept in two different external tanks and pumped through the reactor to start the chemical reaction, is responsible for the reaction (Chen, H et al., 2009), (Nadeem, F et al., 2019). A tiny membrane that separates the electrolytes allows only a small amount of ions to pass through. These ions take part in the reactor's oxidation and reduction reactions, which result in the production of energy (Leung, P et al., 2012). Figure 2.15 displays the flow battery's schematic diagram.

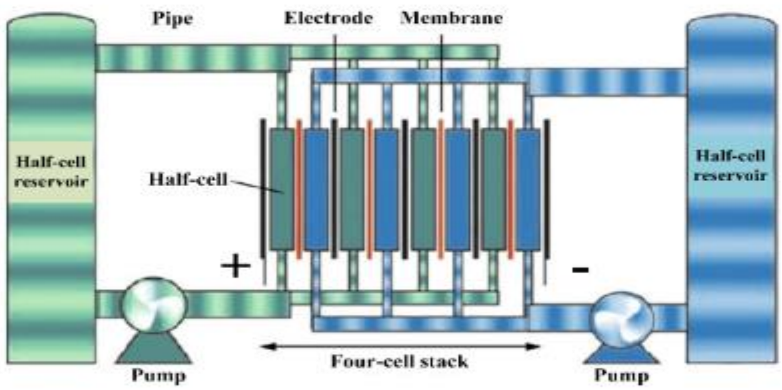


Figure 2.15. Schematic diagram of flow battery. The electroactive species dissolved in the electrolyte flows through the power core, converting the chemical energy to electricity (Chen, H et al., 2009)

Because the internal chemical reactions in flow batteries are reversible, unlike those in fuel cells, they can be recharged without having to replace the electroactive material. Large amounts of energy can be released from flow batteries at a rapid discharge rate (Chen, H et al., 2009). Additionally, they have a good life cycle and can produce 10,000 complete cycles throughout their lives (Nadeem, F et al., 2019. The number of stacks in the cell and the size of the electrode both affect the power rating of flow batteries. On the other hand, the volume of the reservoir and the electrolyte's concentration affect how much energy can be stored. The flow batteries are therefore suited for both power and energy-related storage applications due to their added feature of decoupling between the power rating and energy storage capacity (BU-210b, 2020). Flow batteries also offer a high degree of efficiency, a millisecond response time, and the ability to operate close to the ambient temperature (Guarnieri, M et al., 2016). Redox flow batteries and hybrid flow batteries are two different forms of flow batteries that can be distinguished based on their electroactive components (Luo, X et al., 2015).

Table.2.3. Comparing of different Batteries (Fathima et al., 2014), (Francisco Díaz-González et al., 2012), (Aisheng Chen et al., 2009), (Asian Development Bank, 2018)

Technology	Energy rating (MWh)	Capital cost in $/kWh	Discharge time	Specific energy (Wh/kg)	Cycling capability, @% dod	Self–discharge (%)	Life (yrs)	Energy η (%)	Operating temperature in º C

Li-ion	0.001-50	900-1300	Min-hrs	100-200	1500-3500 @80	1-5	14-16	75-95	-30to 60
Ni-Cd	6.75	400-2400	Sec-hrs	30-80	3500 @100	0.2-0.3	10-20	70	-40 to50
Na-S	0.4-244.8	200-600	Sec-hrs	100-175	2500 @100	No	10-20	75-89	325
Pb-Acid	0.001-40	50-150	Sec-hrs	35-50	500-2000 @70	<0.2	5-15	70-80	-5 to 40
PSB	0.005-120	300-1000	Sec-10hrs	>400	100-13000 @75	No	15	60-75	0 to 40
VRB	2-120	600	Sec-10hrs	30-50	100-13000 @75	Very low	10-20	65-85	0 to 40
ZBB	0.1-4	500	Sec-10hrs	60-85	2000-2500	No	8-10	65-85	0-40

2.7. Fuzzy PID based Pitch Angle Controller

The physical quantities to be taken into account in the controller design of a wind turbine include wind speed, mechanical torque of the rotor, angular speed of the machine, and the amount of extracted power. The extracted power must converge to its set point in this method. Furthermore, because wind speed is a non-linear variable conveyed into the system, the controller construction is particularly complicated due to the relevance of wind speed in wind turbine functioning. As a result, the controller should account for wind speed and continuously change the blades to ensure the wind turbine system's stability (Silpa Baburajan, 2017). One of the most often used ways for regulating devices such as wind turbines is FPID control. Fuzzy PID control is the control strategy which makes use of known PID design techniques before implementing the fuzzy controller.

a. Tune a PID controller
b. Replace it with an equivalent linear fuzzy controller

c. Make the fuzzy controller nonlinear

d. Fine-tune it

A number of assumptions are implicit in a fuzzy control system design. Six basic assumptions are commonly made whenever a fuzzy rule-based control policy is selected.

- The plant is observable and controllable: state, input, and output variables are usually available for observation and measurement or computation.
- There exists a body of knowledge comprised of a set of linguistic rules, engineering common sense, intuition, or a set of input–output measurements data from which rules can be extracted.
- A solution exists.
- The control engineer is looking for a good enough ''solution, not necessarily the optimum one.

For the given time constant of pitch ActuatorT_β, the rate of change of pitch angle is given by:

$$\frac{d\beta}{dt} = \frac{\beta_{d-}\beta}{T_\beta} \quad (2.5)$$

$$T_\beta d\beta = (\beta_{d-}\beta)\, dt \quad (2.6)$$

$$T_\beta \frac{d\beta}{dt} = \beta_{d-}\beta \quad (2.7)$$

$$T_\beta = \frac{\beta_{d-}\beta}{\frac{d\beta}{dt}} \quad (2.8)$$

By applying Laplace transform to equation 2.8, the transfer function of the pitch actuator become:

$$\frac{\beta}{\beta d} = \frac{1}{T_\beta S+1} \quad (2.9)$$

Blades are turned along their longitudinal axis using the pitch actuator. The actuator model describes a dynamic behavior between a pitch demand βd from the pitch controller and measurement of pitch angle β (Vidya G H1 and Ashok Kusagur, 2015).

The wind turbine dynamic drive train is modeled from second law of motion where: J_t is wind turbine inertia and it is given by:

$$JtdWt/dt=Tt-(Ks\delta\theta t + B\delta W) \quad (2.10)$$

$$Dw = d\ (\delta\theta/dt) \quad (2.11)$$

$$JdW/dt=T-BW \quad (2.12)$$

Where B is the total friction, by applying Laplace transform to equation 2.7 the first order transfer function of the require system is given by:

$$\frac{W}{T} = \frac{1}{JS+B} \qquad (2.13)$$

A Fuzzy-PID controller is made up of fuzzy controller and identification structure which based on the traditional PID controller. The initial values of PID parameters are set online through fuzzy inference (Vidya G H1 and Ashok Kusagur, 2015). The traditional PID controller parameters are fixed. The expressions describing fuzzy logic PID parameters are given by:

$$Kp\ (k+1) = Kp\ (k)\ [1 \pm \Delta Kp] \qquad (2.14)$$

$$Ki\ (k+1) = Ki\ (k)\ [1 \pm \Delta Ki] \qquad (2.15)$$

$$Kd\ (k+1) = Kd\ (k)\ [1 \pm \Delta Kd] \qquad (2.16)$$

By adjusting the wind turbine's power coefficient based on the difference between the reference pitch angle and the actual output unit's pitch angle, the fuzzy controller may correct the three parameters of the pitch PID controller and accomplish adaptive fuzzy control. The aerodynamic torque of variable pitch wind turbines is changed by adjusting the blade pitch angle (D. Fister et al., 2016).

The FPID controller adjusts the blade pitch angle to regulate the output power for any wind speeds beyond the rated wind speed. Here the system pitch error (e) and the rate of change of error (de(t)/dt) selected as the fuzzy input variables, and made the adjustment in the three parameters (ΔKp, ΔKi and ΔKd) of the output to compose it with the current PID parameters.

2.7.1. Pitch System Controller

The pitch system is an independent sub-control system of the wind turbine, its function is based on the main controller's commands for adjusting blade angle, in order to realize the power start, stop and control of emergency shutdown of wind generator. The pitch system has the three-cabinet structure, for each blade, it is equipped with a set of independent drive electric pitch control cabinet, the mechanical part comprises a slewing bearing, reducer and transmission mechanism. The reducer is fixed on the wheel hub, the inner ring of slewing bearing is installed on the blade, and the blade bearing's outer ring is fixed on the wheel hub. When the pitch system is electrified, the motor drives the small gear of output shaft of the speed reducer to rotate, and the small gear and the slewing bearing's inner ring mesh, which drives the inner ring in slewing bearing rotates with the blade, and it can change the pitch angle. The following main principles and structure of pitch products are as follows:

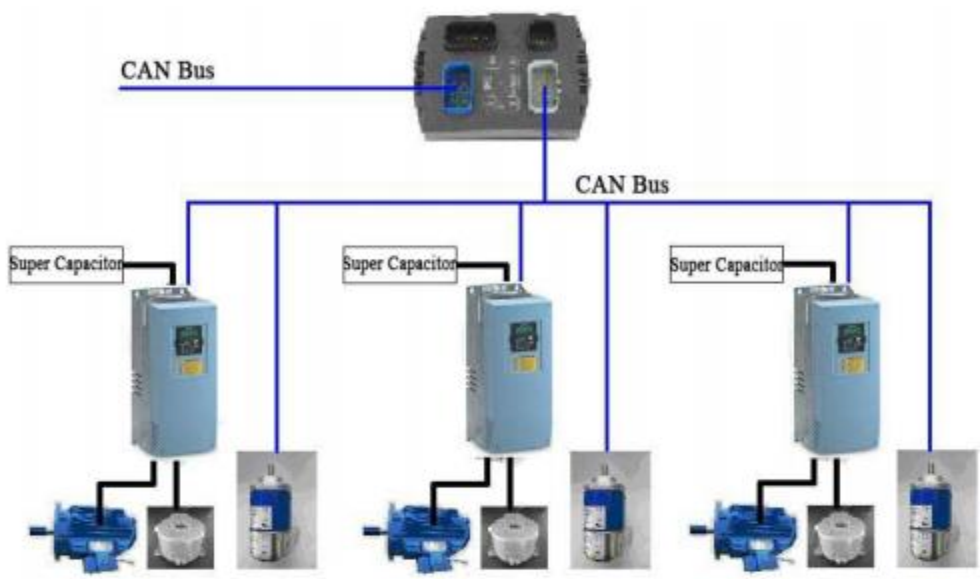


Figure 2.16. General Framework of variable pitch system (SANY ELECTRIC CO., LTD, 2014)

The main control system of the wind turbine and variable pitch controller, variable pitch controller and pitch drive, pitch drive are to communicate via CAN bus. The main controller is to send the pitch angle and speed or command of blade opening and closing to the pitch system via the communication bus, and the pitch system executes the command to complete variable pitch action;

When the other parts of the fan fails, the main control system will trigger the safety chain, notify the pitch system to enter the state of emergency stop for withdrawal of blade; When the variable pitch system has internal fault, the pitch system will enter the emergency stop for withdrawal of blade, and notify the master controller; When the power system fault occurs, the standby power supply enters into the emergency stop, and notify the master controller.
The pitch system has four modes of operation: Wait mode, normal operation mode, emergency withdrawal model (including open loop and closed loop), and manual operation mode.

After power-on of system, if the safety chain is closed, the DI port of standby power supply and variable pitch controller and driver has normal monitoring status, if the switch is not triggered, the pitch system will enter standby mode. If the selection switch is to manual mode, the pitch system will enter the manual maintenance mode. In manual mode, pitch system can be manually adjusted to zero and other operations.
In wait mode, the system is not running, the motor brake is to stop brake. If the safety chain is closed, the master controller sends operation command, the pitch system will enter the normal mode of operation.

In the normal mode of operation, the normal communication, according to the position command sent by master controller, the pitch system will carry out variation of pitch. At this point, if there is communication fault, each DI port's monitoring state error, the main power failure or drive failure, the main controller will open the safety chain, and the pitch system will run into emergency mode.

Emergency mode is divided into closed-loop emergency mode and open-loop emergency mode. When the drive or motor encoder fault occurs, the system into the open-loop emergency mode, at this time, the pitch system will take emergency blade withdrawal at power supply, until trigger the limit switch, the motor brakes to enter into the waiting mode; When the drive or motor encoder is normal, and other fault occurs, there is need for emergency blade withdrawal, the system will enter the closed loop emergency mode, use the driver to the pitch motor to move toward the position operation.

It should be pointed out that in the closed-loop emergency mode, when the main power has failure for more than 3 seconds, the standby power supply will, through the DC bus, supply the power for the driver to realize the urgent blade withdrawal. For variable pitch system's operating pattern, refer to Figure 2.17.

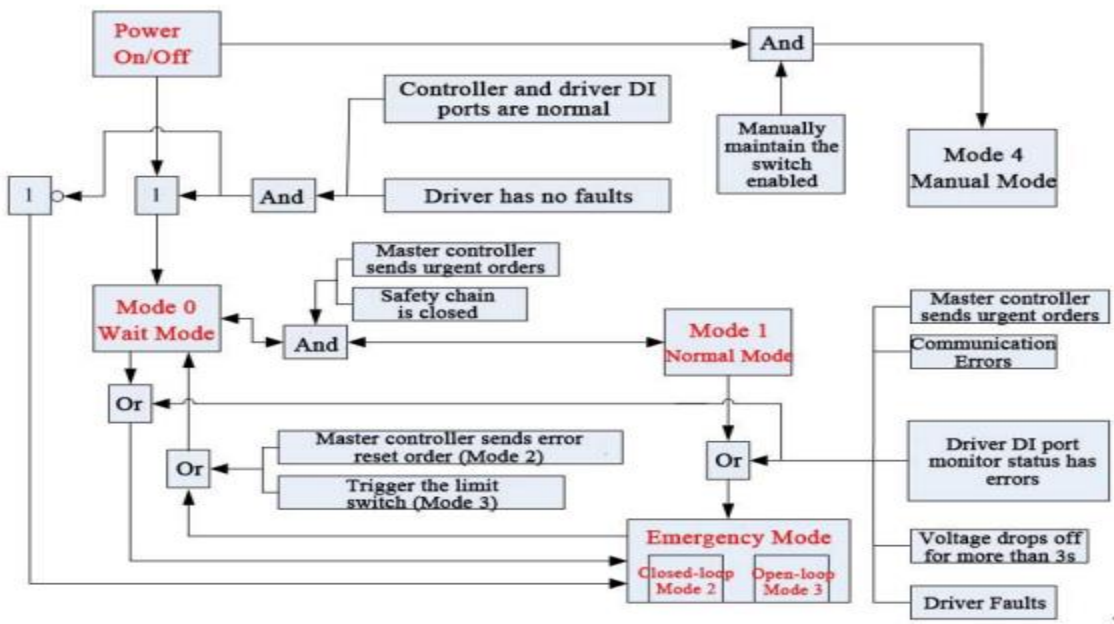


Figure 2.17. Schematic diagram of operation mode of pitch system (SANY ELECTRIC CO., LTD, 2014)

2.7.2. FPID Fuzzy inference system Modeling

The fuzzy inference system inputs are the signals of error and change of error in pitch angle wind turbine. The output is the control action inferred from the fuzzy rules. The configuration of this fuzzy inference system for fuzzy controller is given in the following figure 2.18.

The error and change of error between measured rotor speed and the reference rotor speed are inputs to the fuzzy logic controller and are normalized to [-1, 1], the output signals are normalized to [-1, 1]. The input signals each consist of seven membership functions. The first input to the fuzzy logic controller is change in speed of rotor of wind generator. This input, when compared to the rated speed of the generator, will tell the controller if the pitch angle needs to be increased/decreased or if it is operating at its initial condition. The second input to the controller is the rate of change of speed error. This input describes how fast the speed is changing. The controller controls the output rotor speed constant by controlling the pitch angle based on those two input signals. The second step is choosing an appropriate membership function for inputs and outputs which is simple for implementation and also to have an acceptable performance. The shapes and the universe of discourse for each functions is found by trial and error after many simulations were done. The third step is choosing the correct labels for each fuzzy set which, in this paper namely as linguistic variable. It is due to that the actual frequency can be higher/lower than the desired one which means the error can be negative as well as positive. Values of speed error with a negative sign mean that the current output speed has a value greater than the set point value. On the other hand, linguistic values of e(t) with a positive sign mean that the current value of speed is below the set-point value.

The change or speed error with negative sign means that the current output speed has increased when compared with its previous value w(t-1), since $de(t)/dt = e(t) - e(t - 1) = -w(t) + w(t - 1) < 0$. Linguistic values of de(t)/dt with a positive sign mean that w(t) has decreased its value when compared to w (t -1). The output variable, pitch angle generated must be positive it is not like the input variables, the speed error and change in error.

The universe of discourse for the system error (e) and the rate of change of error (de(t)/dt) is taken in the range of -1 to 1 as [-1, -0.8, -0.6, -0.4, -0.2,0,0.2,0.4,0.6,0.8,1], and divided it into seven levels, the linguistic values of the 7 fuzzy sets were taken as negative high(NH), negative medium(NM), negative small(NS),zero(ZE), positive small(PS), positive medium(PM), positive high(PH).

