

Islanded Operation of Wind Turbine with Solar Power and Battery Storage

A Step towards Fossil Free Energy

Master's thesis in Sustainable Electric Power Engineering and Electromobility

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Gothenburg, Sweden 2024

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Abstract

This master's thesis provides a thorough investigation into the utilization of wind power in islanded operation along with solar power and power from energy stored in the battery. The data for wind speed and solar irradiance is taken from the Chalmers research wind turbine located at Björko. The research work uses MATLAB Simulink software for mathematical modelling and simulations. The wind turbine and solar panels models are designed according to real data of wind speed and solar irradiance for 24 hours and for 1422 seconds. Considering the load profile of an island, a battery model is designed indicating charging and discharging of the battery. A controller is also designed which makes decisions based on available power source and load to control the islandic operation. Different scenarios at different load conditions are studied to validate the results. The analysis and performance evaluation for islandic operation is carried out, considering various factors such as load consumption and power generation from available sources. After analysing the simulation results of wind, solar, battery models under variable load conditions, the performance outcomes and their accuracy is discussed. The designed system for islandic operation demonstrated and confirmed the efficient utilization of power from available resources for every instance over a period of 24-hours and a period of 1422 seconds.

Keywords: wind turbine, solar power, battery storage, islandic operation, mathematical models, Simulink, load consumptions.

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List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

Cp	Power Coefficient
I _{mp}	Current at Maximum Power Point
I _{ph}	Photo Current
LIB	Lithium-Ion battery
PV	Photo Voltaic
SEI	Solid Electrolyte Interface
SOC	State of Charge
SOV	State of Voltage
TSR	Tip Speed Ratio
VOC	Open Circuit Voltage
V _{mp}	Voltage at Maximum Power Point

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1 Introduction

This chapter provides the introduction of the thesis work with a brief background of the topic and why this subject is worthy of research. The chapter also describes the aim and scope of the research work. Furthermore, the methodology is given at the end of the chapter.

1.1 Background

In recent times, many researchers around the globe have been putting efforts in research on standalone hybrid energy system with wind turbine as major source of energy along with solar panels coupled with battery storage system. Researchers are exploring ways to make this standalone system work better than before. Different ideas are executed, and new technologies are being implemented to find the most optimal solutions. These efforts demonstrate a strong dedication to finding cleaner and greener energy sources for future societies. Markvar in his research work provided a graphical construction method to enhance the sizing of PV/wind energy systems [1]. This technique involves a detailed examination of the monthly average solar and wind energy data along with variations. By exploring these variations over different periods, the approach seeks to refine the efficiency of such renewable energy systems, ensuring they are appropriately sized to harness renewable energy potential effectively throughout the year. Morgan conducted research on the behavior of battery units within an autonomous hybrid energy system under different temperature conditions [2]. Instead of concentrating just on the state of charge (SOC), Morgan studied the state of voltage (SOV) to know how batteries work at different temperatures. According to a report issued by the Statistical Review of World Energy consumption, it is found that the world energy consumption has increased from 122,857 terawatt-hours (TWh) in 2000 and reached 178,899 TWh in 2022 [3]. On the basis of investigation carried out by the International Energy Agency (IEA), it has been found that 745 million people across the world are living without access of electricity in 2023 [4]. According to the report issued by World Nuclear Association (WNA) in October 2022, there are annually 34 billion tons of carbon dioxide (CO₂) emissions worldwide from the combustion of fossil fuels for electricity generation which is an alarming situation. A standalone islandic operation containing wind and solar power with battery storage is a perfect solution to address the challenges of increased energy demand, electrification in remote areas, and to reduce carbon emissions. A standalone system containing wind and solar power with battery storage is economically cheap as compared to grid-connected supply in remote areas. The reason for using standalone wind and solar system along with battery storage is to avoid extremely expensive nature of extending transmission lines to remote areas and the higher energy losses that occur when centrally generated power is distributed over long distances to remote locations. Moreover, if a large power system breaks down it can be split into smaller operation island and some of the costumers can get access to the power in a fast way.

In recent years, wind and solar power generation systems with battery storage have become a very attractive solution to supply electric power to its load, in particular for islandic operation where power from national grid is not possible. The combination of wind and solar with battery storage can provide better reliability and their power cost is more economical. The integration of wind and solar with battery storage can reduce the power dependence on fossil fuels which is a major cause of natural resources depletion. The power generated from fossil fuels causes

huge CO₂ emissions which cause climate change. To overcome the CO₂ emissions and climate change wind and solar power with battery storage is a perfect solution [5]. Furthermore, all over the world, many remote areas and villages are still not electrified. To electrify these remote areas and villages, a hybrid wind and solar power system with battery storage is a perfect solution. The battery is used to store the surplus power generated from wind and solar irradiance during windy and sunny days and release energy during cloudy days and nights. Different methods are used for state of charge for the battery such as fuzzy logic, neural network, specific gravity measurement, open circuit voltage estimation, Kalman/extended Kalman filters and Ampere-hour counter [6]. The hybrid wind, solar along with battery storage have tendency to provide more reliable power supply to load than a system with single resource. Due to this, this hybrid power system has brought researchers attention worldwide. Nowadays, there is a notable surge in research and development in related domains in this industry like PV cell manufacture, rotor blades configurations and battery life enhancement.

1.2 Aim and Scope

The aim of this project is to design effective power flow promoting balance between power generation, consumption and energy storage to achieve energy independence in an islanded operation. Unlike traditional setups, the wind turbine in this study operates independently, without being connected to any external grid. This setup is also beneficial for remote locations with no access to the national grid. The main aim of the thesis involves developing a complete power flow model for the wind turbine using MATLAB Simulink. The simulation model in Simulink includes components such as the wind turbine generator, solar panels, batteries, and electric load. All the components will be designed as individual models in Simulink and then integrated through a controller. A crucial aspect of the research involves designing a load supply controller within Simulink. This controller will analyze input from the load model, enabling informed decisions on the optimal energy source for supplying the load, thereby enhancing the overall efficiency of the system. The controller is used to manage the power balance between generation and consumption and decides when to use power from a wind turbine, solar panels and from battery storage for ensuring a reliable and stable power flow operation. Upon successful implementation of the islanded operation, the next phase of the research involves exploring the potential ancillary services that this islanded wind turbine can provide to the main grid, further enhancing its overall utility and contribution to the broader energy landscape.

Following are the research questions which will be tried to answer in this thesis report.

1. How an islandic operation is designed to integrate wind turbines, solar panels and battery storage system for optimal power production, storage and its usage?
2. What strategies are implemented in order to ensure a stable and reliable power supply in islandic operations containing wind power, solar power and power from energy storage in battery?
3. How does the controller maintain the optimal power flow between wind power, solar power and power from battery.?

1.3 Proposed Methodology

The master thesis work focuses on the comprehensive simulation and control of a hybrid renewable energy system comprising wind and photovoltaic (PV) sources, alongside energy

storage via batteries, all interconnected with a load. The project entails the implementation and thorough investigation of modeling and simulation methodologies using MATLAB Simulink software. The core components of the simulation work developed in MATLAB Simulink consists of the following:

Theory, Modeling, Simulation and results of Wind Power Generation System

This block shows the detailed modeling and simulation of a wind turbine system, including its mechanical and electrical components and its power conversion stages. It accurately represents the behavior of the wind turbine changing wind speeds and operational parameters.

Theory, Modeling, Simulation and results of Solar Power Generation System

This module shows the modeling and simulation of photovoltaic array under variable irradiance and different temperatures.

Theory, Modeling, Simulation and results of Battery for Energy Storage System

This section contains the modelling and simulation of battery along with charge-discharge characteristics and state-of-charge (SOC) estimation.

Theory, Modeling, Simulation and results of Load Profile

This model indicates the behavior of the load or energy demand in the system, accounting for dynamic variations, load profiles, and power consumption patterns. It enables the evaluation of system performance in meeting load requirements.

In the island power system, a controller is developed which coordinates and manages the power flow dynamics among the wind turbine, solar panels, battery storage system, and electrical load to ensure supply and demand matching.

Following are the different scenarios explaining how controller works:

Scenario 1:

During intervals of sufficient wind power generation, the controller directs the entire electrical load to be exclusively met by the output of the wind turbine. Neither solar power nor battery storage energy is utilized in this scenario. After meeting the load demand, the power in excess from load will be directed to charge the battery. After charging the battery, the extra power is spilled through the wind spilling system.

Scenario 2:

In instances of reduced wind power availability, the controller manages a hybrid power supply approach, combining the outputs of the wind turbine and solar panels to sustain the electrical load. During this scenario, the battery storage system remains inactive, preserving stored energy for subsequent utilization.

Scenario 3:

When wind power generation is reduced to a point where it is unable to meet the load demand the controller seamlessly transitions the electrical load to be supplied by the combination of available wind power, solar power and energy stored within the battery storage system. In this

configuration, the wind turbine generates very low power while the load is majorly met by solar power and battery storage power.

Scenario 4:

In this scenario, the load is met by wind power and energy stored in the battery and there is no solar power available.

2 Wind Power

In this chapter a brief summary of how the wind turbine is used to produce electric power from wind is provided. The basic parts of wind turbine, the elementary systems associated with wind turbine and the equations used to model a wind turbine are introduced. Furthermore, the chapter emphasizes the literature review, methodology used in model development and simulations, and verification and troubleshooting of wind turbine models. At the end of this chapter a comparative study of the simulation results and measured results is provided for detailed analysis.

2.1 Wind Turbine

If we travel across Sweden either from Gothenburg to more south or north, amidst the windy and green fields we get to see huge towers like structures with airplane propellers or fans wings like huge mounting at their upper top spinning around their axis but stationary. These white color stationary structures are wind turbines. Wind turbines are the turbines which serve the purpose of converting kinetic energy in the wind to electrical energy [31]. Energy from the wind is one of the abundantly available renewable sources and wind turbines harness that wind energy to generate electrical power [31]. Invention of wind turbines is a major milestone towards fossil free energy and green future technologies.

The basic idea of producing electrical power using turbines is to transform mechanical energy, either potential, rotational or kinetic into electrical energy. Turbines are allowed to rotate with the help of working fluid either liquid or gas (atmospheric air in case of wind turbines) and this rotational effect is then used to rotate a conductor in the presence of a magnetic field thus giving rise to electric potential and currents.