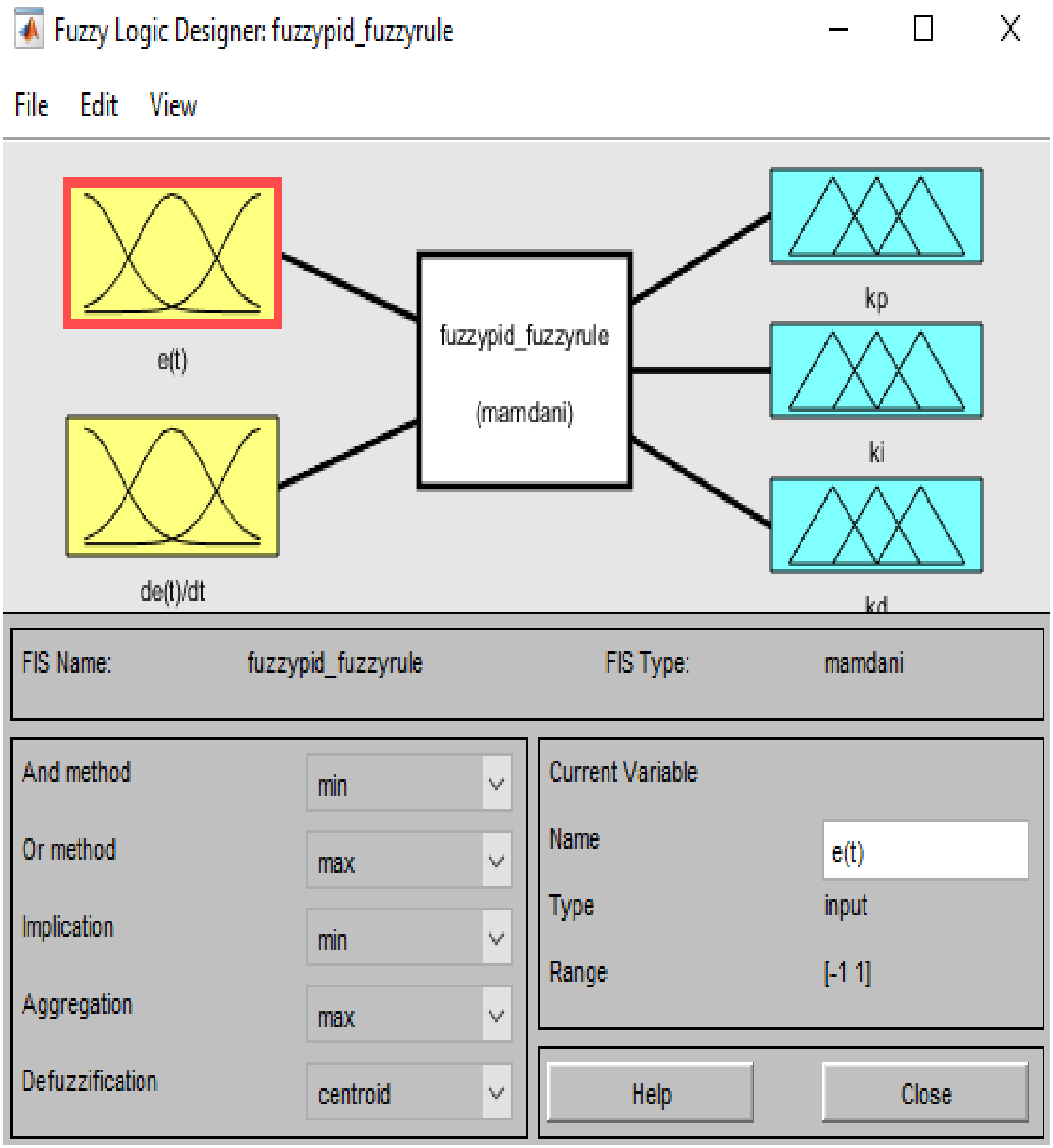


Figure 2.18. Mamdani FIS model of FPID controller

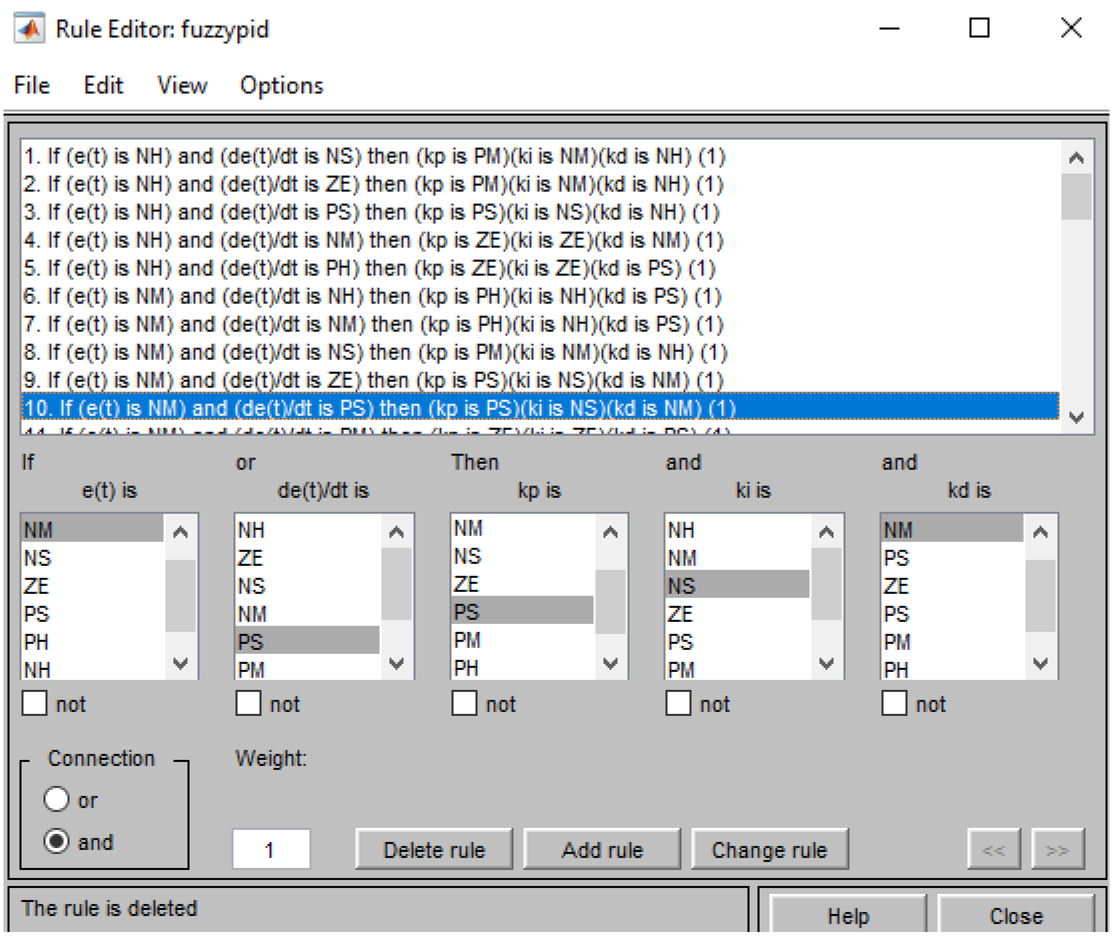


Figure 2.19. Fuzzy inference rule of FPID

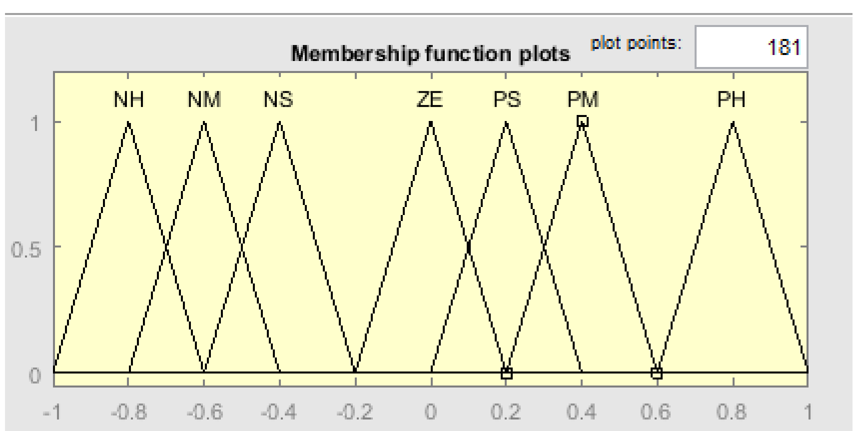


Figure 2.20. Membership function for inputs

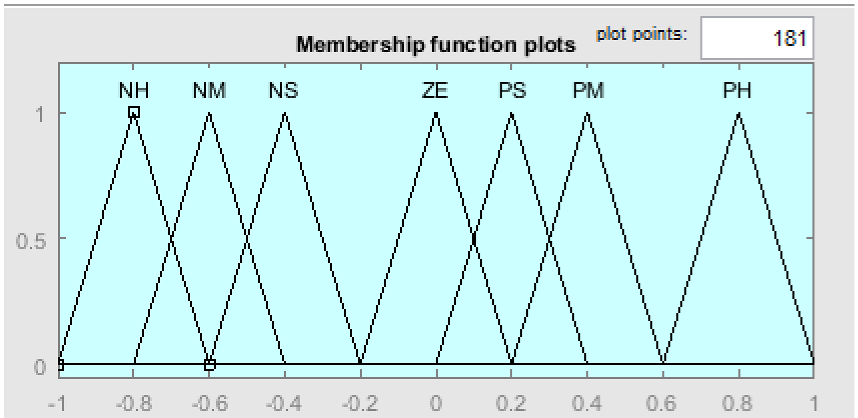


Figure 2.21. Membership function for output

There are total 49 fuzzy rules for each ΔKp, ΔKi and ΔKd are established according to (H. S. Chen et al., 2009) as shown in table 2.4 below.

Table 2.4. Rule table

Output		Change in error						
		NH	NM	NS	ZE	PS	PM	PH
Error	NH	NM	NM	NH	NM	NM	NS	ZE
	NM	NH	NH	NM	NM	NS	ZE	PS
	NS	NS	NM	NM	NS	ZE	PS	PM
	ZE	NM	NM	NS	ZE	PS	PM	PM
	PS	NM	NS	ZE	PS	PM	PM	PH
	PM	NS	ZE	PS	PM	PM	PH	PH
	PH	ZE	PS	PM	PM	PH	PH	PH

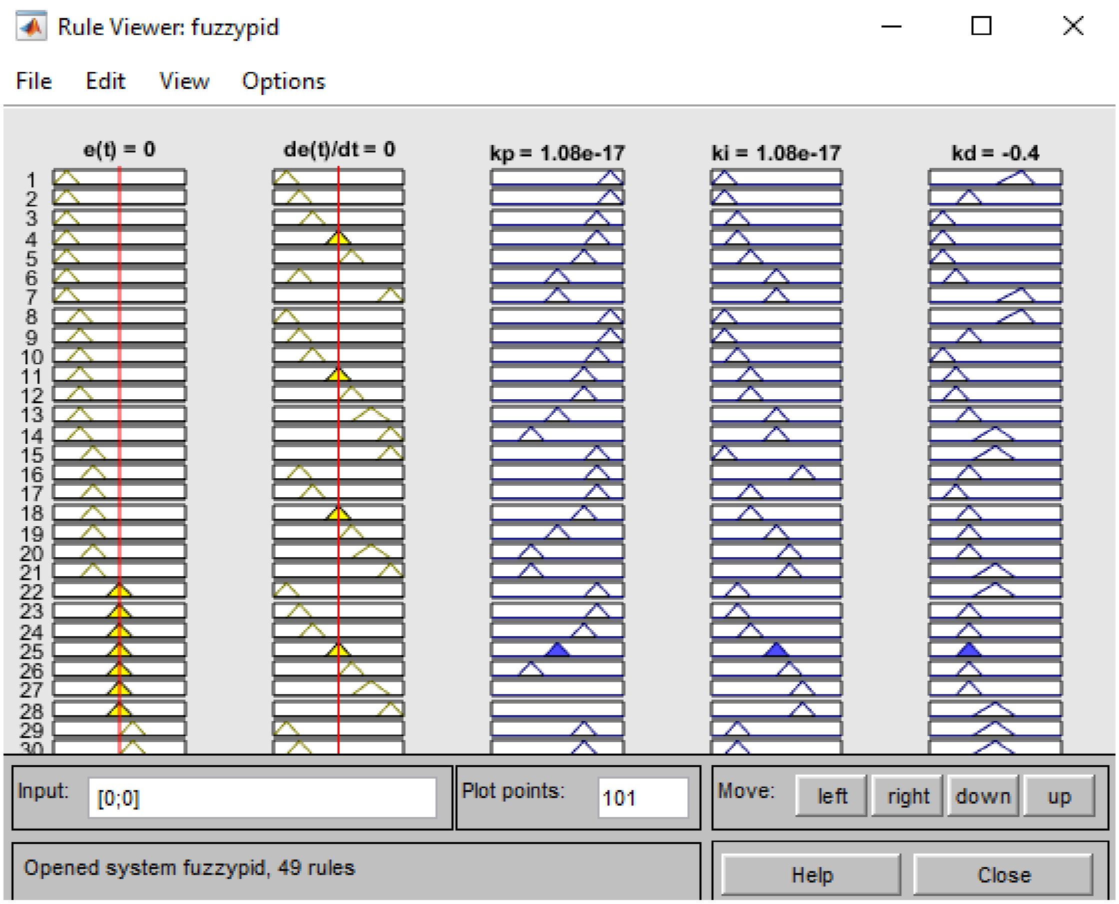


Figure 2.22. FPID Overall Rule Viewers

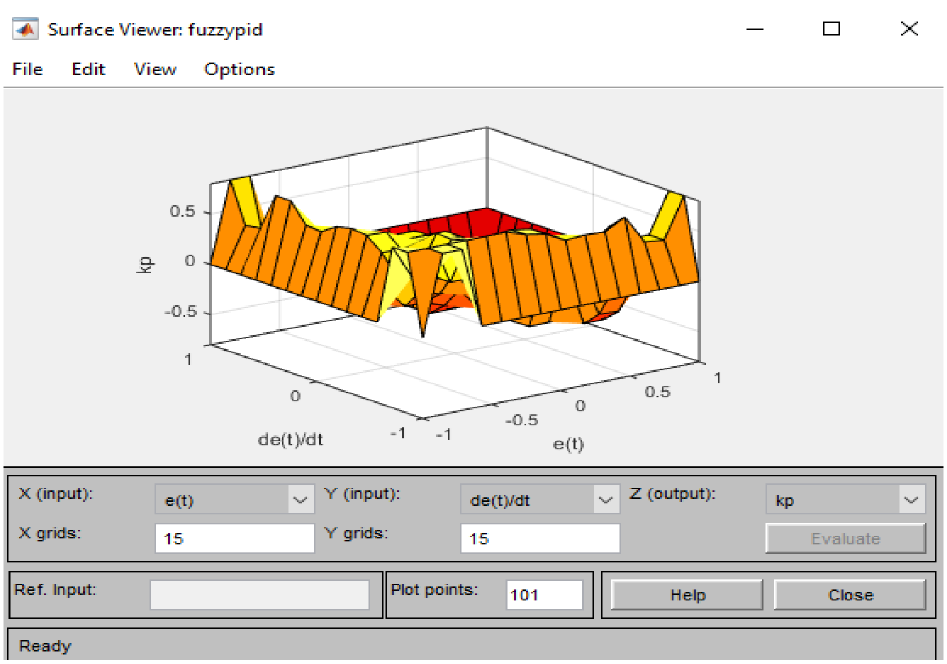


Figure 2.23. Surface rule Diagram for any gain of PID

2.8. Related Work

The integration of wind power into national power grid has been going on for a couple of years in Ethiopia and there are enough literatures addressing various aspects of the technology. Here for this thesis work focus on fluctuation smooth mechanism for Adama II wind farm. This section presents a review on the origin and development of wind power smoothing research emphasizing the use of BESSs. Several studies are described, ranging from the first reports on the power fluctuation problems of wind power generation to the most recent studies that propose sophisticated techniques using BESSs.

In the paper (Zhang F et al., 2017), an improved control and sizing scheme of a BESS for wind power smoothing were discussed. In this study, the reference output and the time duration of each cycle control period are determined by a multi-objective optimization model. The multi-objective model considers the minimum power variation between adjacent charge/discharge intervals and the maximum time duration of each cycle's control period. This duration of intervals is determined as an integer multiple of the trading period for a specific market, e.g., an hour. Thus, the energy capacity and power of the BESS were sized considering a probability function of the charge and discharge energy and power. This strategy was tested with real power data from a 36 MW wind farm in China, where the results validated the performance of the schemes. This research group discussed in paper (Zhang F et al., 2017), a novel sizing method for BESS planning for wind smoothing. In this article, the authors use three different indexes to evaluate the smoothing performance: deviation energy, curtailed energy, and the frequency of the SOC limit violation. The results demonstrated that the BESS mitigated wind power fluctuations effectively.

In the paper (Sattar A et al., 2020) performed an experimental analysis of a BESS integrated with wind generation. The smoothing method used was a low-pass filter with adjusted time constant. The ESS was modeled with its own inverter connected in parallel with the PMSG inverter. All the simulations were conducted in a real-time digital simulator with the battery and its DC–DC converter connected in the loop. The results showed that the BESS was stable under transient conditions, and it could moderately smooth the power output of the WTG.

A paper (Jannati M and Foroutan E, 2020) presented a new method for reducing the demanded BESS for short-term wind power smoothing purposes. These authors highlight that the BESSs cost is one of the main difficulties in the investments for the wind farms, and, thus, is necessary to protect the lifetime of the BESS, for example, utilizing an optimized power allocation strategy.

The proposed power allocation method was tested through simulations using the power output data from a 99 MW Chinese wind farm, with 66 DFIGs of 1.5 MW. Nine different strategies were judiciously analyzed, and the proposed strategy was effective while controlling the switching actions of the BESS units. In (H. Beltran et al., 2013), the BESS capacity was selected as 560 kWh for a 1.2 MW PV plant in Tudela, Spain. The BESS could help the PV plant achieve constant power production, active power ramp rate limitation and regulation of frequency and voltage. Reference (W. F. Su et al., 2020) analyzed the minimum energy capacity ratings that an energy storage system should accomplish in order to achieve a defined constant power production in a PV power plant. A few researchers have investigated BESS designs for utility-scale PV plant applications as well. A 1 MWh BESS was integrated into a 1.5 MW PV plant (C. A. Hill et al., 2018). The BESS was applied to achieve ramp rate control, frequency droop response, power factor correction, solar time-shifting and output leveling. These functions of the BESS could optimize the benefits of the plant. In (L. Xiangjun et al., 2019) a 1 MWh BESS was connected to a 1.26 MW PV. This BESS design was able to smooth the output power and regulate PV plant power fluctuations.

A study on paper (Farm Zhang Wei, 2014) discussed power fluctuation reduction using a BESS in a DFIG-based system considering the wind power output for different wind speeds. More recently, Cao et al. (Nian Shi, 2017) presented a sizing method for BESSs to make the wind power system more dispatch able. In this study, the BESS sizing method was based on practical aspects, such as the energy loss on conversion and dynamic operations of the system.

Mittal (Zeinab Mousavi Karimi, 2014) modelled and simulated a system which included a wind turbine (WT), a PMSG, a three-phase diode rectifier bridge, a DC bus with a capacitor and a current-regulated pulse width modulation (PWM) voltage source inverter. The complete modeling of a wind power generation system with PMSG and power electronic converter interface along with the control scheme was developed using MATLAB/Simulink. The performance of the developed model was studied for different wind speeds and load conditions and the simulation results showed that the controllers were able to regulate the DC link voltage, and the active and reactive power produced by the wind power generation system.

In a new study, Cao et al. (Y.Yang, 2014) presented a different method to design the BESS regarding the battery size impact on the wind power smoothing using a predictive strategy. They concluded that longer dispatch windows require larger energy and power capabilities from the BESS to maintain the same level of power fluctuation.

2.8.1 Summary of Literature review

Jonas Lindstens,''Study of a battery energy storage system in a weak distribution grid'', Upsala University, June 2017 -Studied distributed BESS configuration.

In this configuration the BESS capacity is not enough, the effect of stable output power is not obvious and mostly used in scenario of small and few in number wind power plant.

Yuan Cong,''A Power Smoothing Approach Based on Battery Energy Storage System for Power Fluctuations of Wind Power Generation'', China 2018- Studied Aggregated (semi-distributed) BESS configuration.

In this case the BESS at each individual turbine only partially reduces the wind power fluctuations and suffer to high cost and to be at containers or needs placement room when in aggregated at different location of wind farm.

In this research BESS configuration at Point of Common Coupling (PCC) discussed, which is better power fluctuation improve at a common bus bar and solve different grid related problems, like; Electric supply capacity in normal operation, Voltage support, Black start which means used to energize transmission, distribution lines and station power to bring power plants on line after a catastrophic failure of the grid.

CHAPTER THREE

METHODOLOGY AND SYSTEM MODELING

3.1. Introduction

The system modeled comprises a 153MW grid connected Adama II wind turbine which uses a DFIG with converter topology and is connected to a bidirectional boost-buck converter. The schematic diagram of the proposed system architecture is shown in Figure 3.1. The BESS, converter, Power Management Unit (PMU), wind farm, transmission line, and main grid are the components of the system. To smooth the wind power put into the grid at PCC, the BESS is connected to the grid and charges/discharges power through the converter.PG(t): Grid-connected power at time t, PW(t): Wind farm output power at t, PB(t): Output power of energy storage battery, SOE: state of the energy, and PMU: Power management unit. A key component of the design of the wind storage system is the BESS PMU used for smoothing the wind power grid (Yun, P et al., 2018).

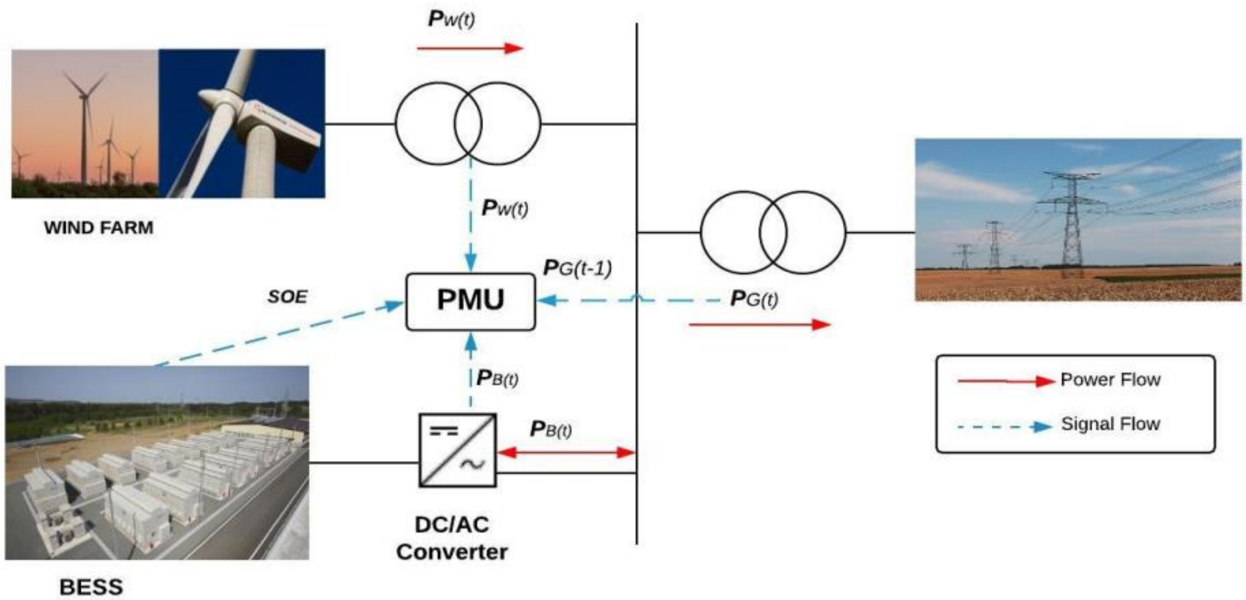


Figure 3.1. Scheme of Grid integrated Wind Farm BESS (Zarei Fard, 2017), (Mandisi Gwabavu and Atanda Raji, 2021)

3.2. Methodology

As mentioned above, this research is mainly concerned to model and analysis of Battery Energy Storage System (BESS) for Adama wind Power II. This is done through the following methodologies:

Literature review: Related literatures on DFIG wind power modeling and controls in grid connected wind power with BESS done in Ethiopia as well as abroad are reviewed. This includes journals, papers and books related to the proposed system

Data collection: The primary work is field data collection, which includes information and specification of each component and Adama wind farm of each cluster at whole as well as the feeder load and grid kV capacity to which the wind power is integrated and other related activity has collected through direct visit, interview and communication with the technical expert of Adama wind power station.

System modeling: Moreover, the data collected from different sources have been analyzed using multiple techniques to model the BESS Capacity to compensate the rejected wind energy with integration of grid. Finally, the system is modeled and simulated using MATLAB/Simulink sim Power model block.

3.3. Wind Turbine and DFIG Modeling

Wind power is one of the most promising renewable energy sources. A machine called a wind turbine converts the kinetic energy of the wind into electrical energy (Musyafa, 2010), (Y. Bhanu Chandra M.E and Josyula s l tejaswi, 2015), (SilpaBaburajan1 and Dr. Abdulla Ismail, 2017), (Jian Chen et al., 2019). The principal energy converter component is the wind turbine. The amount of energy available in the wind is proportional to the cube of the wind speed. As a result, the wind speed is the most important piece of information needed to assess a site's power potential. The weather system, local land terrain, and elevation of the site all influence wind. It is never stable, no matter where it is. A probability distribution function will be used to explain the variations in wind speed over time, while the probability density function and the cumulative distribution function will be used to describe the variations in wind velocity. A probability density function f (v) best states the variation in wind speed. It is used to model the wind velocity variation. A probability density function f (v) provides the probability that an event will occur between two end points. The area under the curve between any two speeds greater than zero will equal the probability that wind will blow somewhere between those two speeds.

The probability density function (f (v)) represents the fraction of time that the wind is moving at a particular velocity v and is written as:

$$f(v) = \frac{k}{c}\left\lfloor\frac{v}{c}\right\rfloor^{k-1} * e^{-(v/c)} \tag{3.1}$$

Where, k is the Weibull shape factor and c is scale factor. For a given average wind speed, a larger shape factor indicates a relatively narrow distribution of wind speeds around the average while a smaller shape factor indicates a relatively wide distribution of wind speeds around the average.

It's critical to situate the measuring equipment high enough to prevent turbulence caused by trees, buildings, or other obstacles. In most circumstances, the data should be logged at a resolution of 10 m. For wind energy calculations, it's crucial to adapt the measured wind speed to the hub height. The logarithmic law, which assumes that wind speed is related to the logarithm of height above ground, will be used. On the basis of the roughness height of the landscape, data acquired at any height can be extrapolated to other heights. Wind speed increases in a logarithmic manner with height due to the boundary layer effect. If the wind data is available at a reference height Zref, then the velocity Vd at a hub height Zref is given by equation below (3.2) (SilpaBaburajan1 and Dr. Abdulla Ismail, 2017), (Jian Chen et al., 2019).

$$Vd = \frac{Vref \ln(\frac{Z}{Zo})}{\ln(\frac{Zref}{Zo})} \tag{3.2}$$

Where Vd = wind speed at desired height (Z) above ground level

Vref = reference speed, i.e. a wind speed at height Zref

Z= height above ground level for the desired velocity v

Zref = reference height, i.e. the height at which wind speed is Vref,

Z0 = surface roughness length in the current wind direction

The turbine output power, extracted by the rotor which drive the electrical generator can be given as:

$$P = \frac{1}{2}\rho * A * V^3 * Cp(\lambda, \beta) \tag{3.3}$$

Where $Cp = (1 + \frac{Vo}{V})(1 - \frac{Vo}{V})$**,** it is power coefficient of the rotor or rotor efficiency

ρ is the air density (kg/m3)

A is the turbine swept area

V is the wind speed (m/s)

λ is the tip speed ratio of the rotor blade tip speed to wind speed

β is the blade pitch angle (degrees)

The wind power output can be normalized and converted to per unit (pu) system as:

$$P_{pu} = k_p cp_{pu} \, v^3{}_{pu} \tag{3.4}$$

Where P_{pu} it the power in pu of the nominal power for particular value of air density and area, cp_{pu} is the performance coefficient in pu of nominal maximum value of cp, $v^3{}_{pu}$ is wind speed in pu of the base wind speed in meter per second, k_p is power gain for cp_{pu}=1pu.

3.3.1 DFIG Modeling

An induction generator with wound rotor and slip rings is one of the possible generator configurations used in a wind turbine system. Such generators are also called cascade generators because the electrical power is applied at the stator as well as at the rotor terminals. In all of the applications, the stator winding is connected to the grid. A three phase rotor-side converter is connected to the rotor windings through slip rings.

a) Generator equivalent circuit

The generator model in the doubly-fed induction generator control program is based on a single-phase equivalent circuit of the generator that is referred to a stator reference frame (rotor-side quantities are scaled to the stator reference frame). The figure 3.2 below shows the generator equivalent circuit in the stator reference frame.

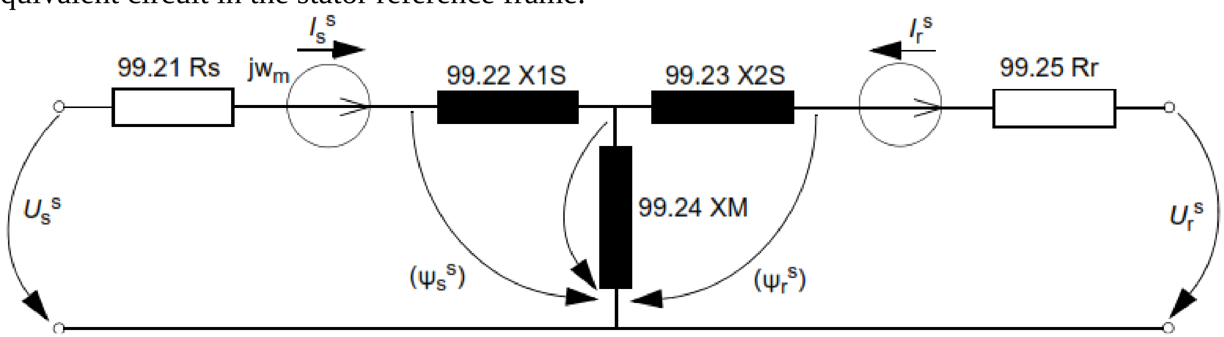


Figure 3.2. The generator equivalent circuit in the stator reference frame (ACS800-67 (+C236), 2018)

3.3.2 DFIG Based Wind Generator

Figure 3.3 depicts a wind energy conversion system (WECS) using a DFIG. The stator and rotor windings are connected by two back-to-back voltage source converters, and a transformer is required between the line side converter and the supply, as previously indicated. The line side converter is in charge of controlling the dc bus voltage, while the rotor side converter is in charge of controlling the machine's speed and pf. The line side converter may also produce reactive power, dictating the generator pf in conjunction with the rotor side converter.

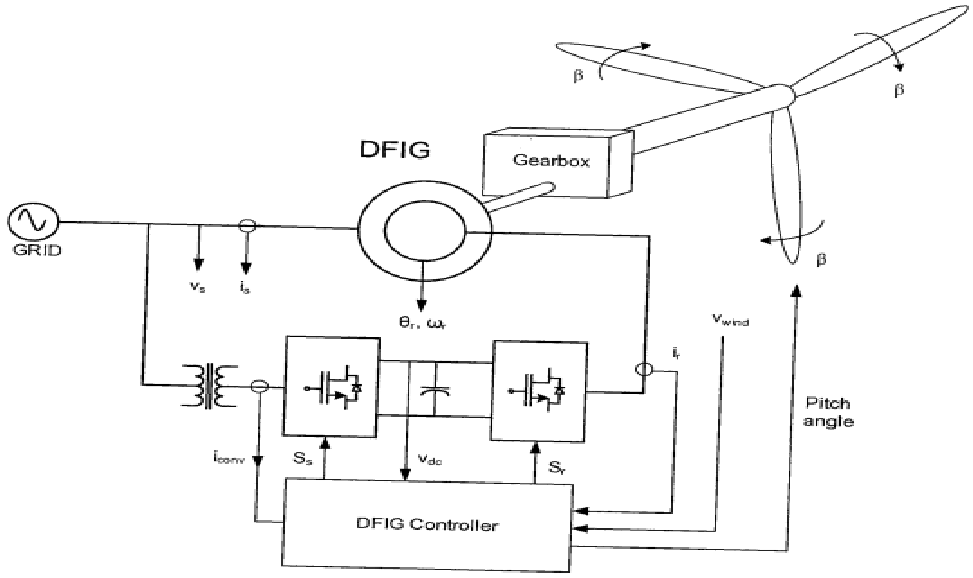


Figure 3.3. DFIG wind energy conversion system (Chad Abbey, 2004)

The ratings of each of the converters as well as of the generator itself must be respected and therefore, current limits must be implemented in each of the two control algorithms. The speed is limited as well in order to respect the mechanical limitations of the system. The summary of the control objectives of the two converters as well as the machine are given below in Table 3.1.

Table 3.1. Control oobjectives for converters and DFIG-WECS

Converter	***Objective***	***Vac regulation***	***Reactive power source***	***Speed control***
Rotor side	Ps, Qs control	Yes	Yes	Using P ref
Supply side	Regulate dc bus	Yes	Yes	No

3.3.3 Steady-State Equivalent Circuit

The induction machine can be represented by it steady-state equivalent circuit as is given in all machine theory textbooks, such as (Paul C. Krause, 2013). It is presented in Fig. 3.4 in order to develop the basis for decoupled control of *Ps* and *Qs*. From the equivalent circuit one can derive the following equations which relate the steady-state quantities of the rotor and stator sides.

$$\begin{bmatrix} 1 & R_S + jX_S & 0 \\ 1 & 0 & R_r/_S + jX_r \\ 1 & jX_m & jX_m \end{bmatrix} \begin{bmatrix} V_m \\ I_s \\ I_r \end{bmatrix} = \begin{bmatrix} V_s < 0^0 \\ V_r/_S < \delta_r \\ 0 \end{bmatrix} \tag{3.5}$$

If the stator side voltage is used as the angle reference then the remainder of the quantities can be defined assuming a fixed stator voltage magnitude and given the required real and reactive power. From *Ps* and *Qs*, one can then define the magnitude and phase of the current, *Is* as follows:

$$Re(i_s) = \frac{P_S}{V_S} \tag{3.6}$$

$$Im(i_s) = -\frac{Q_S}{V_S} \tag{3.7}$$

The first and third row equations are then used to obtain Ir, followed by the second to find the needed voltage supplied at the rotor terminals, all using the formula (3.6). This seemingly simple study is the foundation for rotor side converter transient control. Of course, there are a number of technical challenges relating to signal synchronization and the application of the appropriate forward and reverse transformations, but the control algorithm emerges from this simple analysis.

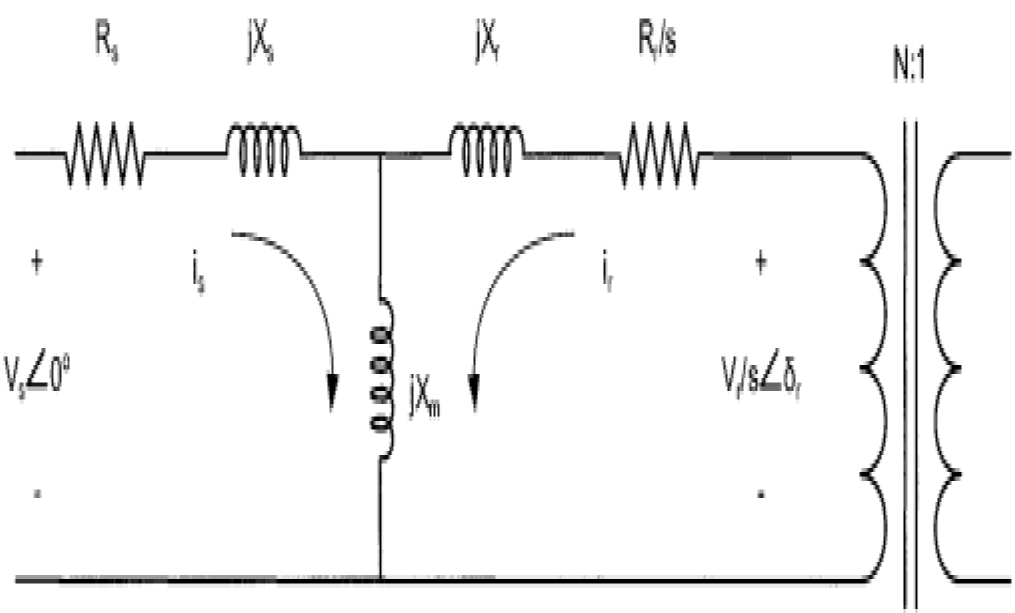


Figure 3.4. Wound rotor induction machine equivalent (Chad Abbey, 2004)

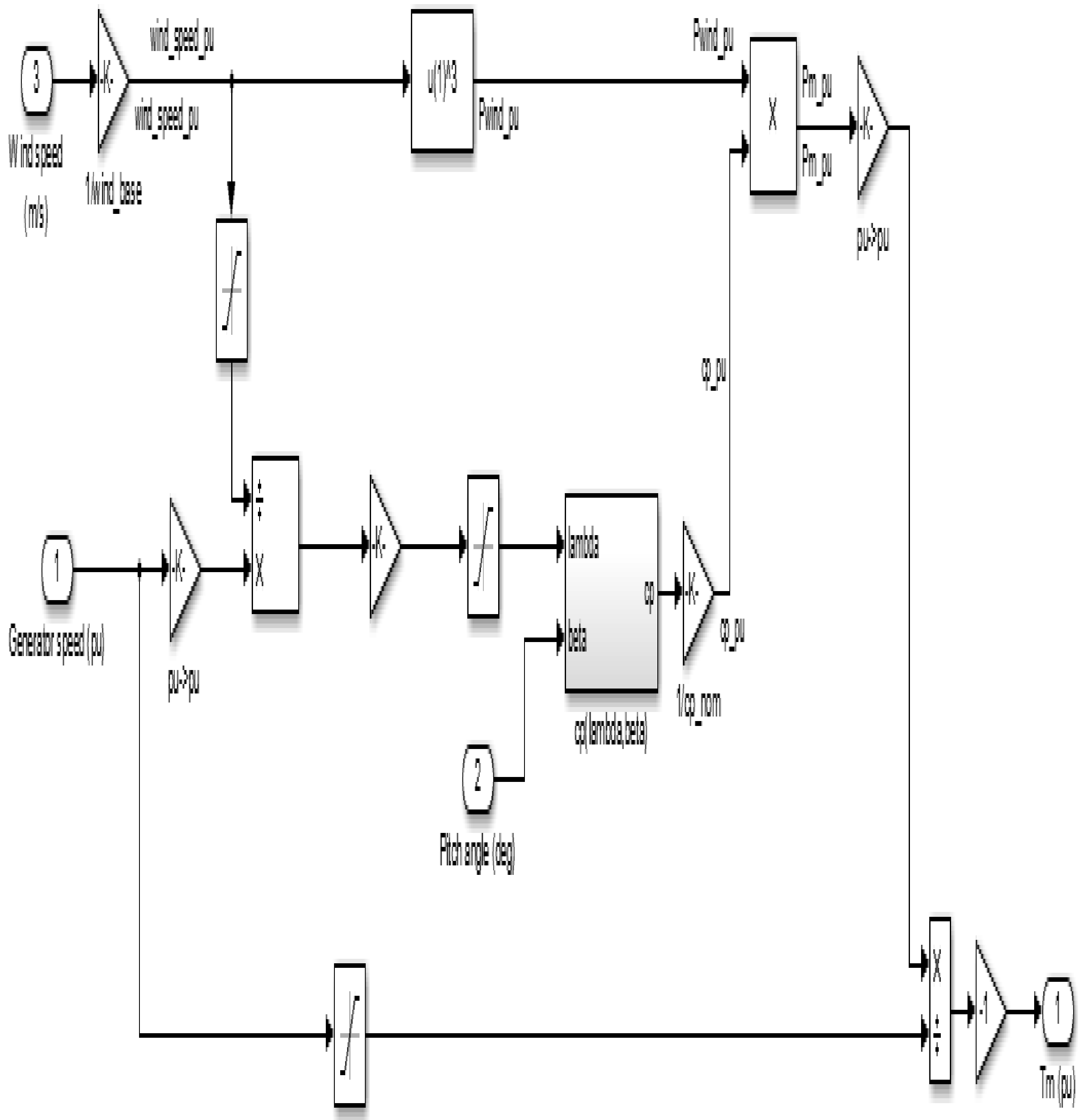


Figure 3.5. Model of wind turbine in Simulink.