The kinetic energy in the wind is caused by the solar radiation's energy by sun. The solar radiation from the sun is responsible for heating the atmosphere. As all parts on earth don't receive equal solar radiation and this causes a temperature difference in different areas. This temperature difference leads to the pressure difference of air. In order to equalize this pressure difference wind starts to blow from high pressure area to low pressure area [18].

Wind turbines use kinetic energy in the moving mass of the air and convert it to rotational energy and then to electrical energy through a generator. The basic physics principle involved in this phenomenon can be understood by the wind kinetic energy equation given by

$$K.E = \frac{1}{2} * mv^2 \quad (2-1)$$

Where m is the mass of the body while v is the velocity with which mass is moving. As the wind turbines under consideration are horizontal axis wind turbines, the area swept by the wind turbine rotor blades is circular which is denoted by A . Any air which is outside that circular area does not have any impact on the wind turbine. [13]. The radius r of this circular area is equal to the length of the wind turbine blade. When wind passes through this area some of the energy in the wind is captured by the wind turbine and is converted to electrical energy [32]. If the wind is blowing with a velocity of v and travels some distance within time t seconds, then the power can be given by kinetic energy per unit time.

$$Power = \frac{K.E}{t} = \frac{1}{2} * \frac{mv^2}{t} \quad (2-2)$$

Where m/t is the mass flow rate in kg/s indicating air flowing through area A . If air has a density of $\rho \text{ kg/m}^3$ and it travels 1 meters within time t seconds, then the air volume will be product of area A and length l . Volume times the density will give us mass [13].

$$mass \text{ flow rate} = \frac{m}{t} = A * \rho * \frac{l}{t} = A\rho v \quad (2-3)$$

By putting all these values in equation 2-1 above we get the power equation of wind turbine

$$Power(watts) = \frac{1}{2} A\rho v^3 \quad (2-4)$$

For fixed wind speed, the power from wind turbine is dependent upon the area of the rotor blades [32]. If we need more power, then we need to have a bigger area, that is the reason that the wind turbines which produce energy in multiples of Mega watts are huge in size and have huge rotor blades. The second important factor in this equation is air density. The density of air is dependent upon the ambient temperature, pressure, and height of the tower above the ground [16] as the height of the tower increases the pressure and air density are reduced [17]. Another important factor to take into consideration is the velocity of air. If the velocity of the is doubled the power produced will not be doubled, it will increase eight times, so it is very important to operate the wind turbine at controlled speed [18]. The optimal wind speed to produce electric power from wind is from 6m/s to 14m/s. The wind turbine starts to operate at 5m/s while the rated wind speed lies between 11 to 14m/s. The latest wind turbines can operate up to a wind speed of 35m/s and when the wind speed exceeds this limit then the rotor starts to move slowly without producing any power.

None of the wind turbines is this much efficient so that all the kinetic energy in the wind is converted to electrical energy by wind turbine. There are multiple losses in the turbine such as frictional losses and mechanical losses due to the involvement of rotatory parts, aerodynamic losses due to drag and losses in the electric generator also due to rotation [18]. In order to compensate for these losses and accurately present the energy conversion efficiency of the turbine, it is important to introduce an efficiency constant C_p which is known as the power coefficient. The value of this power coefficient typically lies between 0.4 and 0.5 and does not exceed this limit. The theoretical maximum value for the power coefficient is 0.59. Power coefficient is used to determine the fraction of the available wind power captured by the wind turbine which can be converted to electrical power [33]. The power coefficient is different for different turbines and depends on the design of the turbine [33]. It is one of the design characteristics depending upon two parameters λ and β . λ represents the tip speed ratio (TSR) which is a ratio of the speed at the tip of the turbine blade to the wind speed. If the speed of the turbine rotor is represented by ω rad/s and R is the radius (meters) of the circular area swept by rotor then ω times R give the speed at the tip of the blade [14]. If v is velocity of wind in m/s then TSR can be given by equation 2-5 below:

$$TSR = \frac{\omega R}{v} \quad (2-5)$$

On the other hand, β is the pitch angle and this refers to the position of the blades in the rotor plane. β is the physical angle of the blades with values lying between 0 and 360 degrees. Power coefficient C_p is a function of both λ and β [34]. The optimum values of λ and β are identified through experiments at the design stage. The shapes of the blade and turbine aerodynamic design are some of the major factors which determine the optimal value of power coefficient.

2.2 Parts of the Wind Turbine

Rotor

Rotor is one of the most important parts of the wind turbine converting the kinetic energy of wind into rotational energy. It is the component responsible for capturing the energy in the wind and producing aerodynamic torque from the wind. The rotor comprises blades, hub, and pitch system [18].

- **Blades**

Blades are the fan's wing-like structures mounted at the top of the tower rotating around their axis. Mostly horizontal axis wind turbines have three blades. Blades are responsible for producing torque by capturing the energy from wind. Blades are thicker closer to the hub and thinner at the tip. A blade can be 0 to 120 meters long and can weigh up to 20 tons. Glass fiber material along with reinforced carbon fiber is mostly used in making blades [18].

- **Hub**

Hub is the part of the rotor to which the blades are attached. The blades are also attached to the main shaft through the hub. When blades spin, the hub attached to the blades also rotates which causes the main shaft to rotate as well [18].

- **Pitch system**

The pitch system basically aims to adjust the pitch angle of the turbine blades [35]. The wind speed is not constant, it keeps varying, and to optimize the output of the wind turbine the blade's pitch angle varies along with the changing wind speed. To a small extent the pitch system is responsible for changing the pitch angle of blades but mainly it is employed to limit the incoming forces from the wind, typically a turbine starts to pitch when it reaches the rated power [18].

Nacelle

Nacelle is responsible for converting the torque generated by the rotor to electric power. It is a very significant part as it provides the bed to which all other components are mounted on. Nacelle holds the main shaft, gear box, high speed shaft and generator [35]. The gear box inside the nacelle translates the speed of the low-speed shaft to the high-speed shaft which opens into the generator [35]. On the high-speed shaft, a brake is also mounted to cause the turbine to stand still during high wind speed. In the latest wind turbines, there is no wind braking system as the turbine rotor starts to move slowly at wind speed higher than 35m/s and produces no power [18].

Generator

A generator is the component that converts the rotational energy of the high-speed shaft to electrical energy using the principle of electromagnetic induction [35]. Generator is also the part of nacelle in wind turbine. When the blades capture the kinetic energy of the wind, they tend to rotate a low-speed shaft at a lower speed of 0 to 60 rpm. In large size wind turbines, the speed of low-speed shaft is even lower [21]. Large offshore wind turbines has no gearbox and have a operation speed of 5-10 rpm. Smaller sized wind turbines do not need a gear box and they operate on a direct drive system. The high-speed shaft is connected to the generator and rotates at a speed of approximately 1500 rpm which is the speed required by the generator to generate electricity. A double fed induction generator is most commonly used generator used with wind turbines to generate electric power [20].

Converter

The electricity produced in the electric generator of wind turbine is of alternating nature. These alternating currents are of no use owing to their variable frequency and voltage thus it is required to manage the variable frequency and voltage output of the generator [35]. In order to do so a converter is used which mainly comprises of a rectifier and inverter [20]. The converter stabilizes the generator output, rectifier in converter converts the alternating current produced in generator to direct current. This direct current flows through a cable travelling down the inside of turbine tower. This cable is then connected to the inverter where this direct current is again converted to usable alternating current [21].

Transformer

A transformer is an electric device used to step up or step down the voltage levels in an electric power system. In order to transmit the power produced from wind turbine system it is appreciable to step up the voltage amplitude up to 400kV [35]. The electric power generated by the wind turbine generator is at a voltage level of around 575 V to 690 V [36] [22]. Large turbines can have generator voltage of 3.3 kV or up to 6kV. Within the wind farm a typical voltage value is 33 kV and the transformer is then employed to step up this voltage to 130 kV or up to 400 kV for transmission over long distances thus reducing the power losses [22].

Yaw System

A yaw system is also attached to the nacelle to rotate the nacelle and rotor horizontally in the direction of the wind so that the blades can capture most of the energy from wind and thus optimizing the output of the wind turbine [18] [35].

Wind Sensor

Anemometers are the widely used wind sensors used to measure the speed of the wind and then transmit this data to the control system [35]. Wind sensors are mounted at the back of nacelle to measure the wind speed and estimate the direction of the wind for the yaw system to rotate the turbine in a direction to face the wind [37]. In our case there are three wind sensors used at the site to measure the speed and direction of the air. Wind Speed Gill MaxiMet 600 is used to measure the speed of wind at the height of 22 meters. Wind Direction Gill Observer is the wind speed sensor used at a height of 30 meters to measure the wind speed and direction. Wind Speed Gill wind master is used to measure the wind speed at the height of 38 meters. In our project we will use the readings from Gill Observer wind sensor measuring the wind speed at 30 meters height.

Tower

Tower is the vertical structure that holds both the rotor and the nacelle [35]. If we want to access the nacelle for maintenance purposes, towers are used to reach the nacelle. Most of the towers are made of steel. Sometimes concrete is added to steel structures to increase the mechanical strength of the tower. Wooden towers have also been introduced which offer the same strength and durability while staying more sustainable and environmentally friendly. Typically, the height of the tower lies between 90 to 175m and it can weigh up to 290 tons [18].

Foundation

It's the foundation that holds the whole turbine in place [35]. The foundation guarantees that the turbine stays up straight and holds the tower hard against any oscillations caused by strong wind. Foundations can be onshore or offshore made up of concrete, rock, tripod or jacket depending upon the location of the wind turbine [18].

According to our discussion above it can be summarized that a wind turbine has mainly three degrees of free rotation i.e. azimuth, pitch and yaw. Azimuth is the rotation of the turbine's blades and rotor due to the rotational effect from wind. Yaw is the degree of freedom to rotate the nacelle and rotor horizontally for the turbine to face the wind. Pitch is the rotation of the turbine blades around their axis to increase or decrease the output power from a wind turbine.

2.3 Methodology

The process of designing a wind turbine model involved extensive literature review as it required us to be aware of all the systems associated with the wind turbine and to know how these systems and subsystems can be modelled and implemented in our simulation software Simulink. It is of great importance to identify the systems which need to be executed in simulations to replicate a real wind turbine. After extensive research and literature review, an understanding of the wind turbine's control system modelling equations was developed. The next step was to start simulating the turbine's control system by implementing all the modelling equations in our chosen software Simulink. Simulink is a graphical programming software tool offered by MATLAB. It is a block diagram environment which can be used to simulate multidimensional dynamic or static models with real time data [19]. It utilizes mathematical algorithms available in the form of preexisting blocks to implement complex models and systems. The graphical coding in Simulink can be combined with textual programming in MATLAB script. Simulink is user friendly, interactive, easy to program, troubleshoot and debug [19]. Simulink was a good choice for modelling a wind turbine because it lets the user opt for dynamic simulations using real time data and with the help of inbuilt blocks and programming it is easier to model a dynamic system in Simulink. The programming is done in MATLAB. The MATLAB code is written to define the variables to be used in Simulink and read the measured data from the recorded data files. The simulations are started by making an estimation of the available wind's speed and available wind power. Why this estimation is necessary is discussed in detail in the subsequent section 2.4.1 of this chapter. After estimating wind speed and wind power, modelling of the reference torque generation system was completed. The modelling of reference torque generation system was quite time taking as it involved the implementation of lot of control systems, filters and feedback loop systems so it required rigorous research and frequent changes made to implement the system. After successfully implementing the reference torque generator, we proceeded with simulating the dynamic

system aiming to produce driving torque of the wind turbine. Furthermore, we modelled a wind turbine generator thus providing the electrical torque produced by the wind. Brief details of the modelling of all these subsystems of wind turbine are provided in the following section 2.4.2 of this chapter. The simulations were started by implementing the basic modelling equations then we kept making changes and added new systems until the model started behaving in a desirable manner similar to real wind turbine system. We designed the model and after the design stage we verified our model by comparing the model simulations results with the measured values from the real wind turbine. The measured data was taken from a real wind turbine and was processed in MATLAB to obtain the data plots. By comparing the simulation plots and measured data plots, we troubleshooted and updated the model to ensure that model behaves desirably. After model verification we employed this model in the main simulations for islanded operation.

The data sets used in simulations are taken from the Chalmers wind turbine at Björko. The data is measured using different sensors placed in the wind turbine and in the wind sensor mast. All the readings are taken every 0.05 seconds which means every second 20 readings are taken and stored in text file. As the wind turbine doesn't run for a full day and usually runs for around half an hour so we had data files with 28440 readings from each sensor. As 20 readings were taken each second it means that we had the data for 1422 seconds which is approximately 23 minutes of wind turbine runtime. So, in order to use the data provided in the text file with readings taken every 50 ms, we averaged the 20 readings which give us one value which is assumed to correspond to reading taken every second. Now after averaging the whole data, we have 1422 readings each representing data taken every second during 23 minutes of turbine runtime. In order to study the model's behavior and to verify if the results of the model are near to that of real wind turbine, we used this data and runtime of the simulation is also around 23 minutes or 1422 seconds. This is done to validate if the model behaves in a desirable way as compared to the wind turbine.

It was also concluded that to study the islanding operation of the wind turbine, using the data from wind turbine only for 1422 seconds is not enough to study the model behavior properly so another methodology was implemented where instead of using estimated wind speed and estimated wind power, we used the measured wind speed. The wind speed sensor is used to measure the speed of wind for 24 hours. The wind speed during the time period of whole day is shown in figure 2-1 below.

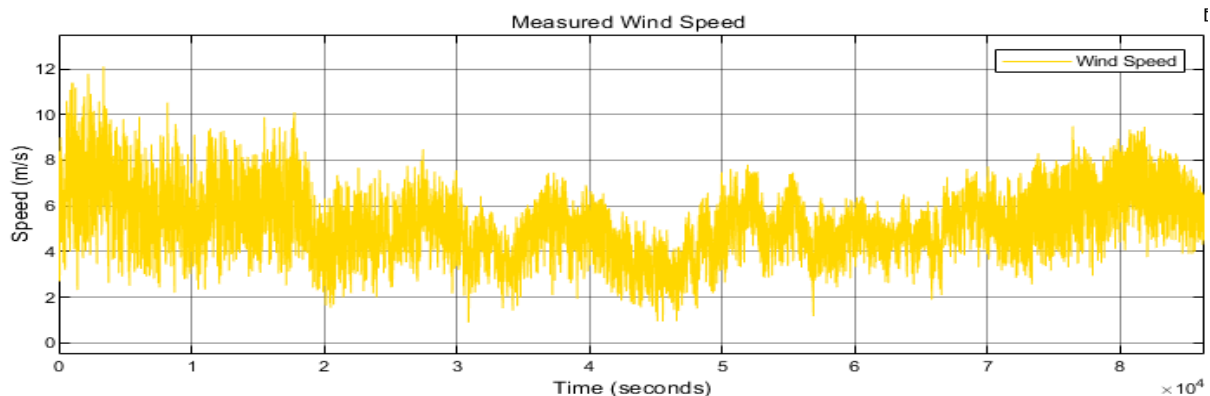


Figure 2-1:wind speed for 24 hours

It can be seen in the figure above that there are lot of fluctuations in the measured wind speed for 24 hours. In order to smooth out the measured wind speed to reduce these fluctuations to make the wind speed data able to be used in the model to get the wind power generated, we used a filter in the MATLAB code which smoothen out the fluctuations and produce an even data. The MATLAB code calculates the centered moving average of the consecutive data for a fixed length window and in result return an averaged data. The wind speed curve after implementing the data averaging code is shown in the figure 2-2 below.

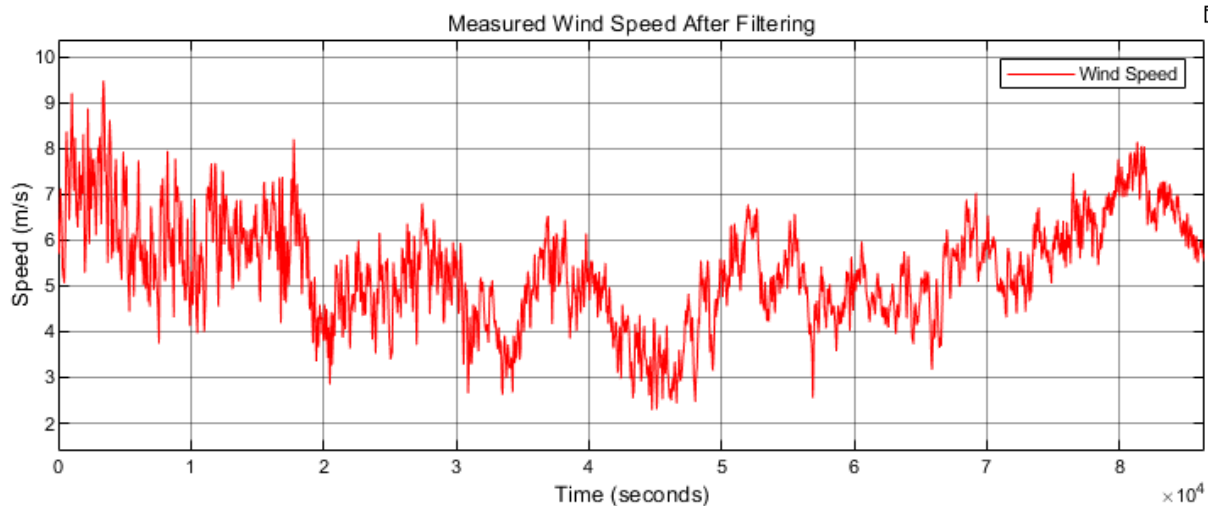


Figure 2-2: wind speed for 24 hours after filtering

The wind speed curve was further smoothed out by using further filtering on the average curve thus producing an averaged and smoothed curve shown in the image 2-3 below.

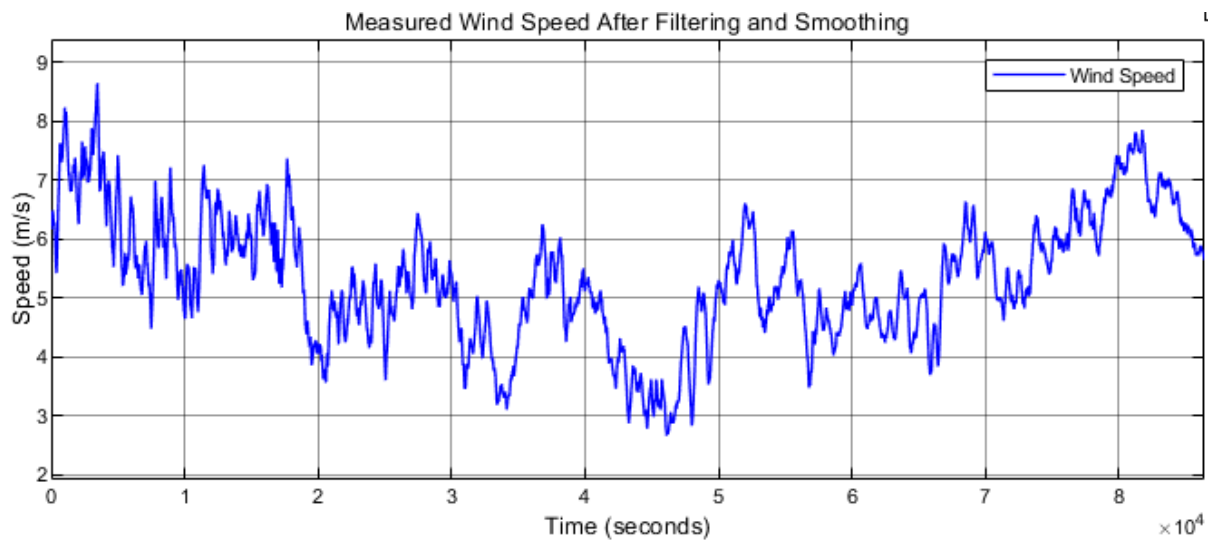


Figure 2-3: wind speed for 24 hours after filtering and smoothing

The curve shown in the figure 2-3 above contains the information about the average speed of wind during a whole day. This wind speed data is then utilized in the wind model to get the wind power produced by the wind turbine.