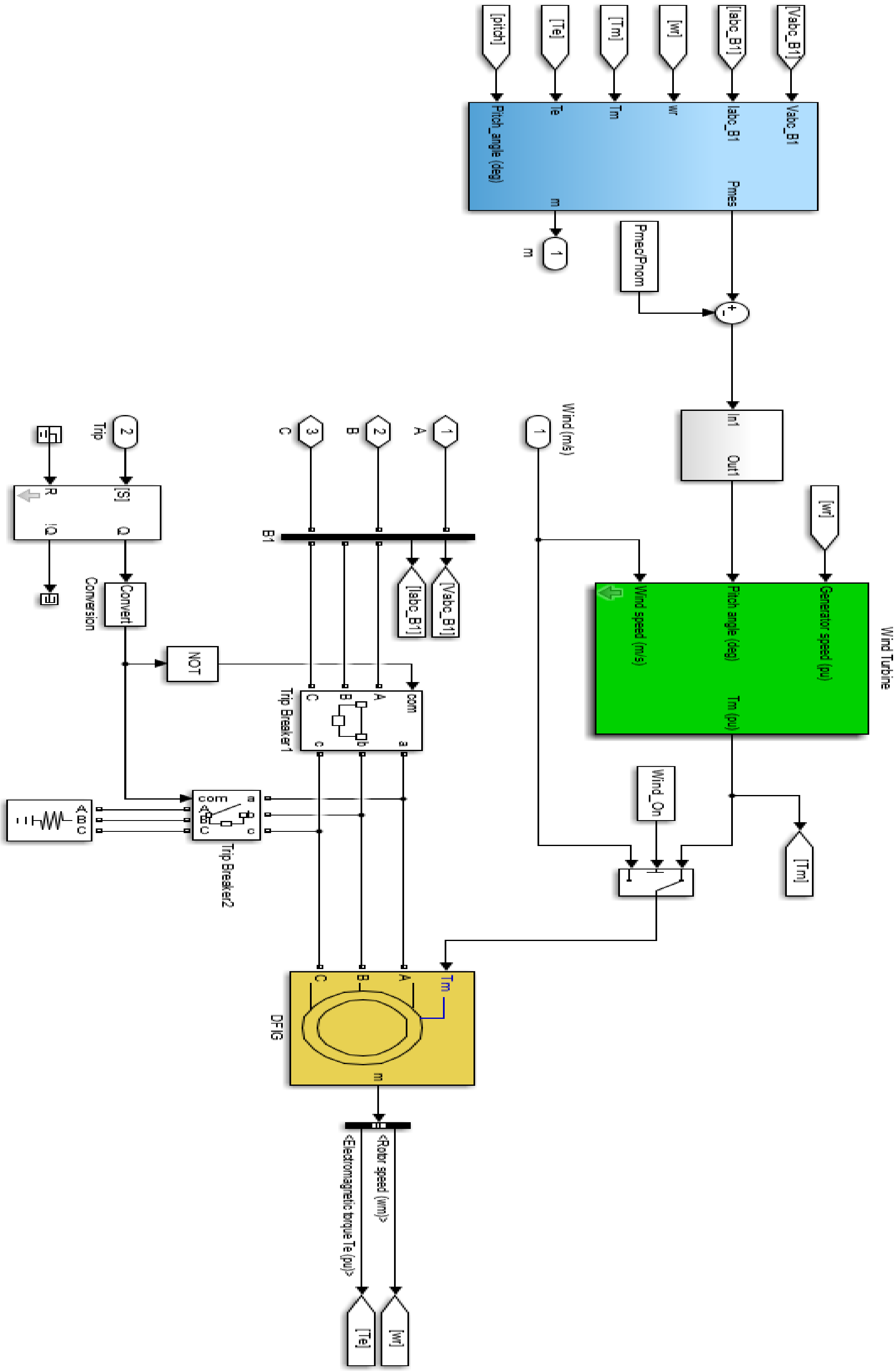


Figure 3.6. Wind Turbine and DFIG Simulink modeling [MATLAB]

3.4. BESS Size Modeling and Placement

The energy storage system's goal is to smooth out stochastic wind variations so that DFIG can get a consistent power production. If the wind turbine's output exceeds the specified level, the excess energy is utilized to charge the store via a stator side converter. When wind power output falls short of expectations, stored energy can be utilized.

On the basis of available wind power output, the charging and discharging power of the energy storage system can be calculated as follows: The charging battery power is given by equation 3.8 below if real wind power Pw is larger than intended power Pd, and the reverse is true for discharging power (K.Meng, 2015), (Yuan Cong, 2018).

$$Pch = Pw - Pd \tag{3.8}$$

Where Pch, Pdch, Pd, and Pw are the charging, discharging, desired and actual wind power, respectively.

Wind energy resources face a major difficulty in smoothing out their inconsistent power output. As a result, our challenge is to devise a mechanism for charging or discharging the BESS so that their erratic power output can be smoothed. The state of the BESS's charging restrictions should also be examined. To govern charging or discharging of the BESS, we use the power differential between the measured power of the wind turbine and the power reference. The BESS can be broken down into two phases: charging and discharging:

Battery charging phase: This is known as the power peak phase. When the power reference is lower than the measured power of the wind turbine, the battery stores excess energy.

Battery discharging phase: This is known as the power valley period. When the power reference exceeds the measured power of the wind turbine, the battery releases energy (Yuan Cong, 2018).

The stored energy will be comparable to the charging and discharged energy in a 100 percent efficient charging and discharging system, and the charging power will be the same as the discharging power. The storage system's rating must be lower than the converter's rating. Depending on the quantity of energy stored, the voltage across the storage system would fluctuate within 10% of the DC link voltage. The storage size for DFIG can be estimated as follows:

$$E = \frac{1}{2}.C.\left(V_{max}{}^{2} - V_{min}{}^{2}\right) \tag{3.9}$$

$$E = P_{conR}.P_{rated}.t \tag{3.10}$$

Where E, C, P_{conR}, P_{rated}, V_{max}, V_{min} are the stored energy, capacitor, converter power ratings, machine’s rated power, maximum and minimum DC link voltages, respectively.

There are three types battery energy storage system configuration to wind power: distributed BESS configuration, aggregated configuration (semi-distributed) and the configuration at the point of common coupling.

In distributed BESS configuration each wind turbine is connected with certain separate battery bank, as shown in the figure 3.7.

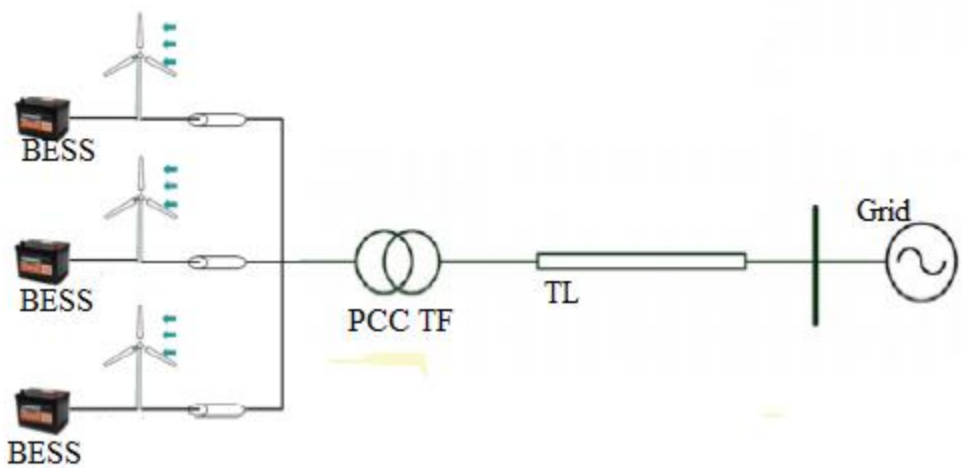


Figure 3.7. Distributed BESS configuration (T. Riouch and R.E. Bachtiri, 2014)

In aggregated semi-distributed BESS configuration, it is suggested for suppression of the wind output power fluctuations. The configuration consists of an aggregated BESS unit and a separate BESS unit at each individual wind turbine as shown in Figure 3.8. This configuration is effective for both wind profiles; wind turbines are situated nearby wind profiles and wind turbines are located far from each other with different wind profiles. The purpose of this configuration is to reduce the BESS capacity to minimize the total cost of the system (Yuan Cong, 2018), (T. Riouch and R.E. Bachtiri, 2014). The BESS at each individual turbine partially reduces the wind power fluctuations and ultimately the total BESS receives less fluctuating power at its input.

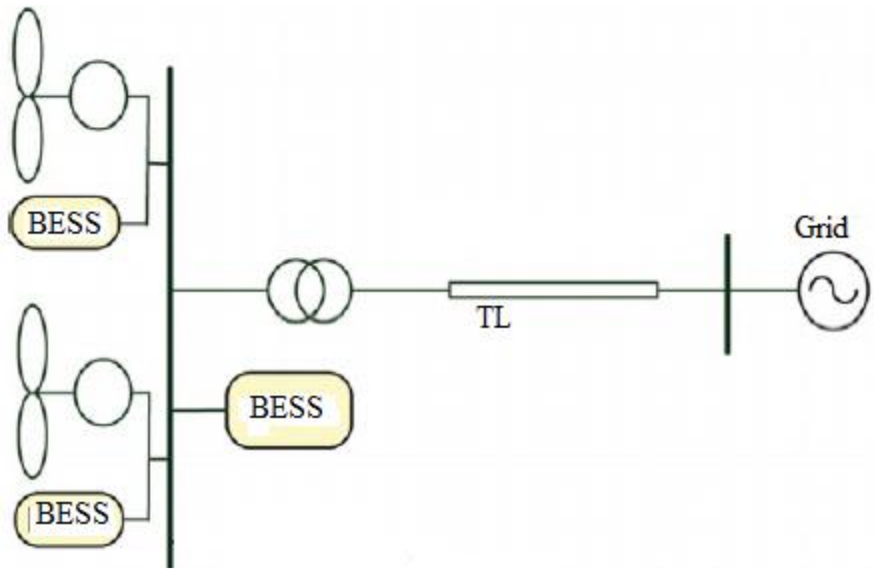


Figure 3.8. Aggregated BESS configuration (Khalid, M. and Savkin, A.V., 2014)

The third type of BESS configuration is at the point of common coupling (PCC) (Liu, Y, 2016). In this case battery bank is connected at point where many proposed wind turbines are connected to form wind farm at the PCC to send the bulky power to the grid as shown in figure 3.9

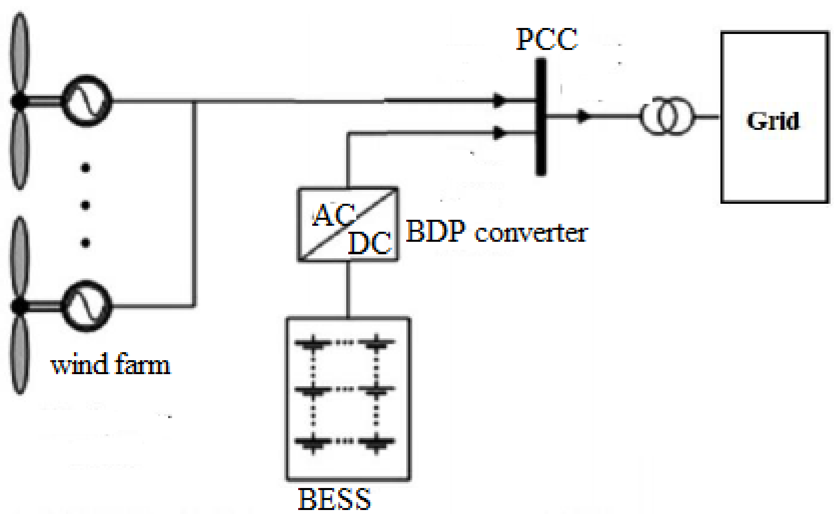


Figure 3.9. BESS Configuration at the PCC (Liu, Y, 2016)

In this research the third type of BESS configuration at the PCC is proposed. And the power produced by the BESS and the rejected Wind Generator power are both assumed to be constant during the proposed time interval. The total number of batteries, N_{bs} that should be connected in series in order to implement one battery string is determined by the DC-bus nominal voltage, Vop and the nominal voltage of each battery, Vbn:

$$N_{bs} = \frac{V_{op}}{V_{bn}} \tag{3.11}$$

The DC-bus nominal voltage is equal to the DC/AC converter DC input nominal voltage rating. The total nominal capacity of the battery bank, Cnom (Ah), depends on the nominal capacity of each battery, Cb (Ah) and the total number of battery strings forming the battery bank, nbp:

$$C_{nom} = n_{bs}.C_b \tag{3.12}$$

The battery bank is assumed to be initially partially charged and the corresponding initial capacity, Cinit, is calculated using the following equation:

$$C_{init} = \left(1 - \frac{DOD_{max}}{2}\right).C_{nom} \tag{3.13}$$

The total number of batteries composing the BESS battery bank, Nb, is calculated as follows:

$$N_b = n_{bp}.n_{bs} \tag{3.14}$$

Where PG is the peak MW generated power and t is the assumed operation time, the total battery energy storage system BESS is calculated as:

$$BESS = \frac{PG*t}{DoD*B\eta} \tag{3.15}$$

3.5 Power Converter

The battery energy storage system can be managed in a variety of ways, such as by monitoring the battery's level of charge to avoid overcharging or by preventing deep drain. In general, a battery management or charge controlling system is necessary for the battery energy storage system (BESS) to maintain optimal battery functioning and prevent battery failure (Jonas Lindstens, 2017).

Another sort of BMS is active and reactive power control, which is a decoupling method that uses the direct-quadrature, dq0, reference system to operate the inverter. This approach converts the abc-phase axes to dq-axes to control the active and reactive power separately. Converting the abc phase voltage and current into dq-axes is the initial step in the dq-decoupling system. The -frame is one method of converting abc-frame to dq-frame. After converting the abc-frame to a -frame, the -frame can subsequently be converted to a dq-frame. The dq-frame, as well as the -frame, are two-dimensional frames that are used to make analysis and control easier.

In the proposed PQ battery power charging control for battery energy storage system, the calculated value for active and reactive power are compared to the reference values from the wind farm.

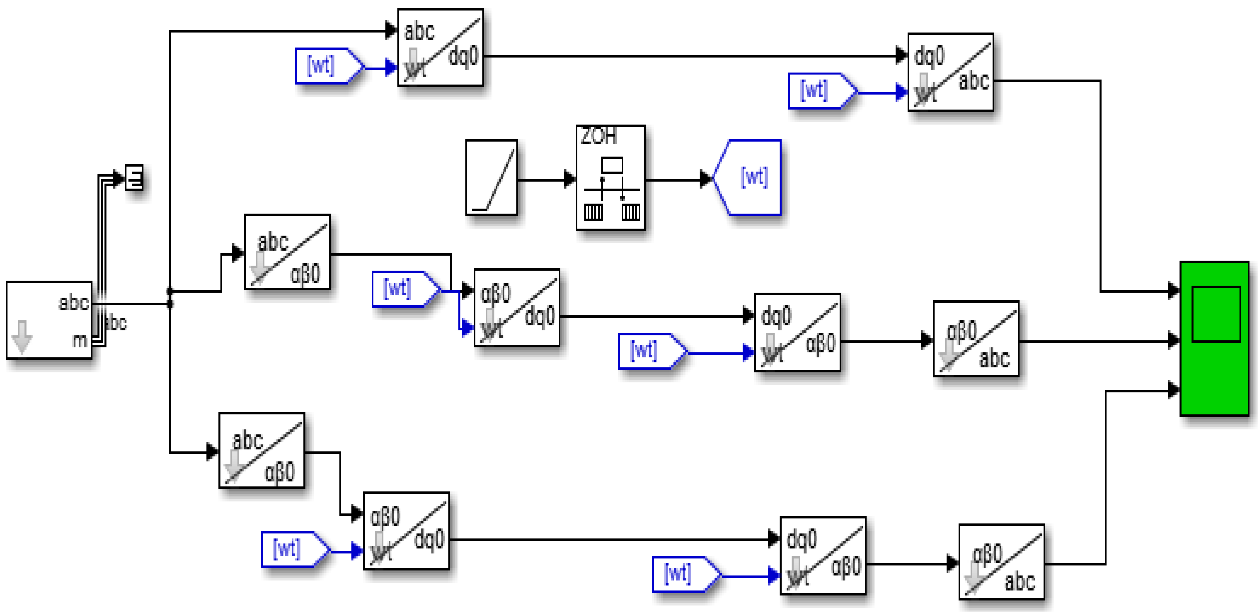


Figure 3.10. d-q power conversion scheme

The total number of DC/AC power converters, Ni, required to implement the BESS scheme under consideration is calculated according to the guaranteed power value, PG (W) and the nominal AC power rating of each DC/AC converter, Pnom:

$$N_I = \frac{F_o.P_G}{P_{nom}} \tag{3.16}$$

where F_o = 1.2 is an over-sizing factor, which is incorporated in order to enhance the power converter reliability in case of increased operating temperature conditions, while simultaneously provides the capability to cover the electric-grid load variations for small time intervals

CHAPTER FOUR
RESULT AND DISCUSSION

4.1. Introduction

This thesis is aimed to model battery energy storage system for wind farm to smooth wind power fluctuation of Adama wind II. In power system configurations the potential sitting of battery energy storage system is heavily dependent on topographical Condition and the installation flexibility. For wind power dispatch purpose, the potential siting is not only within a wind power plant, but also at other locations in the power system for additional benefits, like deferring or avoiding capacity and transmission upgrade, reduced transmission and distribution losses and more robust system stability. For on-site installation of ESS within a wind power plant, ESS can be either placed at Point of Common Coupling (PCC) or equipped with WTGs. The PCC configuration is adopted by the most as hybrid wind power plant with energy storage system. In the latter configuration each wind turbine is equipped with a supercapacitor-based energy storage system connected to the DC link of back to back converter. This scheme enhances the control flexibility of each wind turbine. However, due to the smoothing effect on power fluctuations of distributed wind power plants over large geographic areas, the requirement of power and energy rating is high and not cost-effective.