The methodology can be summarized as follow, that first we designed the model, then we needed to verify the model that if the model is working in desirable manner or not. In order to

do so we must have some results to make some comparison to build our conclusions. As the Chalmers wind turbine doesn't run for the whole day and mostly it is brought in operation for half an hour approximately so first, we ran our model with the data from sensors measurement for 23 minutes to compare both the results from model as well as measurements. When we successfully verified that our model is producing the results in the same manner same as the real turbine so we concluded that the model is working fine and now we can proceed with this model and run it for the whole day to approximate the power produced from wind turbine during its operation for whole day.

Further in this chapter 2 we will discuss about the available power estimation using the data available from Chalmers wind turbine, we will discuss in detail about the wind turbine model and the results regarding the output of the wind turbine model in both cases (for 23 minutes and 24 hours) are discussed in detail in the result section of this chapter.

2.4 Simulink Model

To show the isolated setup of wind turbine demonstrating its islandic operation without support from any grid, it was required to create a model of wind turbine along with its control system. The wind turbine model is created in Simulink.

Figure 2-4 below gives an overview of the wind turbine model designed in Simulink. The model mainly comprises of two main blocks. Each block represents one system. The first block or system is designed to assess the wind speed and make an estimate of available electric power from wind at that occasion. The wind turbine power equation is utilized in the block to get an estimate of the available power. The second block then represents a wind turbine model along with its subsystems for controlling the power generation from turbine. Initially help was taken from the models proposed in [7],[13],[14] and [15] to build wind model and after the model was constructed, iterative and repetitive methodology was used to make adjustments in the model until it started behaving in a desirable manner representing the real wind turbine system.

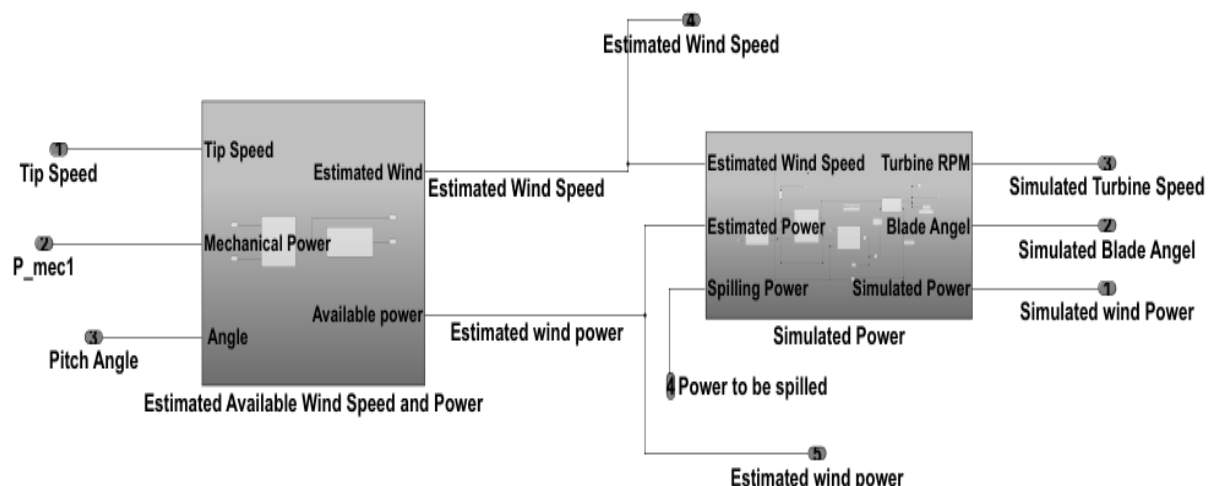


Figure 2-4: wind turbine model

2.4.1 Available Power Estimation

It is very important to estimate the power available in the wind at a given instance in order to accurately predict the maximum power which the wind turbine is able to generate. This estimation of the available power can be very useful if the turbine is supposed to contribute to the frequency support services. Available power estimation is also important for predicting the maximum power generation patterns. These patterns can be helpful in optimal management of the load and battery charging systems. If the predicted generation is more than the load at any time, it can be used to charge the batteries, or the power generated can be reduced by spilling the wind. In the model, available power is also used as a reference signal for other control systems in the model. The spill wind system is an example of one such subsystem which uses available power as a reference signal. The method followed to estimate the available power is discussed in detail in [7]. The below figure 2-5 shows the Simulink model which estimates the available power following the method discussed in [7]. The model block shown in figure a takes three inputs that are mechanical power, turbine speed, and angel from MATLAB program. These inputs are the measured value through the sensors and the data from sensors is processed in MATLAB code, stored in different variables in MATLAB editor which are then used as input in Simulink. The first block shown in figure 2-5 estimates the wind speed while the second block estimates the power from wind based on the wind speed.

The first input to the block is mechanical power which is calculated in the MATLAB code using electric power and efficiency. The second input is the tip speed value which is also a measured value measured with the help of a speed sensor and third input is the pitch angle of the blade measured in degrees with the help of angle sensors.

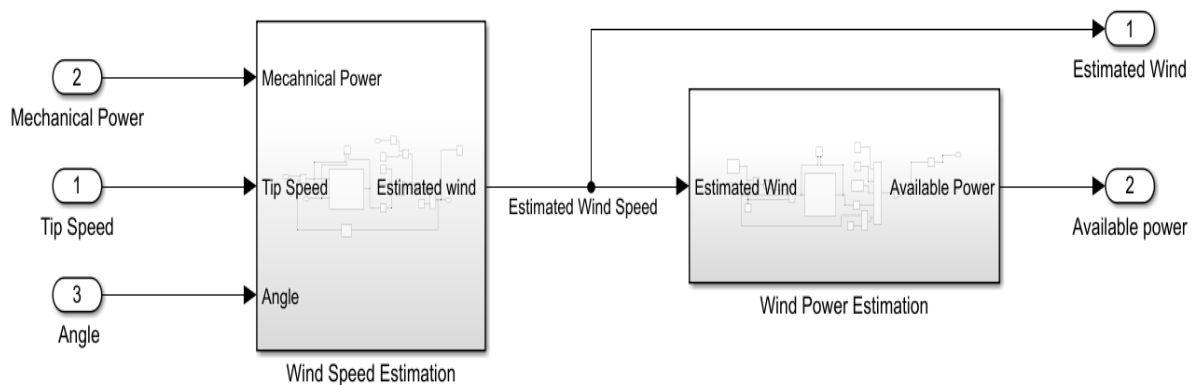


Figure 2-5: available power estimator model

It should be kept in mind that instead of measured wind speed values, estimated values are used. The estimated wind gives a more accurate idea of the wind speed which the wind turbine will experience. The instrument used to measure the wind speed is an anemometer which has a very small area and small moment of inertia, which makes it more sensitive to little variations in wind speed. These variations can impact on the results of available power from the turbine so it is better to avoid these variations. In order to avoid these variations, the wind speed is estimated using the wind turbine parameters and real data. The actual rotor has a large area and inertia, and it is not that sensitive to little changes in wind speed thus it is better to estimate the wind speed using actual turbine parameters to predict the power accurately. In Figure 2-6 wind speed estimation model is indicated. The mechanical power in the rotor or rotor power is obtained from the available wind turbine data from Chalmers wind turbine at Björkö. The Power coefficient is calculated using the tip speed ratio (TSR) λ and pitch angle β . λ along

with β form a look up table to get the wind turbines power coefficient C_p . The pitch angle β is measured value obtained from the wind turbine data while the TSR is obtained by taking the ratio of the tip speed and estimated wind speed [13][38] which is a feedback value in closed loop system.

$$\text{TSR} = \lambda = \frac{v_{tip}}{v_{wind}} \quad (2-6)$$

Where v_{wind} is the estimated wind speed while v_{tip} is the tip speed which a turbine blade experiences at its tip in the tangential axis and calculated as follow.

$$v_{tip} = 2 * \pi i * \frac{v_{turbine}}{60.R} \quad (2-7)$$

Where $v_{turbine}$ is the speed at which turbine is rotating and is obtained from speed sensor connected to rotor. R is the radius of turbine which is equal to the length of blade.

The estimated wind speed is then calculated by rearranging and solving the wind turbine power equation using the rotor mechanical power, air density ρ , rotor area A and power coefficient C_p . The estimated wind speed equation can be given as follow:

$$v_w = \sqrt[3]{\frac{2.P_{mech}}{\rho.A.C_p}} \quad (2-8)$$

The figure 2-6 indicates the Simulink functional block diagram to implement the equation above to obtain the estimated wind speed using the mechanical power. The P_{mech} is the mechanical power calculated in Matlab code using the electrical power and efficiency. The electrical power used to calculate the P_{mech} is obtained by the product of DC voltage and DC current values measured from the current and voltage sensors in the wind turbine. The electrical efficiency is supposed to be 0.89.

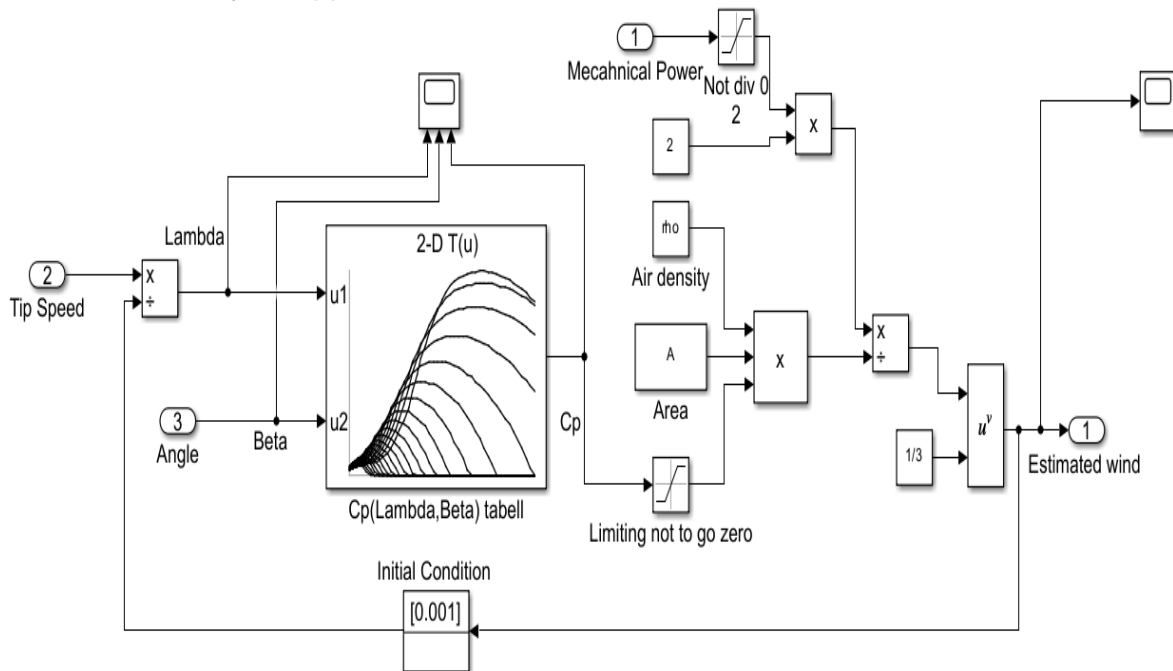


Figure 2-6: wind speed estimator

The available power from the estimated wind speed can be calculated by following the method also described in [13]. Figure 2-7 gives an overview of the Simulink model used to calculate wind power from estimated wind speed. As shown in figure a that the estimated wind speed v_{wind} is the input to the wind power estimation block. The maximum available power is obtained using the wind turbine power equation with parameters like air density ρ , rotor area A , power coefficient C_p and estimated wind speed v_{wind} . The power coefficient C_p is obtained using the look up table comprised of tip speed ratio (TSR) λ and pitch angle β [39]. In order to get the maximum value of C_p , the optimal value of the λ is used. To obtain optimum λ we need to calculate the optimal rotating speed of the rotor. This optimal rotor speed as discussed in [13] is calculated by following the equation below:

$$v_{rotor}^{opt} = \frac{\lambda_{opt} \cdot v_{wind}}{R} \quad (2-9)$$

where λ_{opt} is the optimal tip speed ratio value identified by the turbine manufacturer while designing the turbine. In the case of the Chalmers turbine under study, this value is 7.85. R is radius of the turbine rotor which is equal to turbine blade length and v_{wind} is the estimated wind speed. Rearranging the equation above the optimal value of λ is then calculated for this optimal rotor speed.

$$\lambda_{opt} = \frac{v_{rotor}^{opt} \cdot R}{v_{wind}} \quad (2-10)$$

The most suitable C_p is for this value of λ_{opt} is then calculated at all values of β with the help of a look up table. Finally, the maximum available power is estimated using all the parameters in the power equation.

As shown in the figure below an electrical efficiency η of 89% is multiplied with the mechanical power available to get the theoretical value of the maximum electric power available for consumption.

$$P_{el} = P_{mec} * \eta \quad (2-11)$$

The maximum electrical output of the wind turbine is then limited to 25000W with the help of a signal limiter for not letting the output exceed beyond the upper limit.

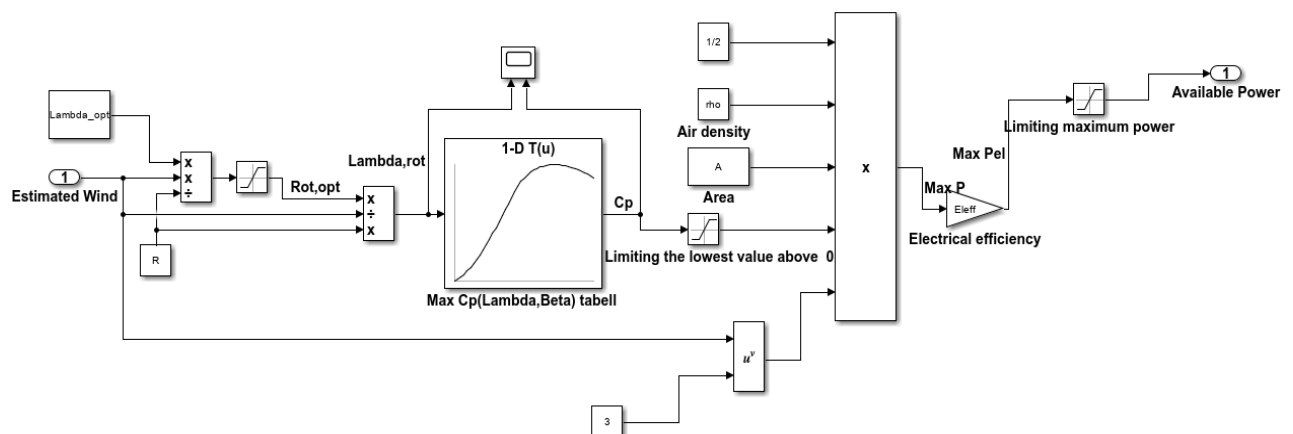


Figure 2-7: maximum available power

2.4.2 Wind Turbine

After making an estimate of the maximum available power, the next step is to simulate the wind turbine model in the MATLAB Simulink. The wind turbine model along with its control systems can be seen in Figure 2-8 below. The model mainly comprises of four blocks. The first block is the wind spill block to spill the wind in order to control the generation of power from wind turbine, if the power produced by wind power plant is more than the required, the wind spill block spills the wind to reduce the amount of power generated by wind turbine. The second block is the reference torque generator block which generates a reference turbine moment for the subsequent blocks to calculate turbine actual moment and output power. In addition to reference moment the block also controls the pitch angle of the blades, thus this second block is responsible to control the normal operation of the wind turbine. The dynamic block is responsible for creating driving torque, the torque which wind is implying on the turbine rotor to rotate the shaft [40]. The DC generator block imitates the electric generator and creates the electric torque available to be used. The wind turbine model block takes three inputs, of which two are estimated wind speed and estimated power that come from estimated wind and power block. The third input is the spilling power which comes from the controller output and determines the amount of power to be reduced by spilling wind. Estimated power and spilling power inputs are used in the wind spill system block, only to reduce the turbine output when required. Estimated wind speed is used as input in the dynamic block to create the driving torque. As discussed earlier, the estimated wind speed offers a better approximation of the wind force that turbine will experience. As shown in figure 2-8 below the model also implements two gear boxes between DC generator block and turbine with a gear ratio of 20:1.

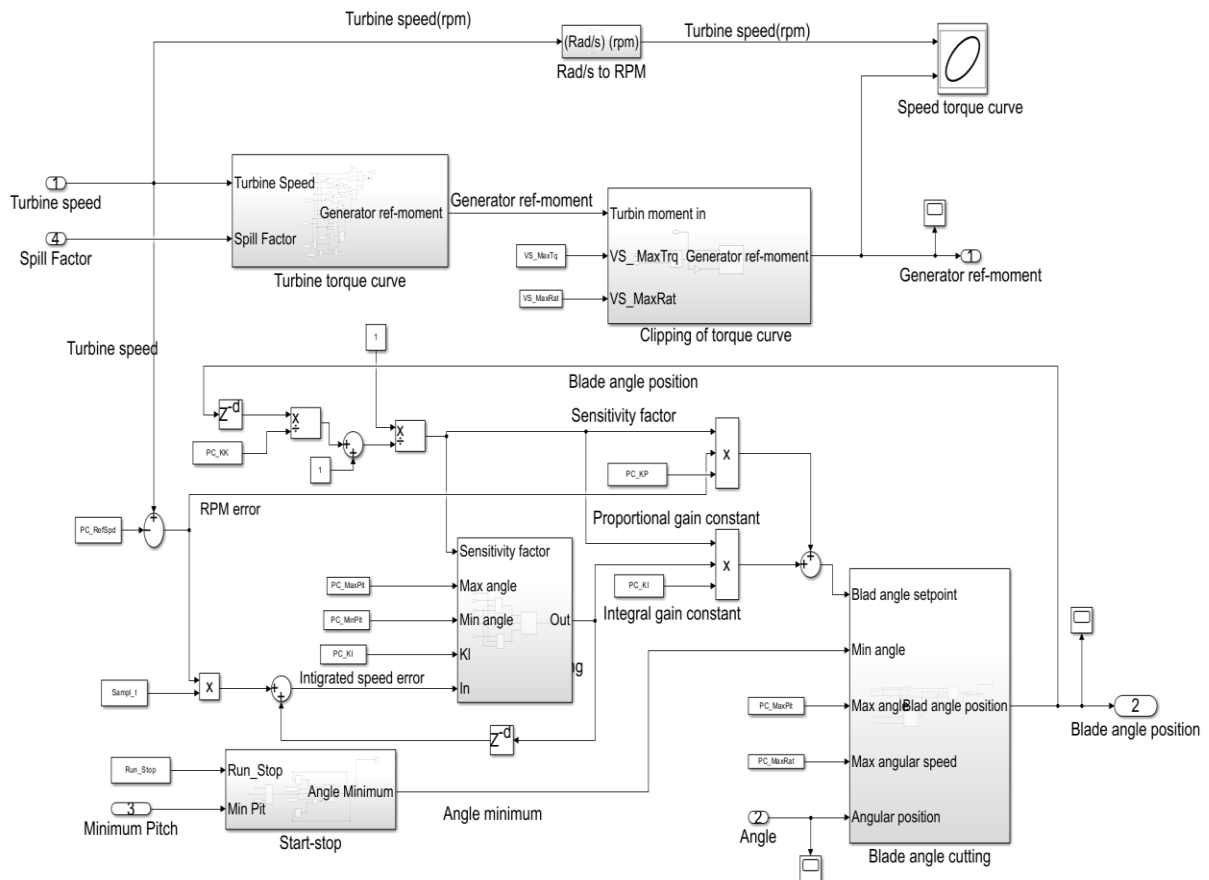


Figure 2-8: wind turbine model with control system

2.4.2.1 Dynamic Block

The dynamic block as discussed earlier creates driving torque [35]. It is the torque which the turbine rotor will generate under the effect of the wind. Figure 2-9 indicates the graphical programming to implement the impact of wind on turbine. The input named “Turbine RPM” is the estimated wind speed which is used to calculate the tip speed following the method discussed in [12] as shown in equation below:

$$v_{peak} = v_{turbine} * R \quad (2-11)$$

Where v_{peak} is the tip speed of turbine, R is the radius of the rotor and $v_{turbine}$ is the nominal turbine speed [13][35].