In this research the Battery Energy Storage System (BESS) is proposed to be connected at the Point of Common Coupling (PCC), as per for each 8 cluster of Adama Wind Farm II. Cluster /group 1 contains 11 number of Wind Turbine. The left 7 cluster contains 13 number of Wind Turbine and for these group same MATLAB Simulink was modeled for simplicity. The MATLAB Simulink modeled for each cluster or Wind Turbine group connected with and battery energy storage system is shown in figure 4.1 and 4.2 and its controller Simulink model is shown in figure 4.7. The output power, voltage and current of each wind farm clusters are indicated in the figure 4.3 to 4.6

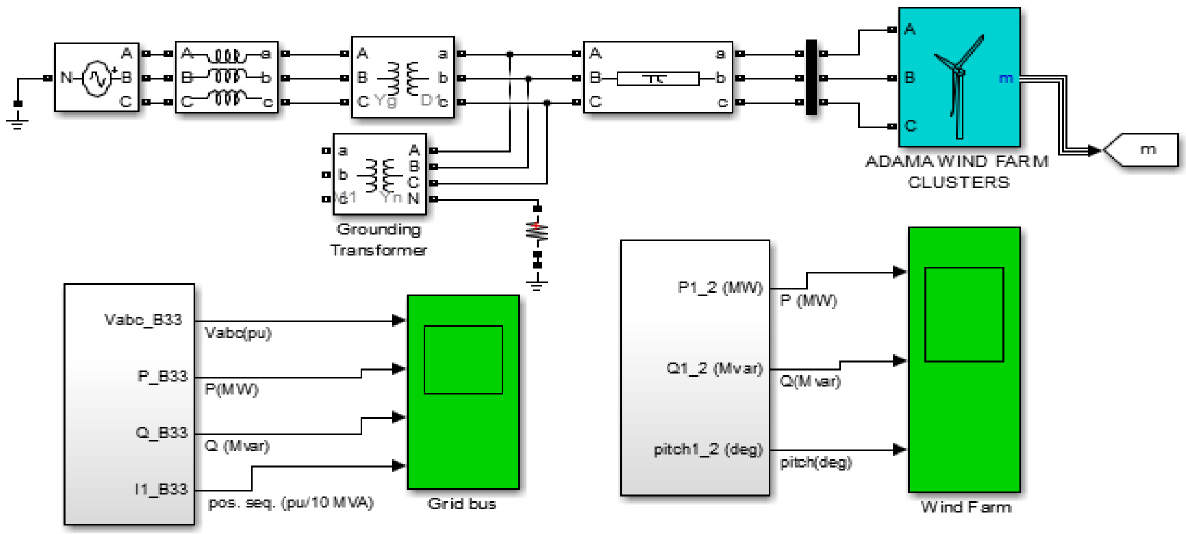


Figure 4.1. Simulink model of Grid connected Adama wind Farm II

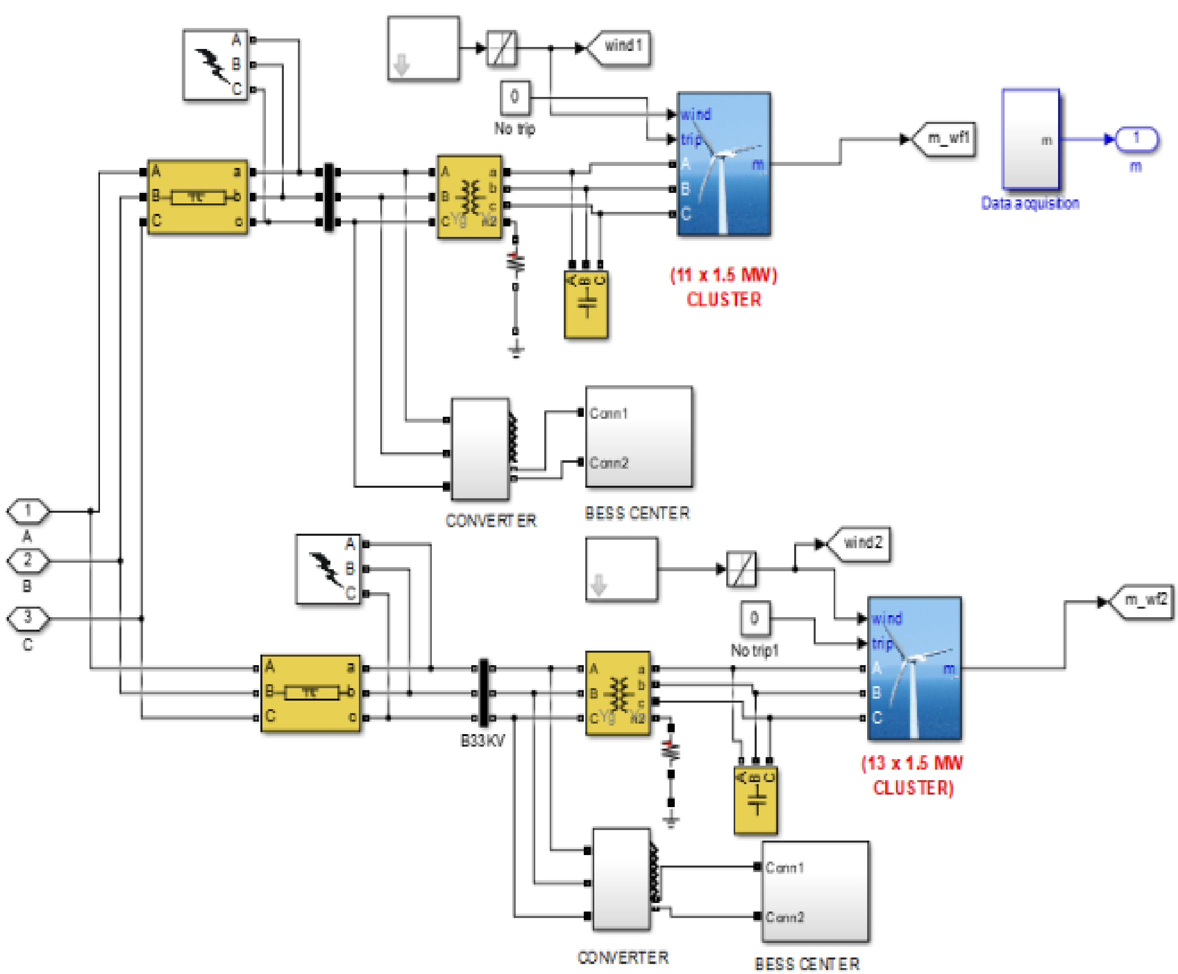


Figure 4.2. Simulink Block of proposed Grid connected Adama wind Farm II with BESS

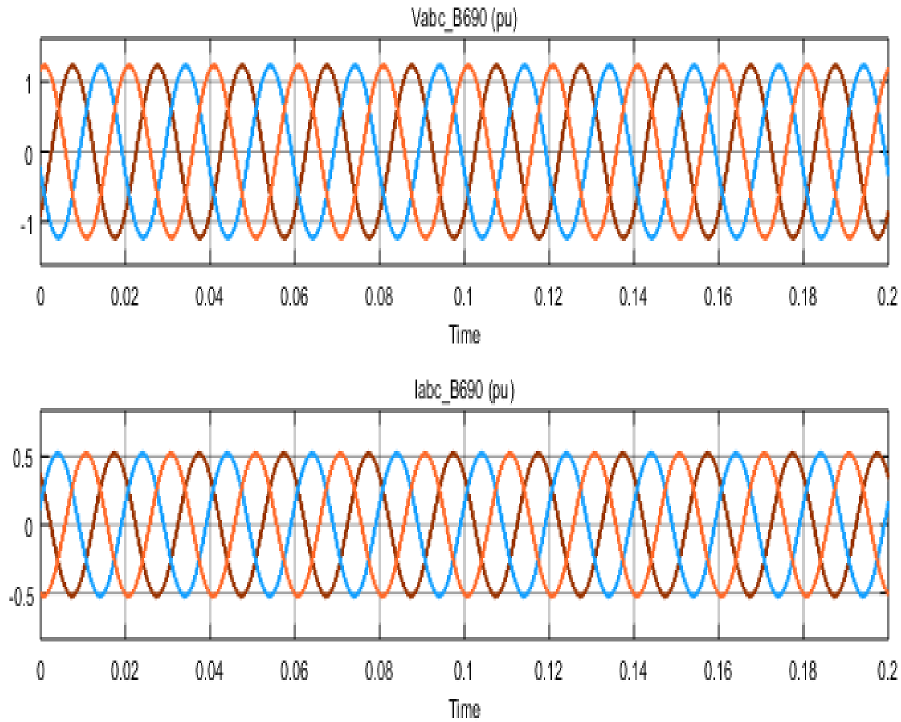


Figure 4.3. Generator side voltage and current output

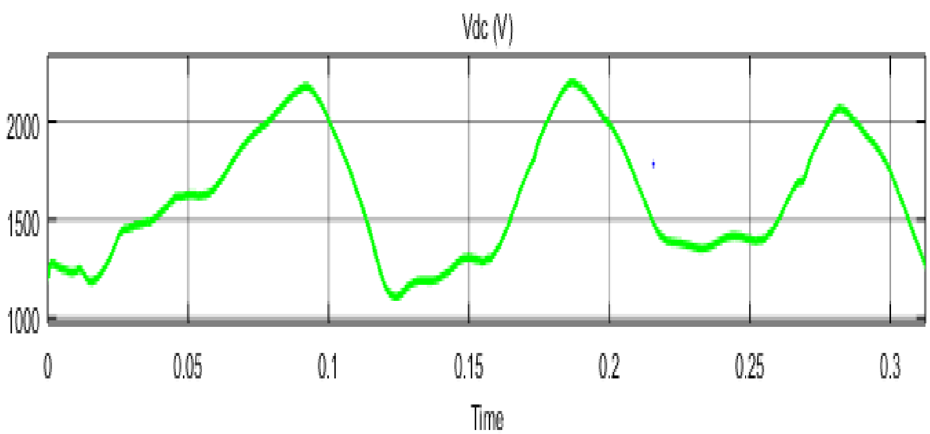


Figure 4.4. DC link voltage of Cluster one WF

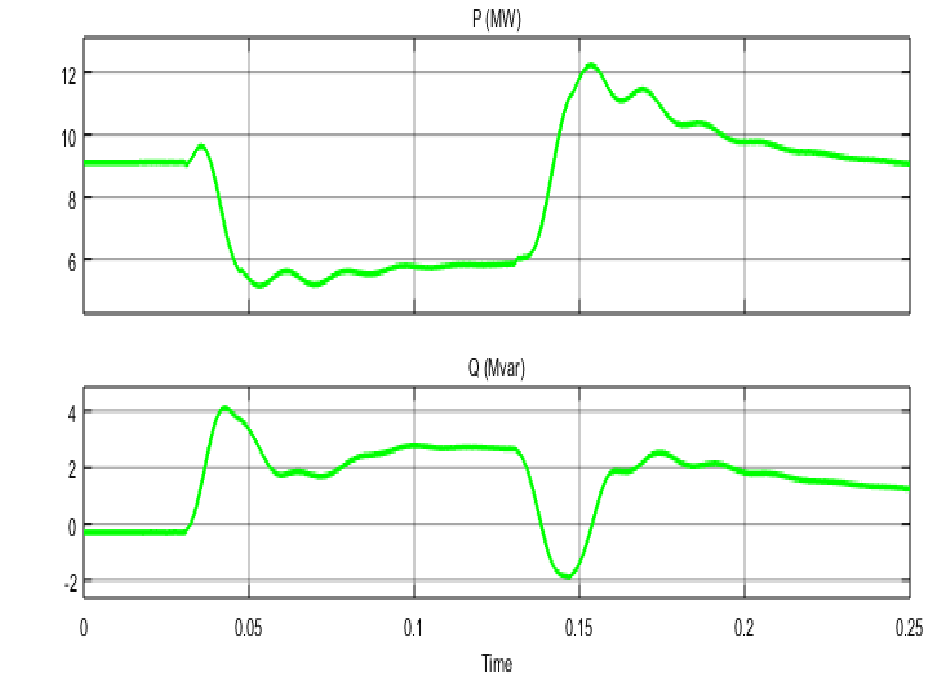


Figure 4.5. Real and Reactive power of cluster one WF

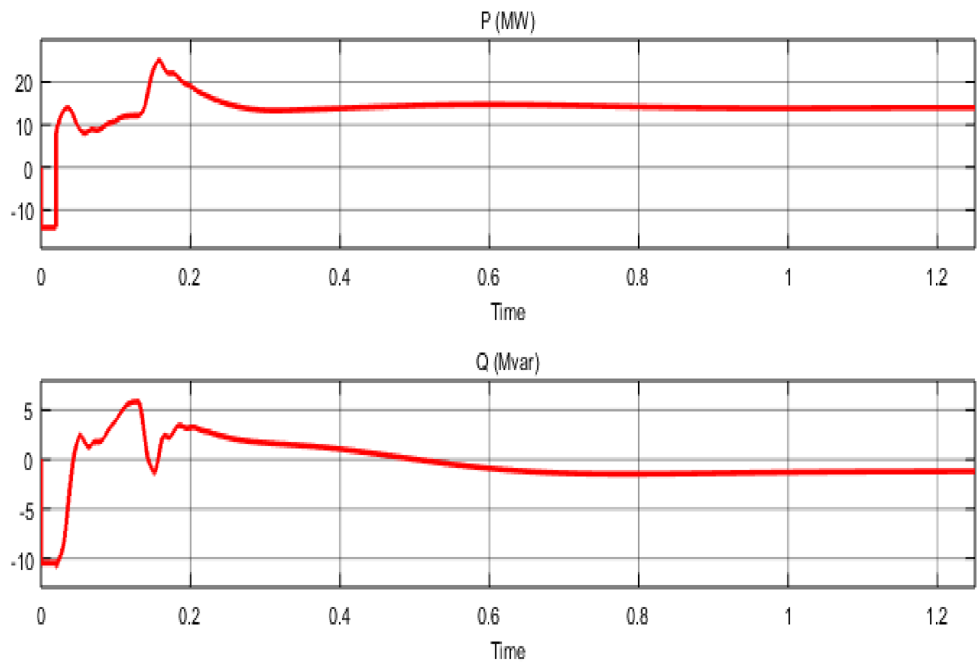


Figure 4.6. Real and Reactive power of WF cluster of containing 13 WT

The BESS is fed to grid connected wind farm through three phase bidirectional converters. The power converter act as an inverter to transmit power from DC to AC, and it acts as a rectifier to transmit power from AC to DC. The power converter can be controlled to operate at delivering or absorbing the power.

In the proposed method, the system operation is simulated for one year with a time step of 15 minutes. In first WF cluster of containing 11 WT, a 11 *1.5 MW wind farm connected to grid of 80 km long TL with 33kV TF is modeled. This energy storage system consists of the capacity of 9.7 MWh.

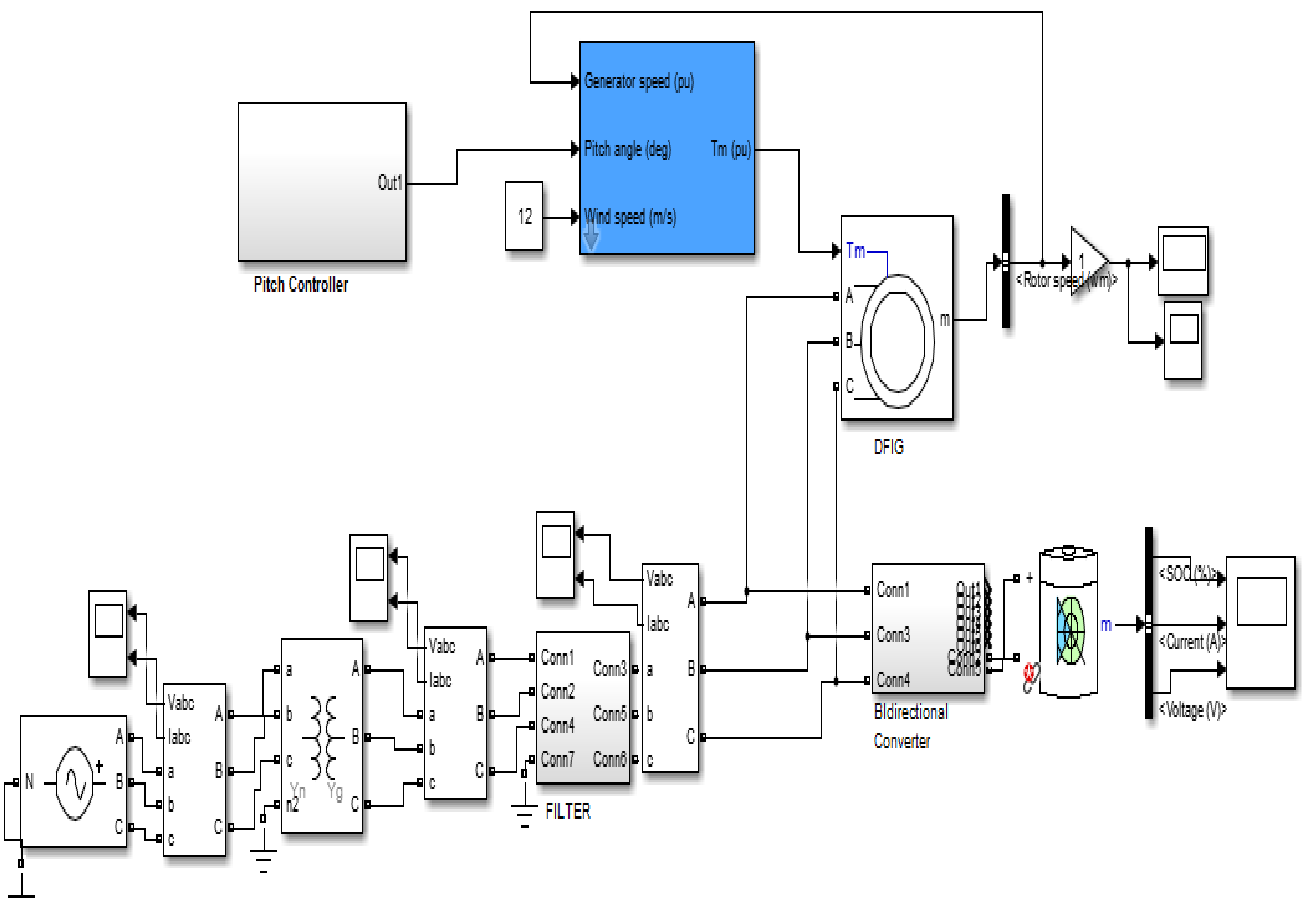


Figure 4.7. Simulink model of proposed system with FPID controller

Similarly, in the left of seven WF cluster of containing 13 WT, a 13 *1.5 MW wind farm connected to grid 80 km long TL with 33kV TF is modeled. This energy storage system consists of a total capacity of 11. 47MWh.