The ratio of the tip speed v_{peak} and the nominal wind speed v_w is then used to calculate the optimal value of tip speed ratio λ . The optimal value of the blade pitch angle β is calculated in the reference moment generator block which is converted from radians to degrees. Then the look up table generates a maximum value of power coefficient C_p corresponding to λ and β . The wind turbine power equation is then used to calculate the turbine mechanical power. The turbines power is then divided by the turbine RPM to calculate the turbine driving moment following the equations below:

$$Torque = \frac{Power}{Speed} \quad (2-12a)$$

$$T_{drive} = \frac{P_{mec}}{v_{turbine}} \quad (2-12b)$$

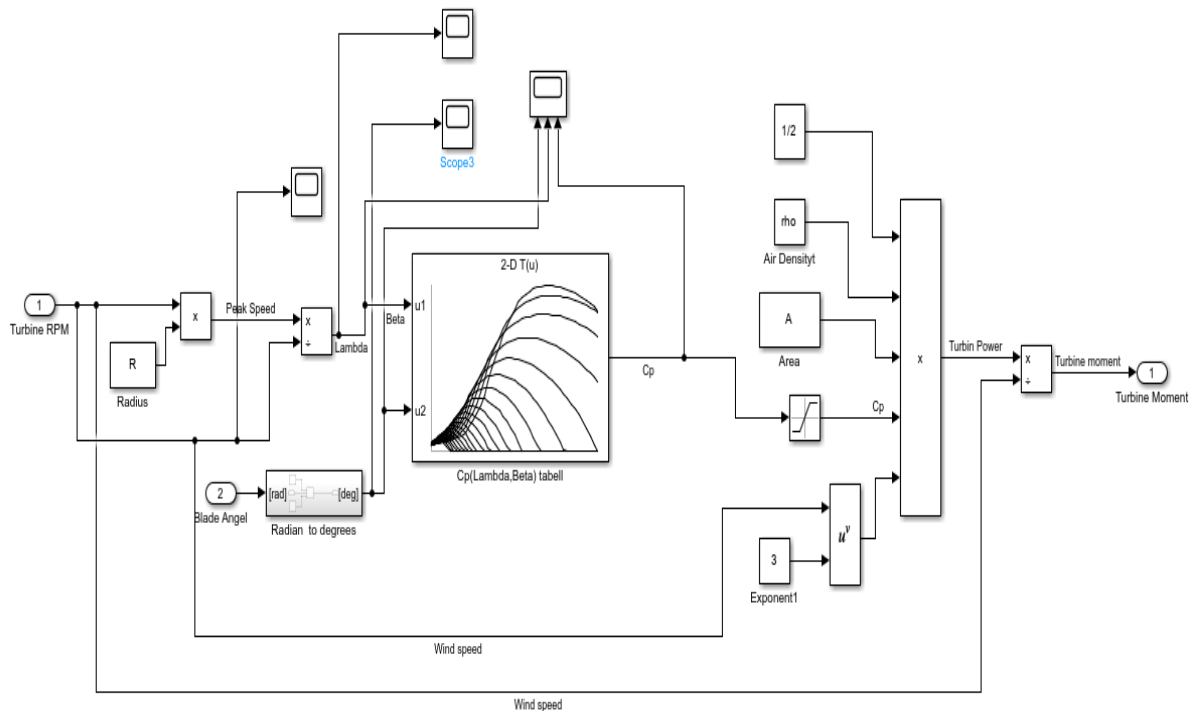


Figure 2-9: dynamic block

2.4.2.2 Generator

The generator block as shown in figure 2-10 gives an overview of the wind turbine generator. This block is utilized to balance the electric torque T_{el} and driving torque T_{driv} . Torque T_{driv} is the mechanical torque from wind which is calculated in the dynamic block and inserted as an input here. T_{el} is the electric loading torque which is obtained by passing the reference torque from PI controllers. This block is balancing both T_{el} and T_{driv} to get the rotor speed using the equation below:

$$w_r = \frac{1}{J} \int_{-\infty}^{\infty} (T_{driv} - T_{el} - b * w_r) dt \quad (2-13)$$

w_r is the speed of the rotor, J is the moment of inertia of the rotating mass, and $b.w_r$ is the damping caused by the friction.

There are two inputs to this block which are T_{ref} and T_{driv} . T_{ref} is calculated and provided by reference torque block while driving torque T_{driv} is provided by dynamic block. T_{ref} is used as a reference moment for electrical torque. A PI controller with a proportional gain of 5 and integral gain of 3 is utilized to create T_{el} from T_{ref} . The electric torque T_{el} and the damping moment which is caused by the friction is subtracted from the drive torque T_{driv} and remaining torque is divided by moment of inertia J to get the rotor speed w_r . The product of rotor speed and electric torque would give the electric power available following the equations below:

$$Torque = \frac{Power}{Speed} \quad (2-14a)$$

$$P_{el} = T_{drive} * v_{turbine} \quad (2-14b)$$

The parameters acquired from Chalmers wind turbine in Björko are utilized in the modeling and are given below in the table.

Table 2-1: parameters of Chalmers wind turbine in Björko

Constant Name	Value and Units	Definition
K_p	3	Proportional gain constant
K_i	5	Integral gain constant
J	4.25kgm ²	Moment of Inertia
b	0.1Nms/rad	Damping constant

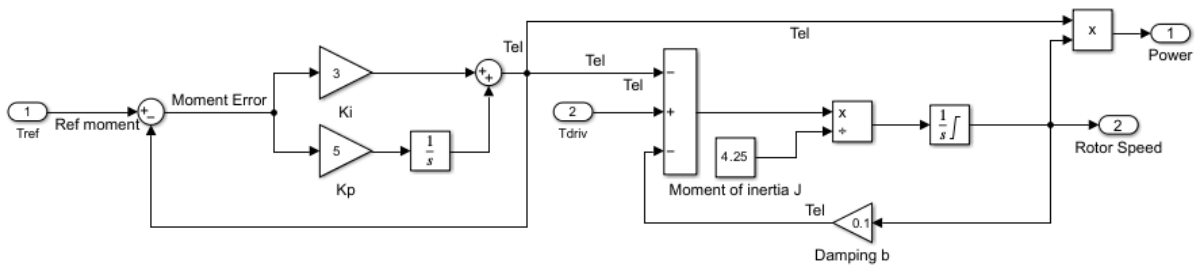


Figure 2-10: generator block

2.4.2.3 Reference Moment Generator

The NREL regulator block is employed to control the wind turbine for normal operation without any frequency control. The operation of the wind turbine is divided into three main regions. These three control regions are indicated in the figure below. The NREL regulator is designed in such a way that it controls the operation in all these regions. The speed of wind turbine ω and wind turbine power are controlled for these regions by controlling the pitch angle β and turbine reference moment T_{ref} . The figure shows the turbine moment T_{ref} plotted against the wind turbine speed ω . When the turbine speed is in region 1, the moment T_{ref} is zero. It means the turbine speed is less than the cut in generator speed and thus the power produced in region 1 is zero. In region 1 the power from the wind is utilized just to speed up the turbine thus increasing ω . When the ω starts increasing, it reaches region 2 and now the wind turbine speed has increased so much that it starts producing electric power and moment is also produced following equation below:

$$Torque = \frac{Power}{velocity} \quad (2-15)$$

Now in region 2 the T_{ref} is required to be controlled to maximize efficiency. The T_{ref} is controlled by controlling the lambda and letting it operate at its optimal value λ_{opt} which maximizes the C_p . The T_{ref} is controlled following the equation below

$$T = \frac{1}{2N} \quad (2-16)$$

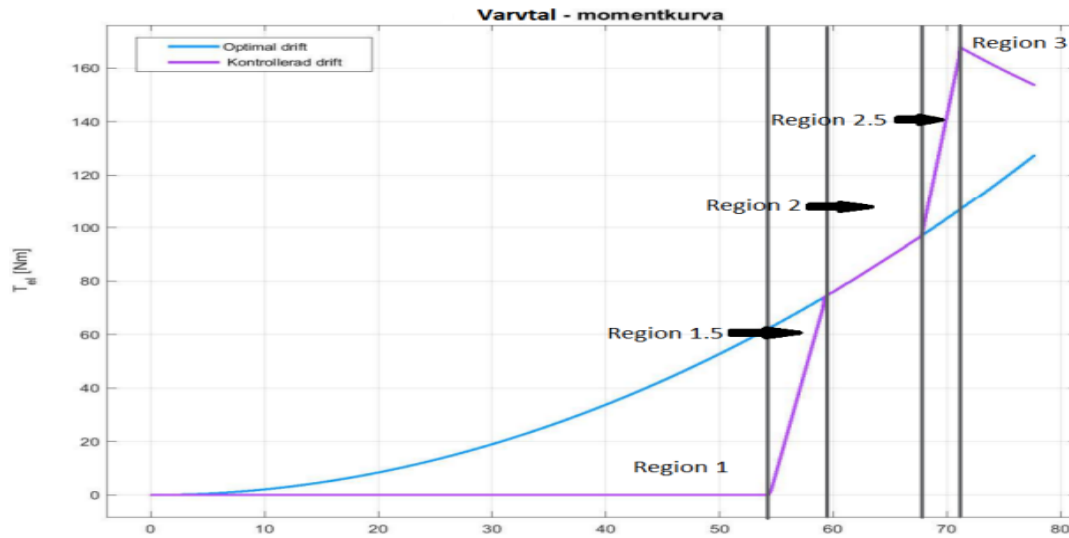


Figure 2-11: operation of wind turbine in three regions

2.4.2.4 Regulator Construction

The NREL regulator block is indicated in the figure 2-12 below. The NREL regulator controls the normal operation of the wind turbine. The block in figure 2-12 below indicates how the turbine loading reference moment is obtained from the turbine speed. As the operation of the wind turbine was divided into three regions as shown in figure 2-11 taken from [7], for each region there is a different T_{ref} depending upon the turbine speed ω . Input to the regulator is the turbine speed which helps determine the loading torque of the generator T_{ref} . Now using the speed torque curve discussed before, we can figure out in which region the ω lies and then T_{ref} is generated in accordance with ω . The curve between the T_{ref} and ω is created in Simulink MATLAB using different logic gates. The logic gate detects which region ω is located in and after calculations produces a T_{ref} in accordance with that. Then the next block is utilized to clip the obtained value of T_{ref} and rate of change of T_{ref} in case the value of T_{ref} falls outside the allowed range.