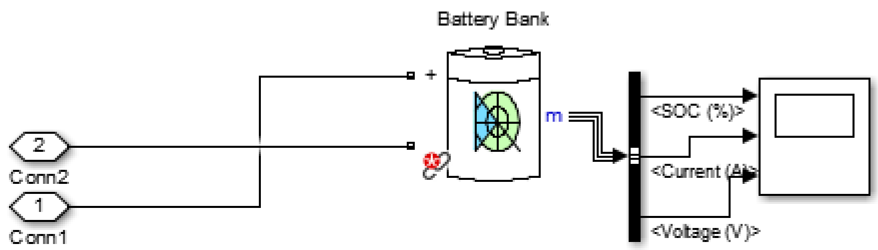


Figure 4.8. BESS subsystems

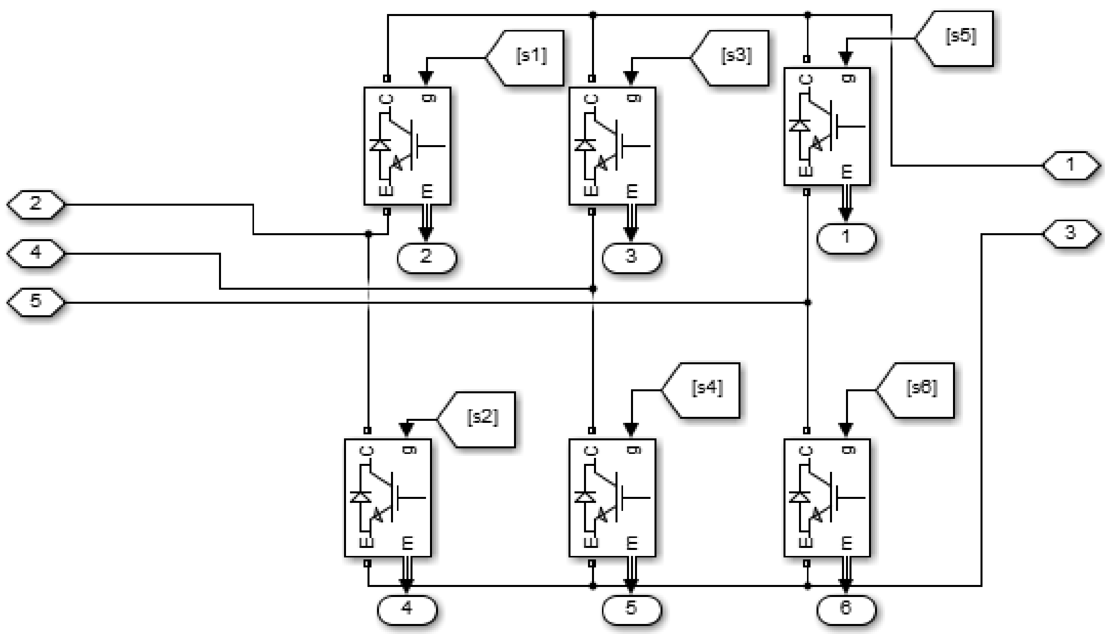


Figure 4.9. Inverter subsystems

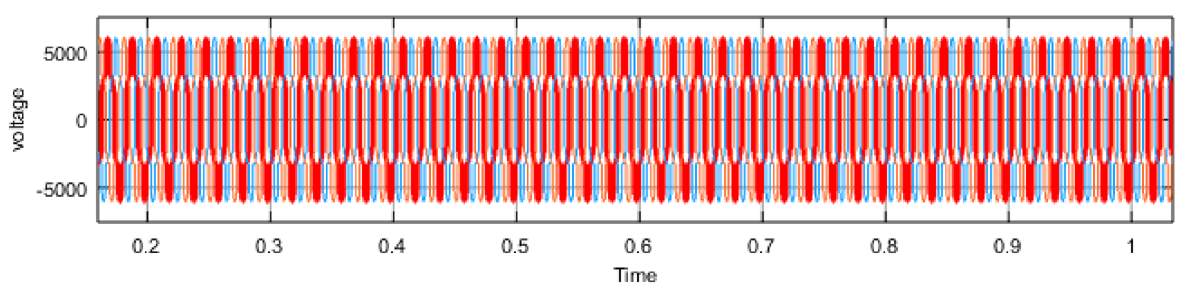


Figure 4.10. The converter output before

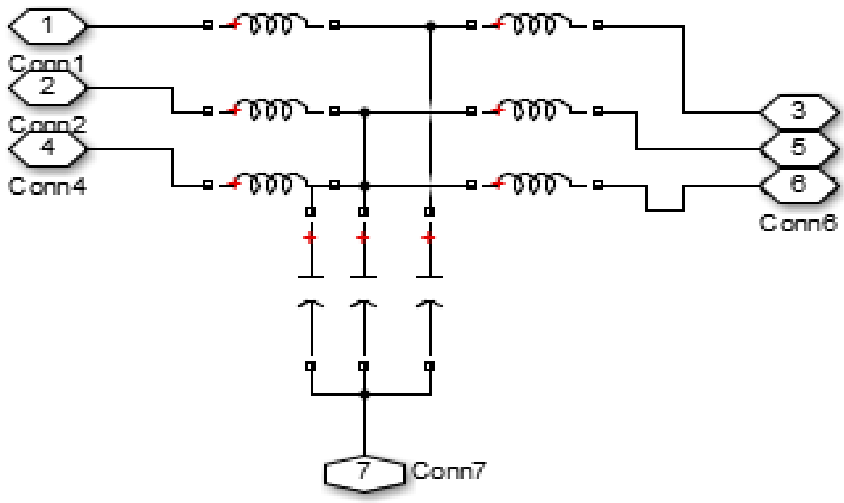


Figure 4.11. Filter model subsystem

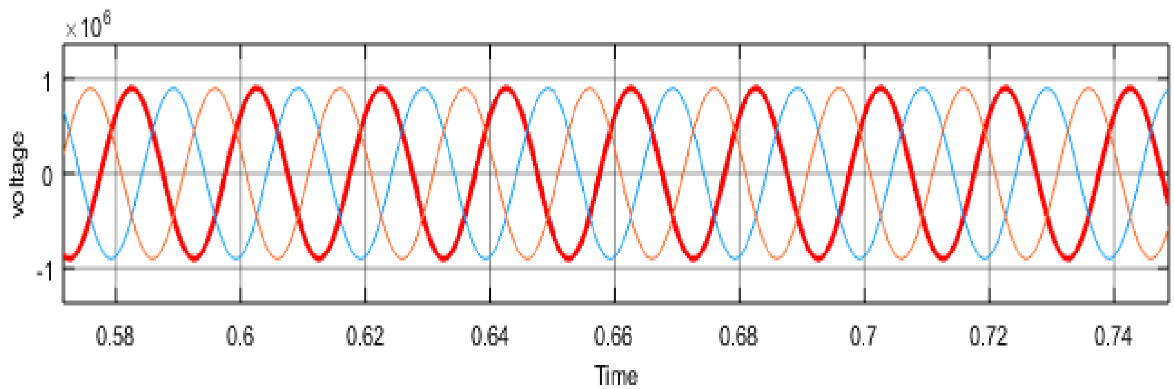


Figure 4.12. The converter output after filter

4.2. BESS Charge Controlling System

The control system proposed in this paper is classified in to charge and discharge battery control system through bidirectional inverter, and wind power controlling through pitch angle control. To compensate with the DC voltage requirement of battery, buck boost converter as per DC part of bidirectional converter was modeled and the pulses are created from the abc-frame signal created in the control system. The PWM control the inverter in which way it should convert the power. The PWM-pulses consist of ones and zeroes that switches the IGBTs off the inverter on and off. The output of this transformation is shown in figure 4.13

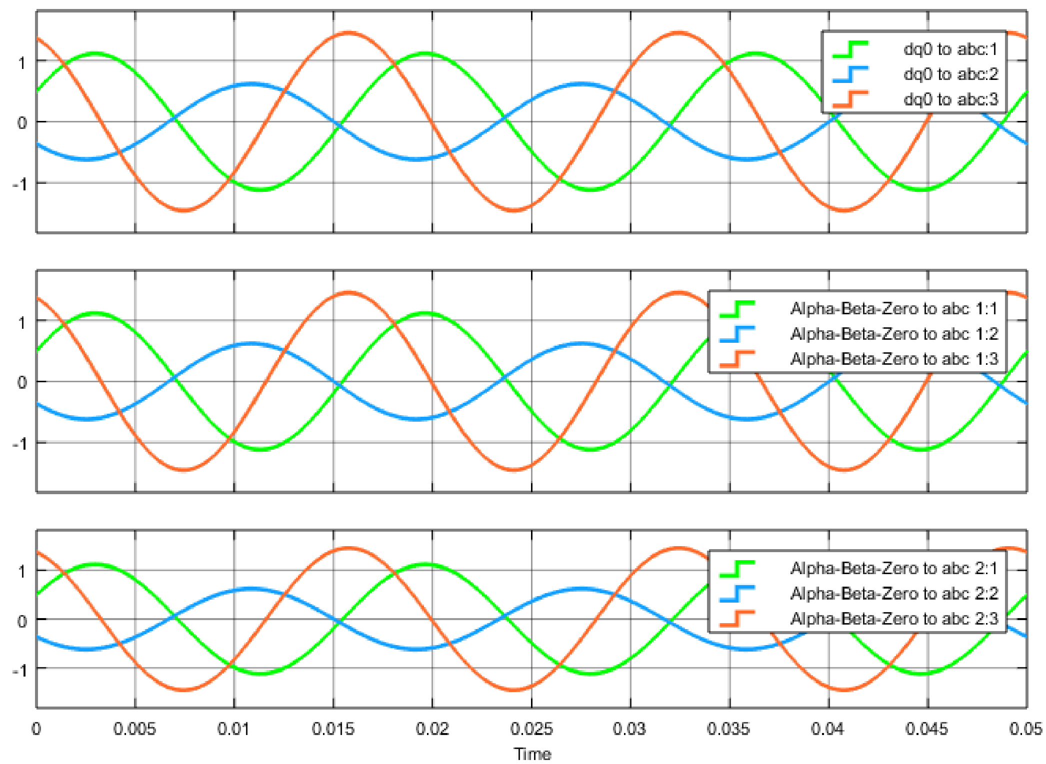


Figure 4.13. Three phase d-q power conversion scheme output

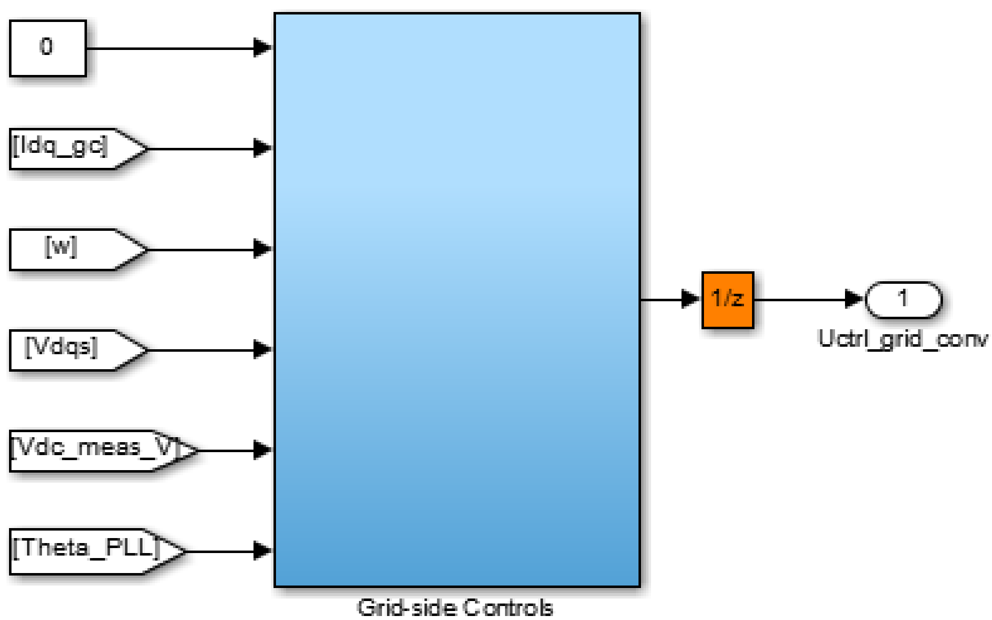


Figure 4.14. Simulink block for the grid-side converter control

In case of grid side, the main purpose of the grid-side converter the controller is to stabilize the DC link voltage at its nominal value and also to ensure that the active power generated by the generator is fed to the grid where the capacitor voltage always varies during wind turbine operation

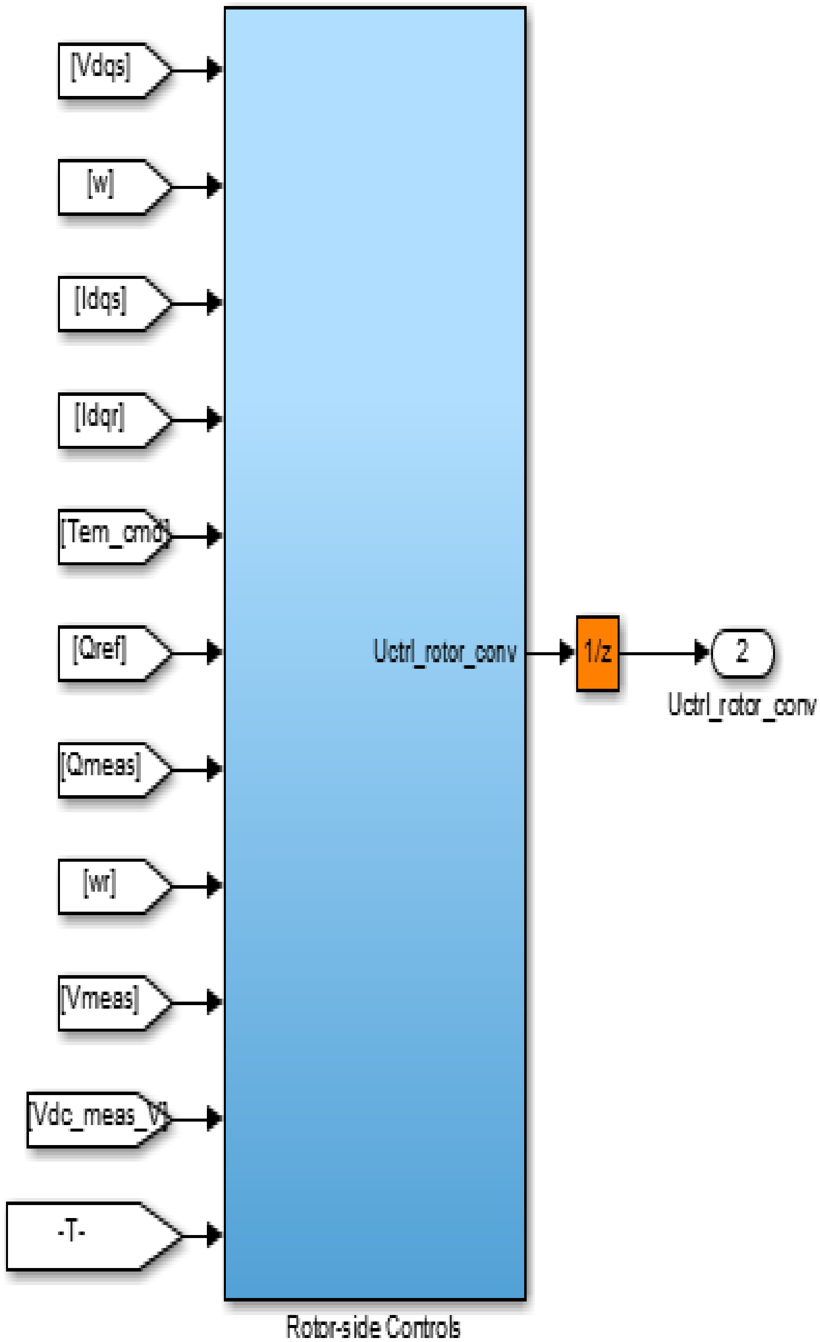


Figure 4.15. Simulink block for the rotor-side converter control

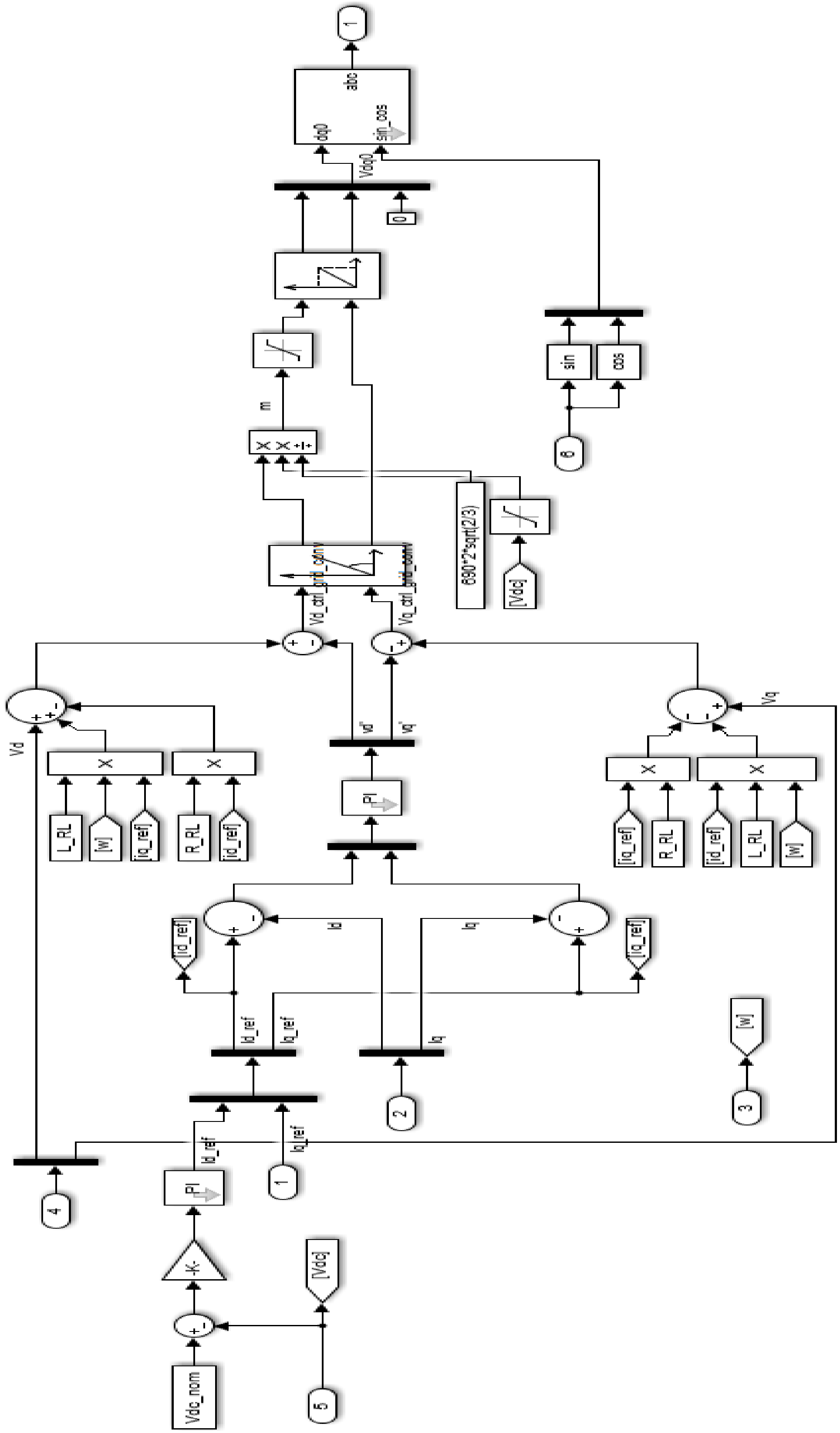


Figure 4.16. Simulink model for the grid-side converter control

The generator-side controller is mainly used to control the wind turbine shaft speed in order to maximize the output power. In a variable speed wind energy conversion system, the maximum power at different wind speeds depends on the power coefficient. To obtain the maximum power, Pmax from the wind turbine and if the wind speed varies, the rotor speed should be adjusted to follow the change of the wind speed. The generator speed control is typically accomplished through the generator-side converter. Hence, the control of the generator-side converter allows the generator to tune the rotational speed depending on the incident wind variation in case fuzzy PID controller was used and this result is shown in figure 4.20. In pitch angle of the wind the FPID controller was modeled and its subsystem is shown in figure 4.17

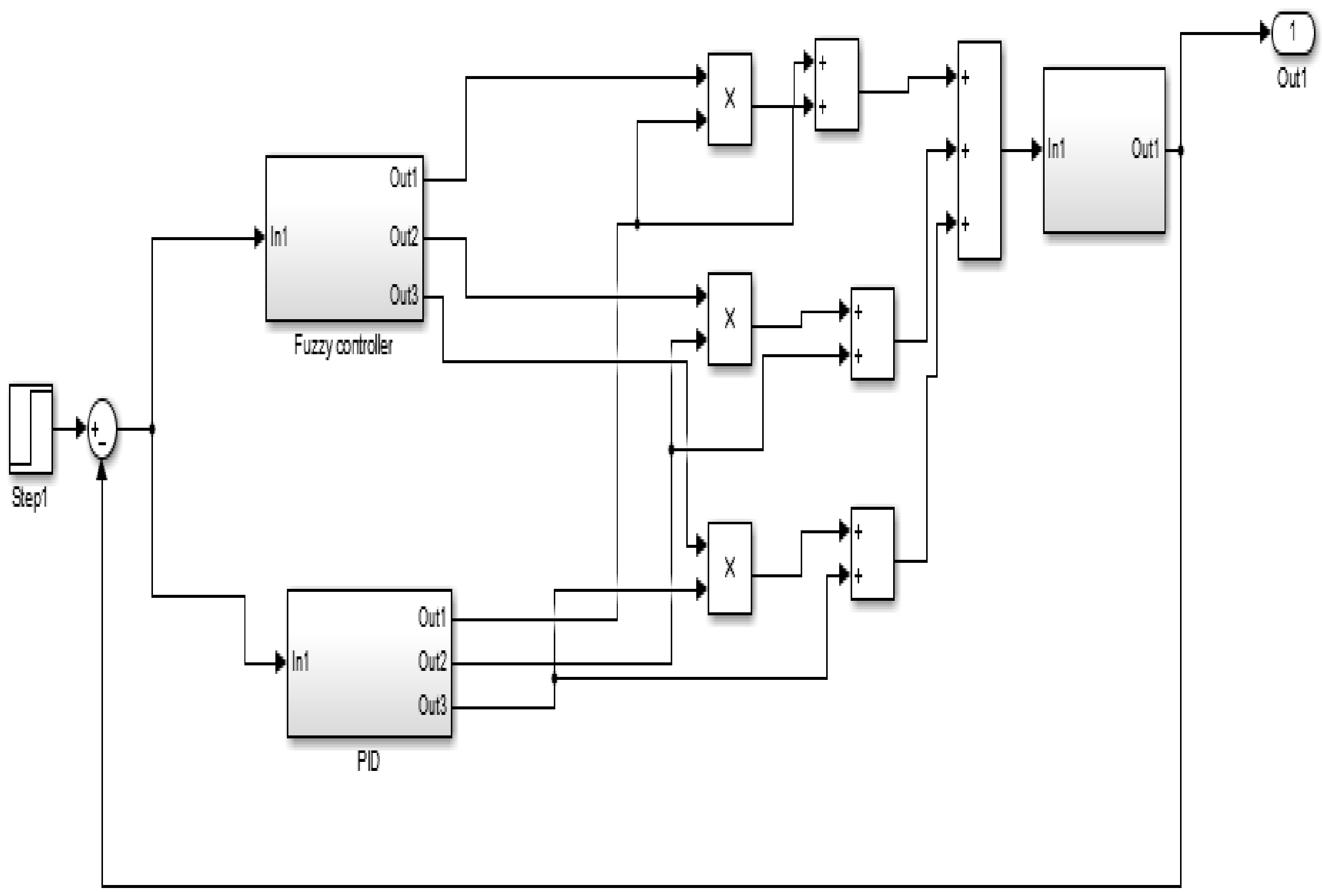


Figure 4.17. Pitch controller Subsystem

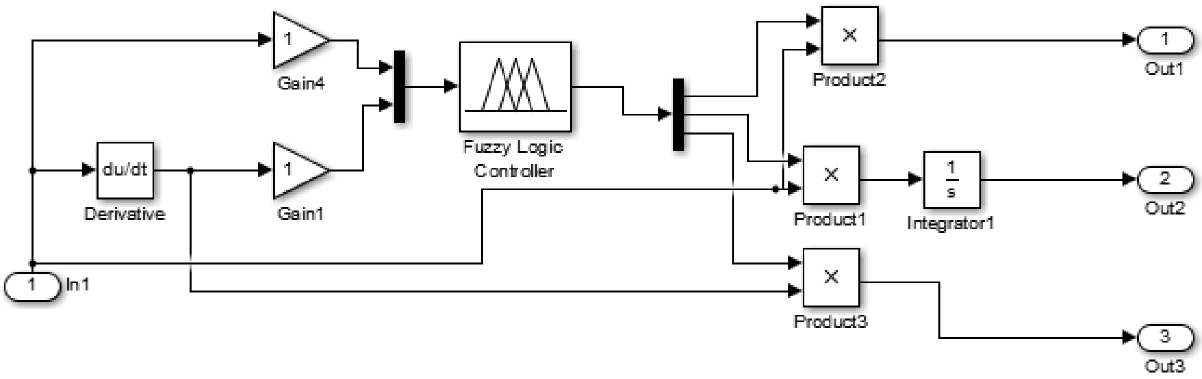


Figure 4.18. Fuzzy controller subsystems

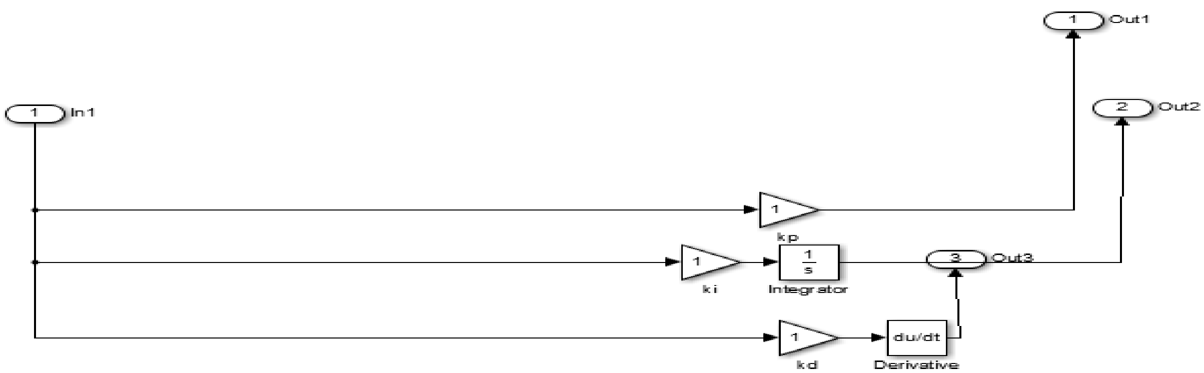


Figure 4.19. PID Controller Subsystem

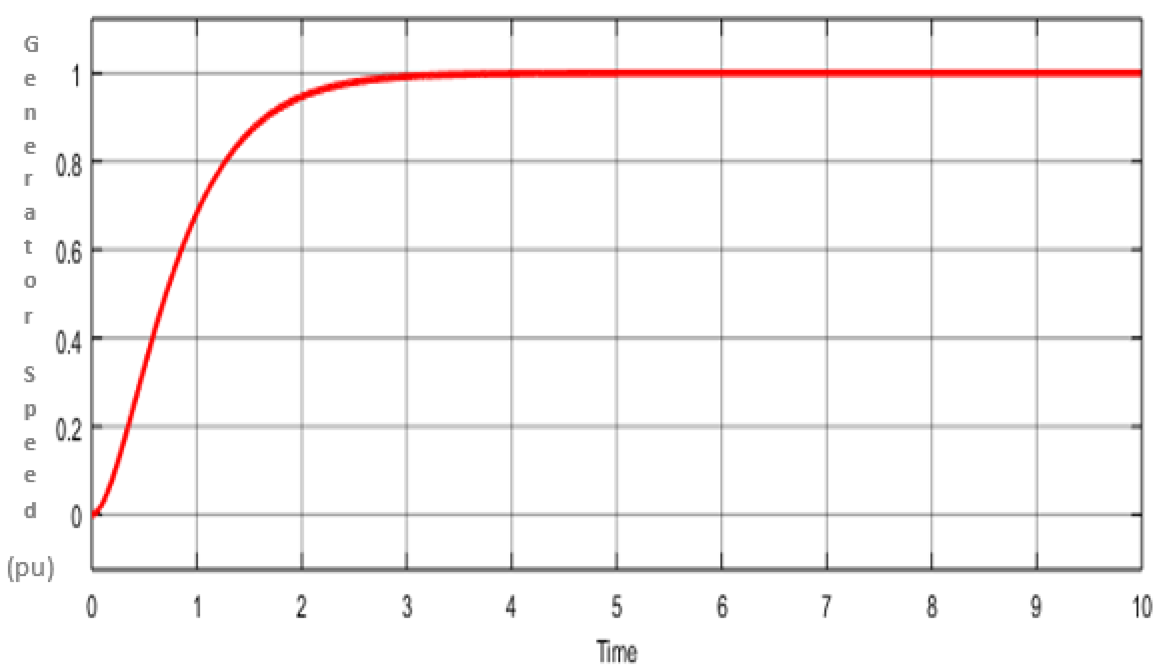


Figure 4.20. FPID MPPT Controller Output

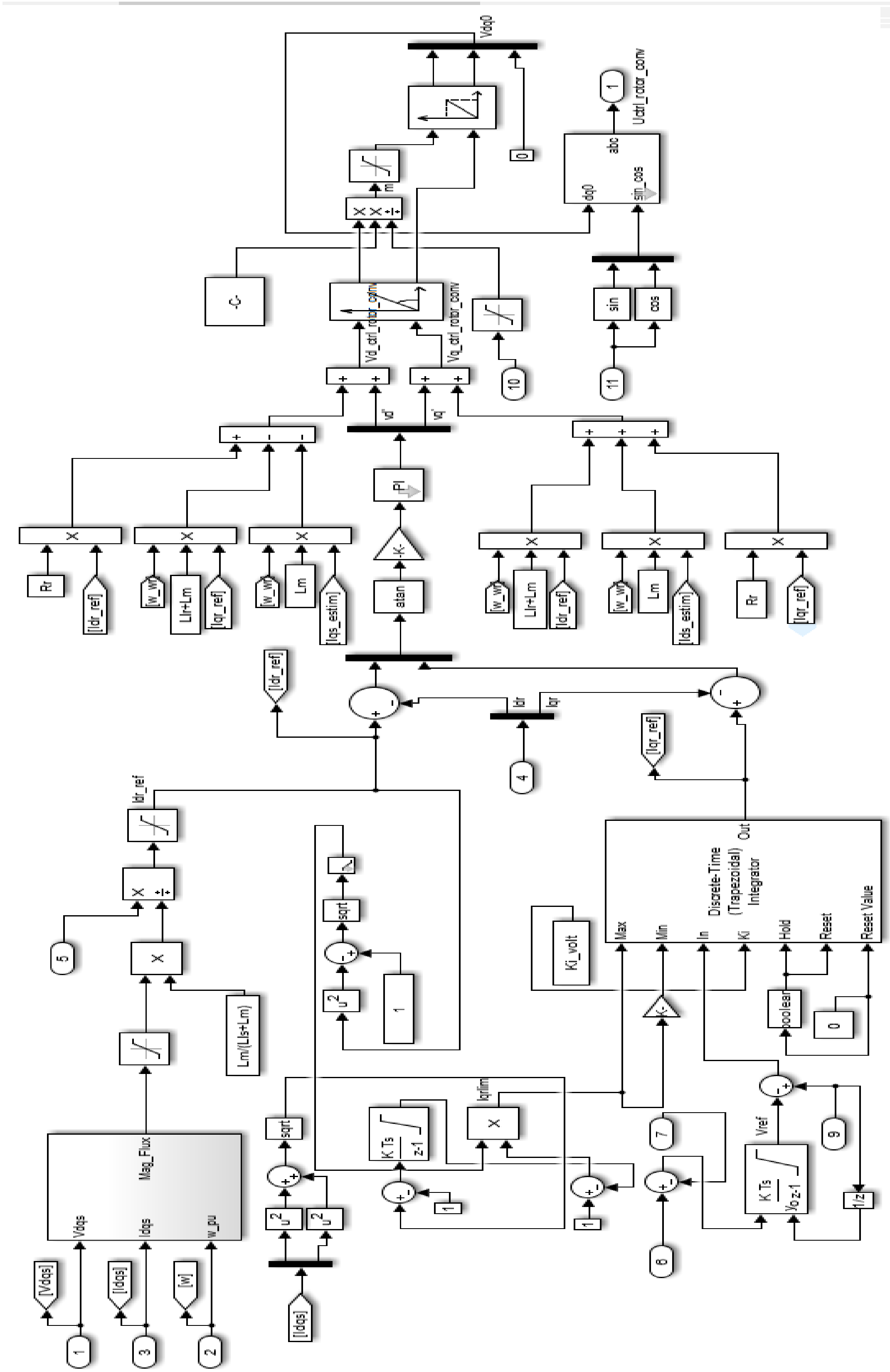


Figure 4.21. Simulink model for the rotor-side converter control

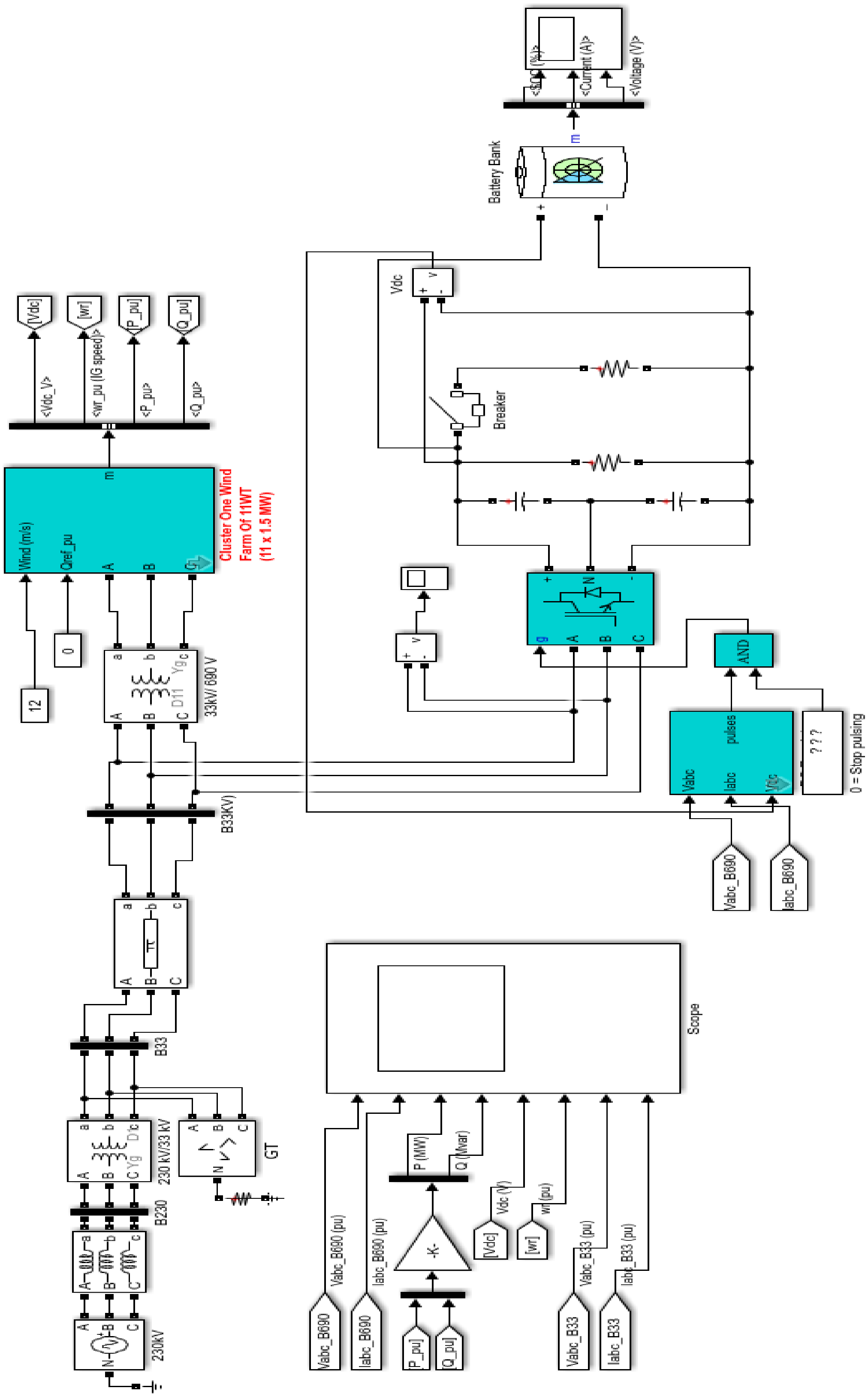


Figure 4.22. Grid connected battery converter controller Simulink

DC Regulator subsystem Simulink model from the system modeled in the above diagram of the grid connected wind farm with battery energy storage system is used to control the DC voltage and current of the battery. And its Simulink block diagram is as of figure 4.23 below.