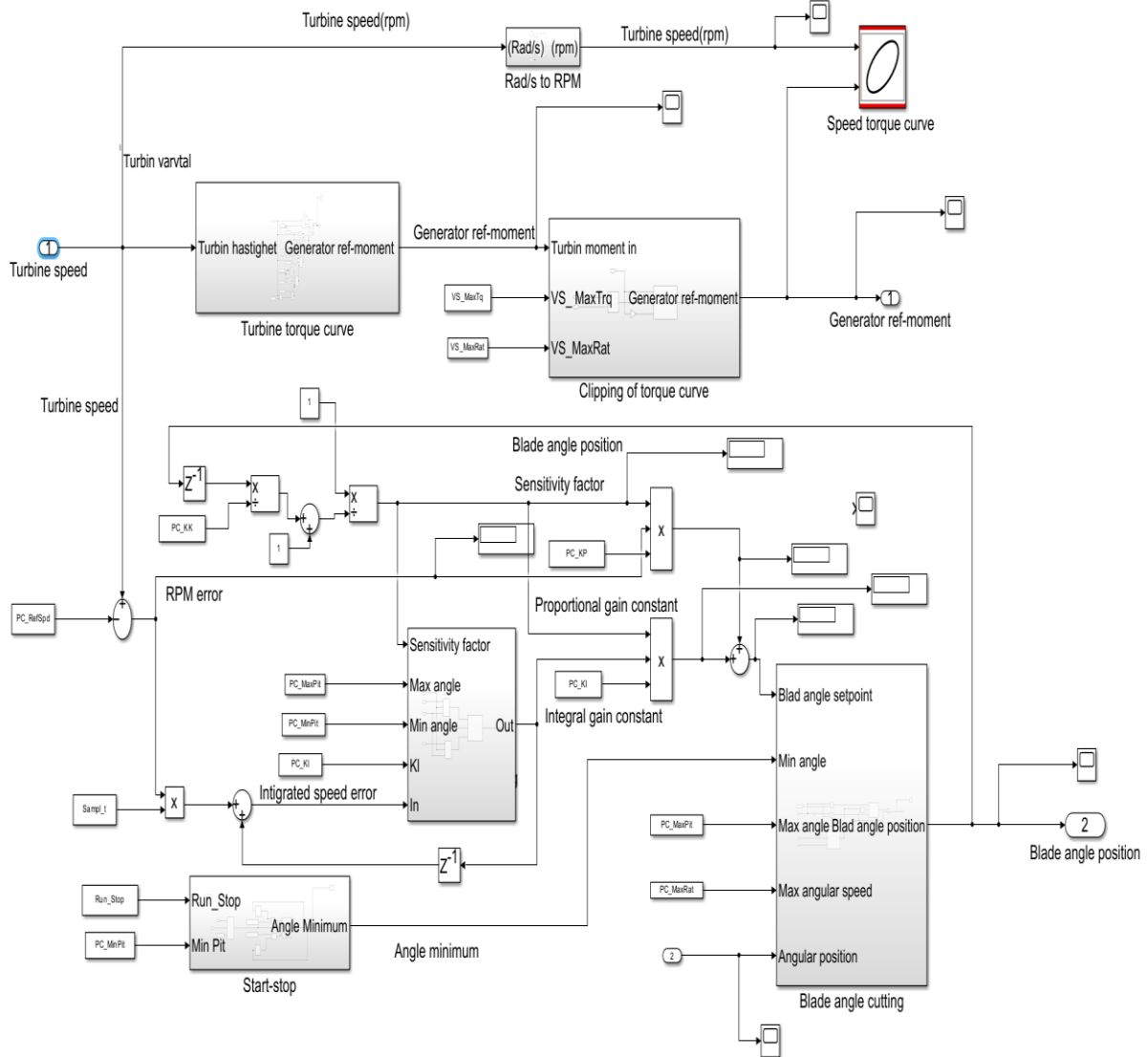


Figure 2-12: NREL regulator block

2.4.2.5 Turbine Torque Curve

The figure 2-13 below shows the use of logic gates for generating the curve between $\dot{\omega}$ and T_{ref} following curve in image 2-11. The speed of the turbine is compared with the cut in speed of the generator. If the turbine speed is less than the cut in speed T_{ref} is zero. If turbine speed is greater than the cut in speed, then the logic is designed in such a way to realize in which region the turbine speed lies and according to the region the T_{ref} is calculated. The parameters used for creating the speed torque curve are the parameters which are normally utilized in controlling the operation of Chalmers wind turbine at Bjorko.

The image below shows how the logic gates are utilized to obtain generator reference moment following the turbine torque curve the turbine torque curve and the spill factor impact on the reference moment. The maximum value for spill factor is one while its value resonates between zero and one depending upon the power to be reduced by spilling wind from the system.

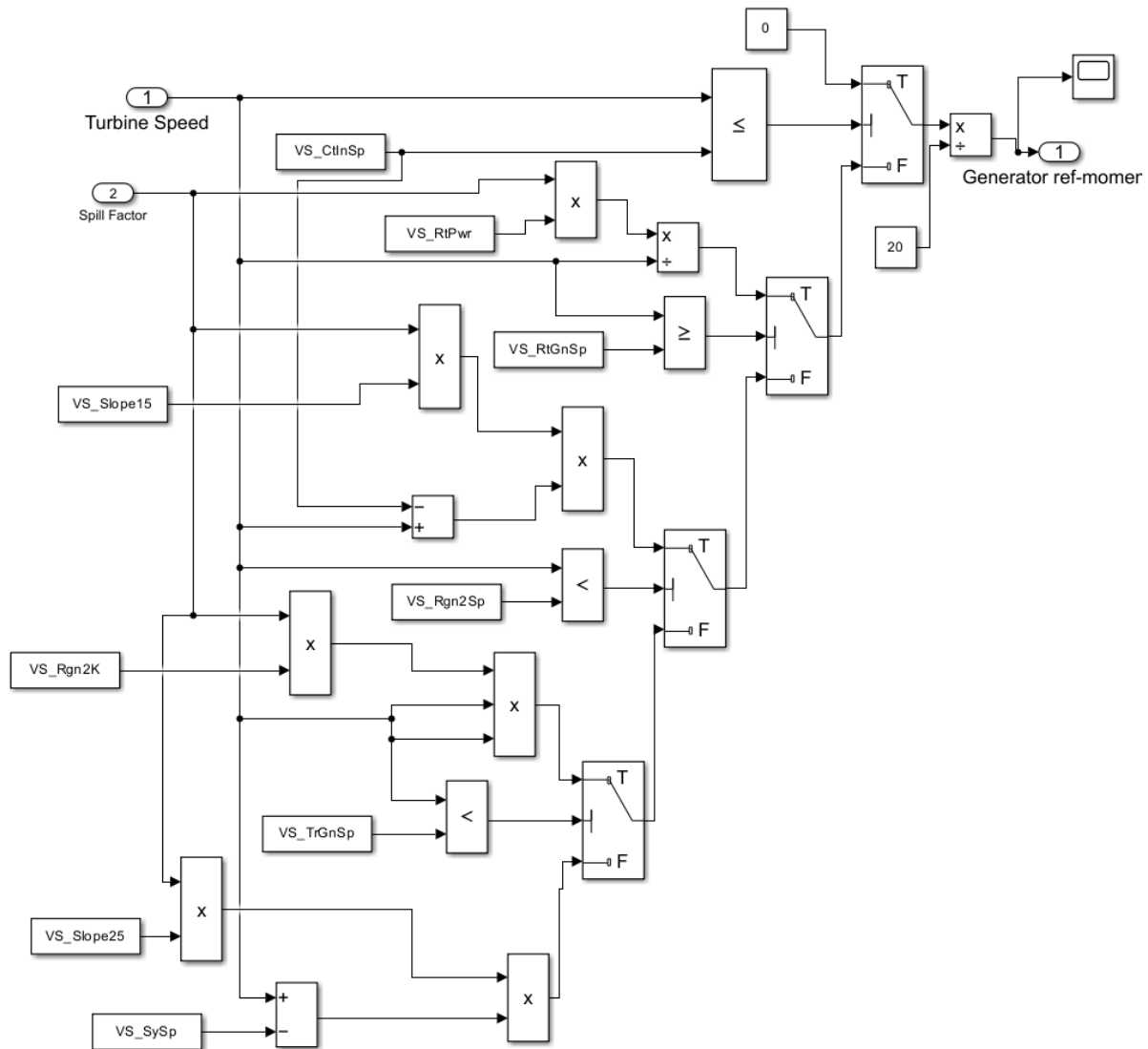


Figure 2-13: generator reference moment

2.4.2.6 Spill Wind

Figure 2.14 indicates a spill wind system as a subsystem to the wind power system block. The spill wind block is added to control the amount of power produced by the wind turbine. If the power generated from wind turbine is excessive than the load required, then this power can be used to charge the batteries. In case the batteries are already fully charged then the excess power is of no use. Since the system is isolated and no grid is connected so we can't export the extra power to the grid. In such a case it's always a rational approach to reduce the turbine output by controlling the amount of power produced from wind turbines. In order to reduce the power output from wind form, the excessive generation is calculated and then this excessive power is used to calculate a spill factor following excessive power. This spill factor can then regulate the wind turbine to lower output by adjusting it by controlling different parameters in the Speed torque curve generation block. The controller module block calculates the total power consumed from all available resources. If the wind turbine is the only source enough to meet the load demand and still the power is in excess, then it will generate a signal P_{spill} . P_{spill} indicates the excessive power in watts which is required to be reduced by spilling wind. As Figure 2.14 shows, P_{spill} is given as input named spilling power to the wind spill system

block. The other input to the wind spill system block is the estimated available power. The block is controlling the power conversion efficiency of the wind turbine to reduce the output power. This is done by controlling the power coefficient of the wind turbine. The power coefficient as discussed earlier is dependent on the blade pitch angle β and TSR λ . The minimum allowed pitch angle β is increased to reduce the power coefficient C_p . This reduction in C_p is proportionate to the watts to be wasted. Figure below shows the detailed modeling of the wind spill system block.