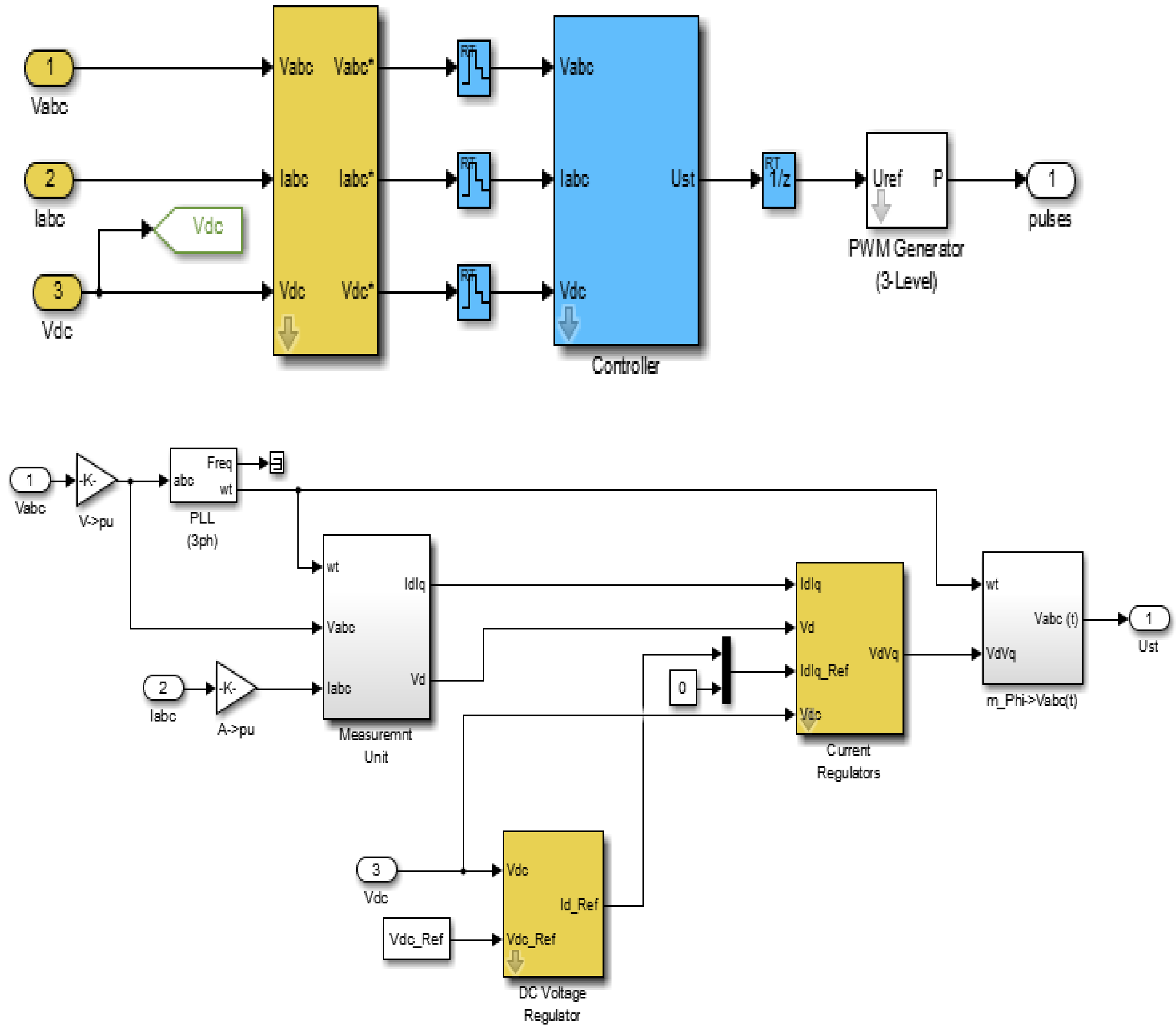


Figure 4.23. DC Regulator subsystem

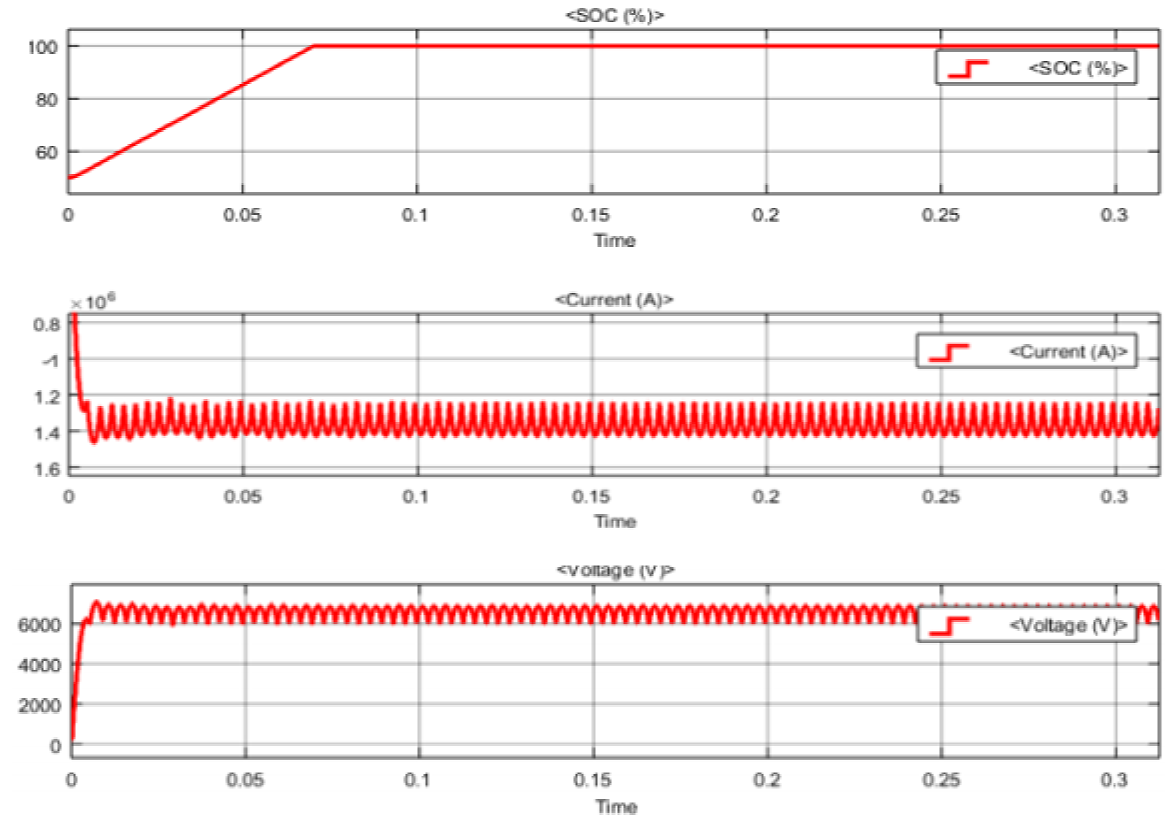


Figure 4.24. BESS charging characteristic

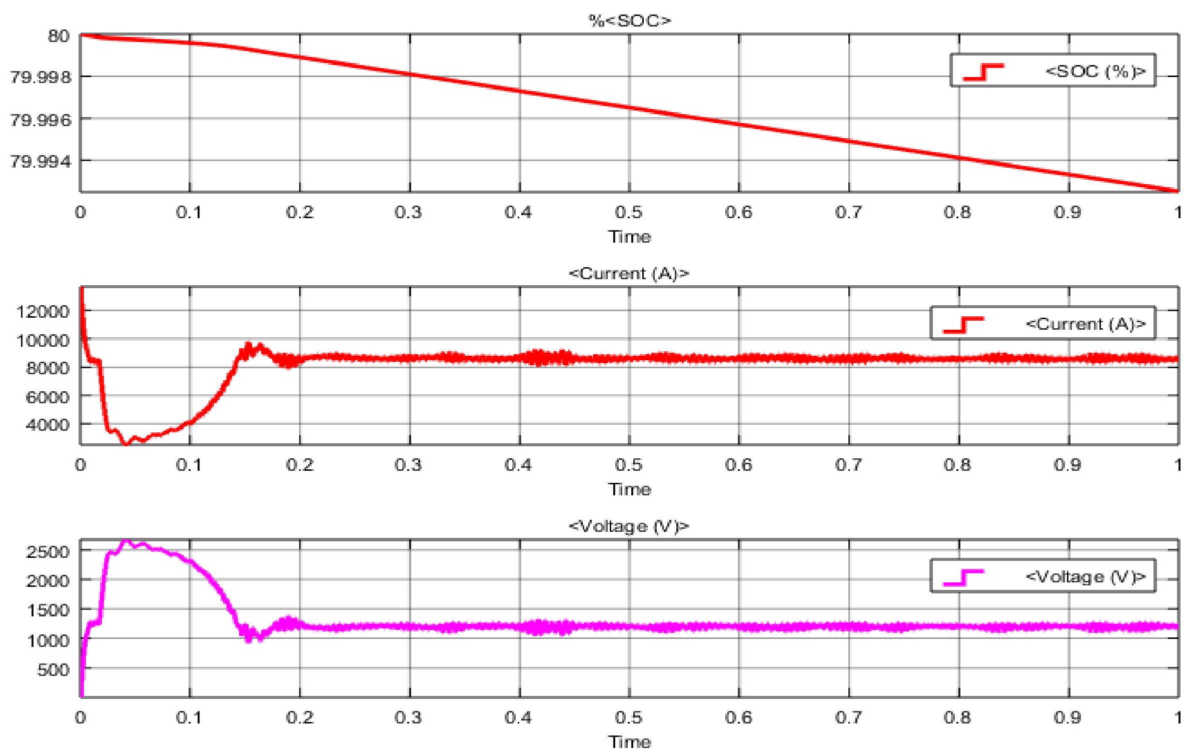


Figure 4.25. BESS Discharging characteristic

4.3. BESS Load flow

As shown from figure 4.26 below the BESS stored energy for each of wind plant clusters in the interval of 15 minutes which is taken as reference of system modeling and power deliver to the gird when the system power is below expected/reference one.

The SOC must equal 1 and be prepared to load energy according to demand once the BESS is fully charged. The charge status is gradually decreased until it reaches zero, at which point electricity is sent to the load. Before the demand for the load or the battery is fully depleted, the SOC is expected to be 0.713 out of 1, and it drops over time.

If the battery is not completely charged (SOC 1), the BESS can only use active power. Additionally, the BESS can only provide active power when the battery is fully charged (SOC > 0). Therefore, if the SOC falls below a particular point, the battery needs to be recharged.

As a result, the BESS is capable of dual active power control. The combined output of active and reactive power shouldn't be greater than the power that appears to be rated**.** So either the active or reactive power needs to have a priority. From a charge controller's perspective, every need was met. For the purposes of the results, it was assumed that the SOC was a signal. The battery voltage and current can also be used to compute the SOC. It is advised to divide the entire controller into smaller portions for a better overview.

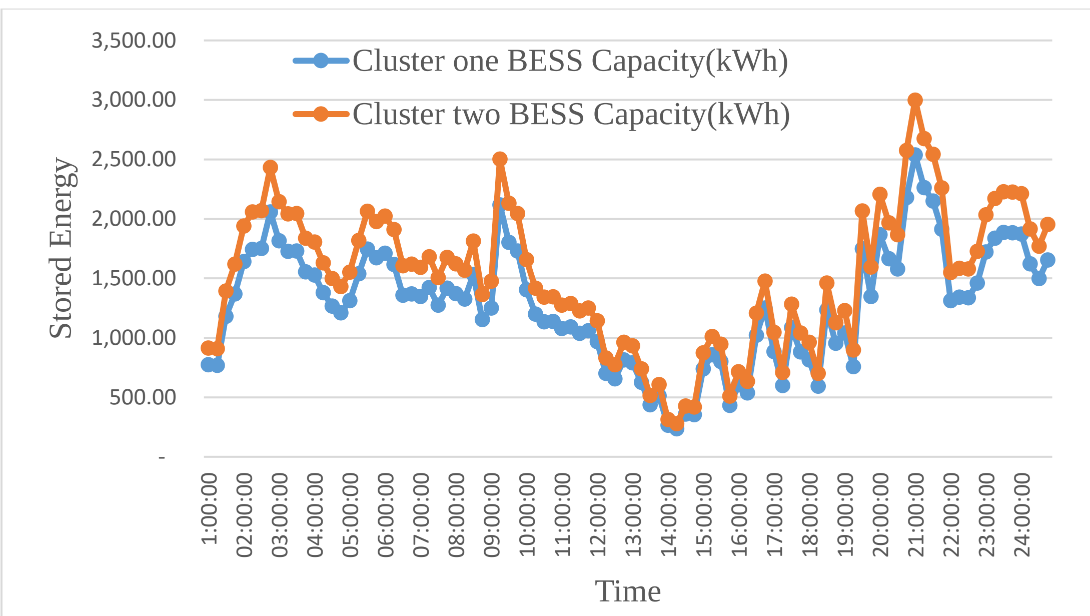


Figure 4.26. Energy stored capacity for every 15minute

4.4. BESS Economical analysis

To compensate the amount of energy rejected during the low wind speed the amount of energy stored by batteries determines how much energy can be used, in particular when there is very little wind. In this research the lifetimes of deep cycle of selected lithium-ion battery are 15 years, and their cost per kWh is 26,500ETB. As a function of energy stored the cost of batteries becomes energy stored in kWh times ETB per kWh.

For primary investment of battery energy storage system, the capital cost or fixed one-time expenses incurred on the purchase of devises is consisted two parts: cost of power converters and battery banks cost. The capital cost of selected power converter is 132,500ETB per kW power. The economic initial required investment of Battery Energy Storage (BESS) integration with Adama II wind power plant is concluded as 2.014bill ETB.

The kWh capacity which can be stored is determined by the number and type of batteries included in the system:

$E_{stored\ kWh}$ =number of batteries*kWh energy per battery

CHAPTER FIVE

CONCLUSION, RECOMMENDATIONS AND FUTURE WORK

5.1. CONCLUSION

In this thesis work the analysis and modelling of battery energy storage system for smooth wind power fluctuation in the case of Adama-II wind power plant is studied. Based on the extracted 15minute annual daily average wind power fluctuation data of each wind turbines in the respective clusters, the Battery Energy Storage capacity is modeled for each wind turbines group or clusters at the point of common coupling and it could be concluded that the modeled battery power could compensate the wind power fluctuation or the rejected wind turbine in each groups for every 15minute per day in the year during discharging phase of battery banks; and for the excess power production from the wind farm it could be stored to BESS through the power converter.

Accordingly, the required BESS capacity that should be integrated at the PCC for the first Wind farm cluster with 11 wind turbines, contains 4 parallel connected battery string with total energy of 9.7MWh for every 15 minute per day, similarly for wind farm clusters with 13 wind turbines 11.47MWh BESS containing 6 parallel connected battery string is required. Totally for smooth wind power fluctuation of Adama II wind power plant it is concluded that 77.95MWh of energy from BESS of containing 46 parallel battery string of the selected packed lithium-ion battery bank is required.

To implement this integration of Battery Energy Storage (BESS) with Adama II wind power plant the economic initial required investment is concluded as 2.014bill ETB.

5.2. RECOMMENDATIONS

For further study the following recommendations are drawn:

The implications of other control systems for the BESS to develop battery charging and discharging management system and to see Steady state and dynamic performance analysis of the overall system.

Even after the implementation of this project, other researcher further Study the intelligent system economic and sizing optimization methodology to model battery energy storage system for wind farm and other distribution grid and to optimize and control the needed energy storage capacity for the system.

Also, the integration of BESS to different placement in more complex distribution system with more power lines could also be studied to observe the grid power stability and other control the possibilities of the overall system.

5.3. FUTURE WORK

Additional work is needed in the field of energy management, specifically how the energy flow is managed for battery storage devices. When the storage element reaches the upper or lower limit, this becomes especially clear. Once the storage device is getting close to its lower limit, reducing the reference power will probably yield the best result. The output power reference should also be increased as the maximum storage capacity is approached. These minor modifications to the basic control scheme can be used to increase the system's remaining duration under normal operation. Additionally, the transition between the stages of operation will probably be more seamless, which will help the system operate better all around. These thesis might be proved for a single wind farm and then expand this battery storage system to the more complex example of a wind farm where further techniques could be needed to fully realize the advantages of battery energy storage.

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APPENDIXES

Appendix A: Technical Specification of Adama II Wind Generator

Table A.1 YSK15-04A generator Technical Specifications

Type	**YSK15-04A**
Rated power/kW	1560
Poles	4
Voltage/V	690
Rotor voltage of open circuit/V	1650
Frequency/Hz	50
Rated speed/ rpm	1800
Speed range/ rpm	1000-2000
Factor of rated power	1.0
Rated efficiency	96.5%
Factor	0.95cap.-0.95ind.
Connection(stator/rotor）	△/Y
Insulation class （stator/rotor）	H/H
Noise level/db（A）	≤90
Moment of inertia/kg·m2	67
Cool method	IC616
Mounting designation	IMB3
IP class	IP54（slip ring IP23）
Duty	S1

Rotating direction	Clockwise （view as DE）
Ambient temperature/℃	-40～+50
Relative humidity	≤95%
Max altitude/m	≤3500
Weight/kg	≤6500
Design life/year	20

Appendix B: Wind Turbine, DFIG and Excitation circuit Parameter

Table B.1 Wind Turbine Parameter

Parameters	Values (Units)
Rated generator power	1.5MW
Rated generator speed	1800rpm
Rated rotor speed	17.21rpm
Rate of change of p. angle	0.7deg/sec
Control accuracy of p. angle	0.43deg
Damping ratio	2.5Nm/rad/sec
Drive train inertia	$0.64Nm^2$
Wind turbine Rotor inertia	$0.8\ Nm^2$
Total friction	3 Nm/rad/sec

Table B.2 DFIG Parameters

Rated Power	1.5MW
Rated Voltage	690V
Stator Resistance	0.01pu
Stator Leakage Reactance	0.15pu
Magnetizing Reactance	3.5pu
Rotor resistance	0.01pu
Rotor leakage reactance	0.15pu

Table B.3 Parameter of Excitation circuit of DFIG

DC link voltage	1.5Kv
DC link capacitor	50,000micro F
Power converter device	IGBT
PWM carrier frequency	2 kHz
Upper limit DC voltage	1.8 kV
Minimum DC voltage	0.75 kV

Appendix C: Lithium-Ion Battery and RIU Energy Storage Inverter

The grid-level energy storage system is critical for balancing power generation and use during the electrical energy transformation process. Because of their quick response time, modularity, and adaptability in installation. The use of batteries in grid-scale energy storage systems has a lot of promise (Jonas Lindstens, 2017). Lithium-ion batteries (LIBs) are a type of battery that has a high energy efficiency, a long cycle life, and a high energy density. Table C.1 below shows the attributes and parameters of a particular LIB in this context.

Table C. 1 Lithium-Ion Battery Parameters

Voltage class	1500V
Battery chemistry	Lithium Ion
Energy capacity (Kwh)	2100
Maximum Power (Kw)	1200
Maximum dc current	800A
Nominal DC voltage	1100V
Minimum DC voltage	600
Individual battery packs	20

Inverters are a bidirectional system converting AC to DC for battery charge and DC to AC for discharge.

Table C.2 RIU Energy Storage Inverter Parameter

Nominal Power	500KW
Rated AC Operation Voltage	10-35 KV
DC Input Range	600-1500V
Maximum DC current	15KA

Appendix D: Adama II Wind Power Plant 33/230KV Substation Single Line Diagram