Available power and spilling power are taken together to calculate the desired power which is then scaled down between 0 and 1 to produce a spill factor by taking the ratio of desired power to the available power. The spill factor is calculated per the following equation. This factor determines the amount of power that would be wasted from the available power at the given instant of time.

$$Spill\ Factor = \frac{P_{spill} + P_{available}}{P_{available}} \quad (2-17)$$

Where P_{spill} is the number of watts to be wasted and $P_{available}$ is the available estimated power. As shown in Figure 2-14 the calculated spilling factor is then multiplied by the maximum value of the power coefficient $C_{p,max}$ to obtain the desired value of C_p . As established earlier the values of power coefficient C_p , blade angle β and TSR λ are interdependent so for a constant optimal value of λ , the blade angle β can be found according to the desired value of C_p . The obtained value of blade angle β is then converted from degrees to radians and the minimum value of blade angle is restricted to 0.034 radians or 2 degrees using a saturation block so that the blade angle doesn't fall beyond the minimum permissible limit for the turbine.

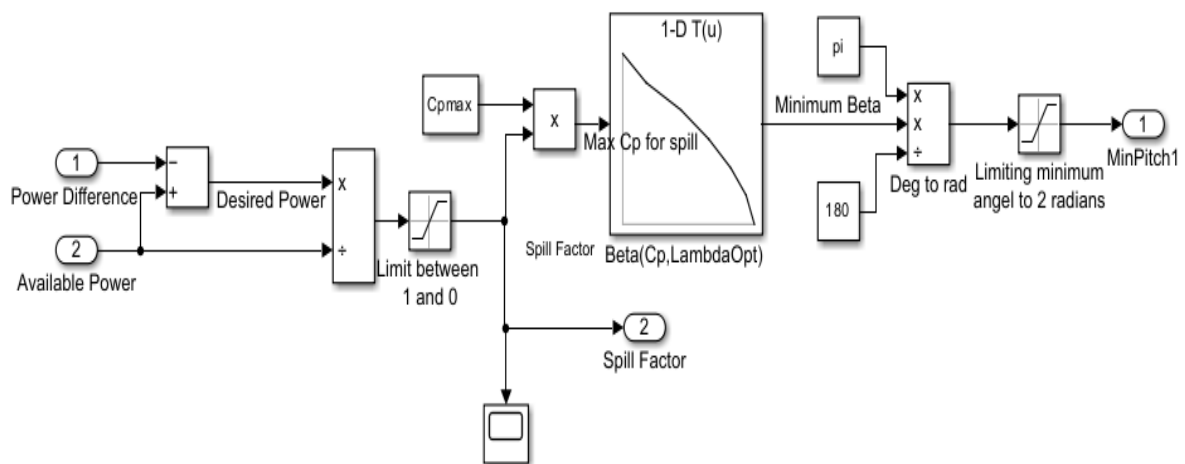


Figure 2-14: modeling of the wind spill system block

2.5 Important MATLAB Settings

In this section the MATLAB settings are discussed which need to be chosen to run the model successfully and obtain similar results. The runtime can be either 1400 sec or 86400 sec depending upon whether the model is being run for 23 minutes or 24 hours. The other settings include solver settings. If the 'Modelling' tab from Simulink toolstrip is chosen, and then 'Model Settings' are clicked it would lead to a new window would pop up with Solver settings. In that

window, on the left hand there is a menu from which we can choose different options such as ' solver' and 'Data Import/Export' settings. If we click on Solver, the solver is selected to be ' Fixed Step' from drop down menu under Solver selection tab and under solver details the Solver-Fixed step (Fundamental Sample Size) size is fixed to 0.05 sec. The Solver setting should look as shown in figure 2-15 below:

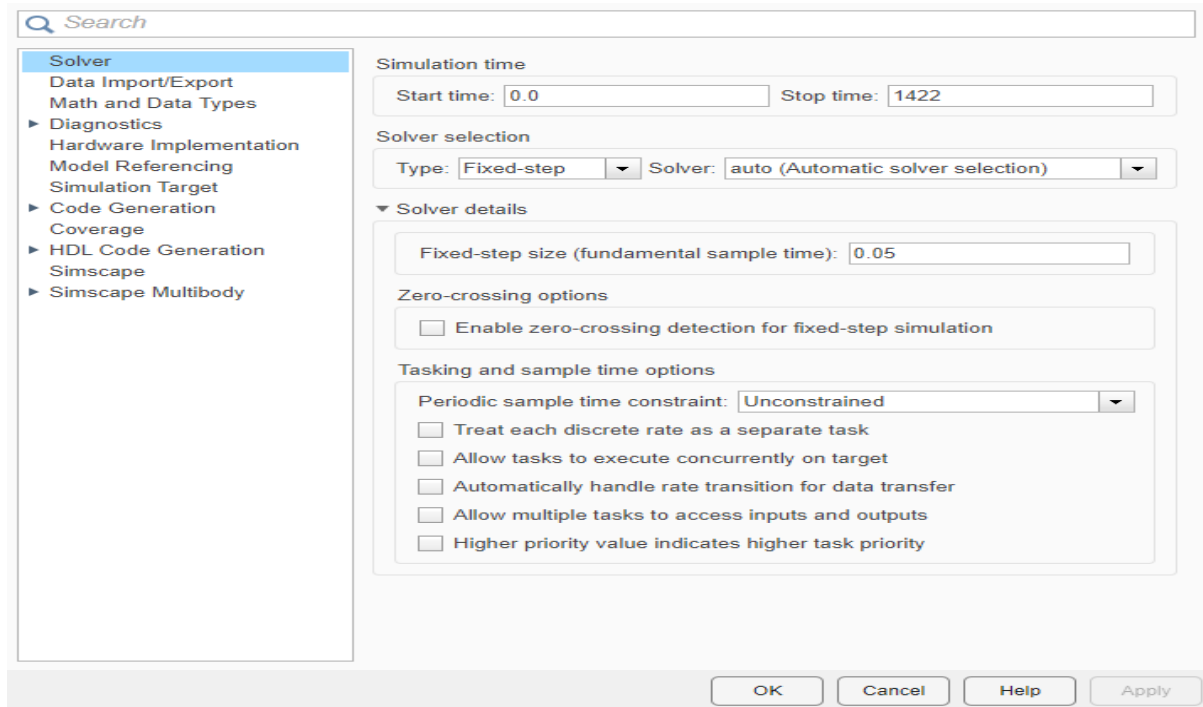


Figure 2-15: MATLAB settings 1

The other important setting is regarding inputs to the model. If the ' Data Import/Export ' tab is chosen from the menu on left hand side, here all the inputs to the model can be put. In our case there are seven inputs to the model and the inputs settings look as shown in the image 2-16 below. The names of the inputs are V_tip, P_mec, Vinkel, Vinkel, Wind, G, GenSpeed .

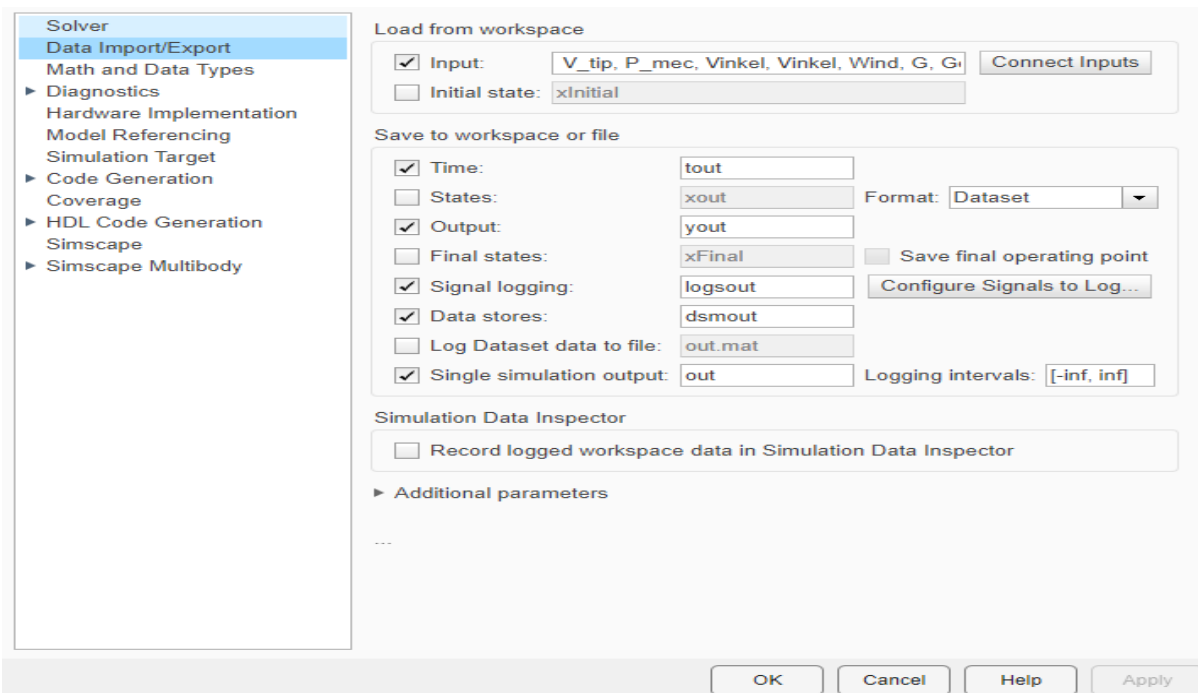


Figure 2-16: MATLAB settings 2

2.6 Results of the Wind Turbine Model

2.6.1 Results for 1422 Seconds Simulation

In this result section we discuss the results for the wind turbine model and analyze the plots and values obtained from wind turbine simulations and compare them with the measured values and plots to know if the Simulink model working in a desired manner or not. The comparison of the simulated and estimated values with the measured one confirmed a high degree of accuracy indicating that the model is reliable and acts as expected. The simulated and estimated values are in close alignment with the measured values. The curves and plots mostly follow the same pattern with very small deviations specially at the start up time

Figure 2-17 shows the comparison of the measured and estimated wind speed. The blue curve shows the estimated wind speed while the yellow curve indicates the measured wind speed. All the parameters used in the simulation model are the same as the ones that were used while taking measurements from wind turbines, which increases the validity of the results. It can be clearly seen from the graph that estimated wind speed follows the measured wind speed curve and they often overlap at most of the points indicating that both the curves are following the same pattern. It can be observed that there exist some deviations in simulated and measured plots for the reason that the response of model is bit slow to sudden changing wind condition which is not the case with the measurement from wind turbine. In the beginning the estimated available wind is zero for the reason that the wind turbine needs to be started to make an estimation about the available wind speed and available wind power.

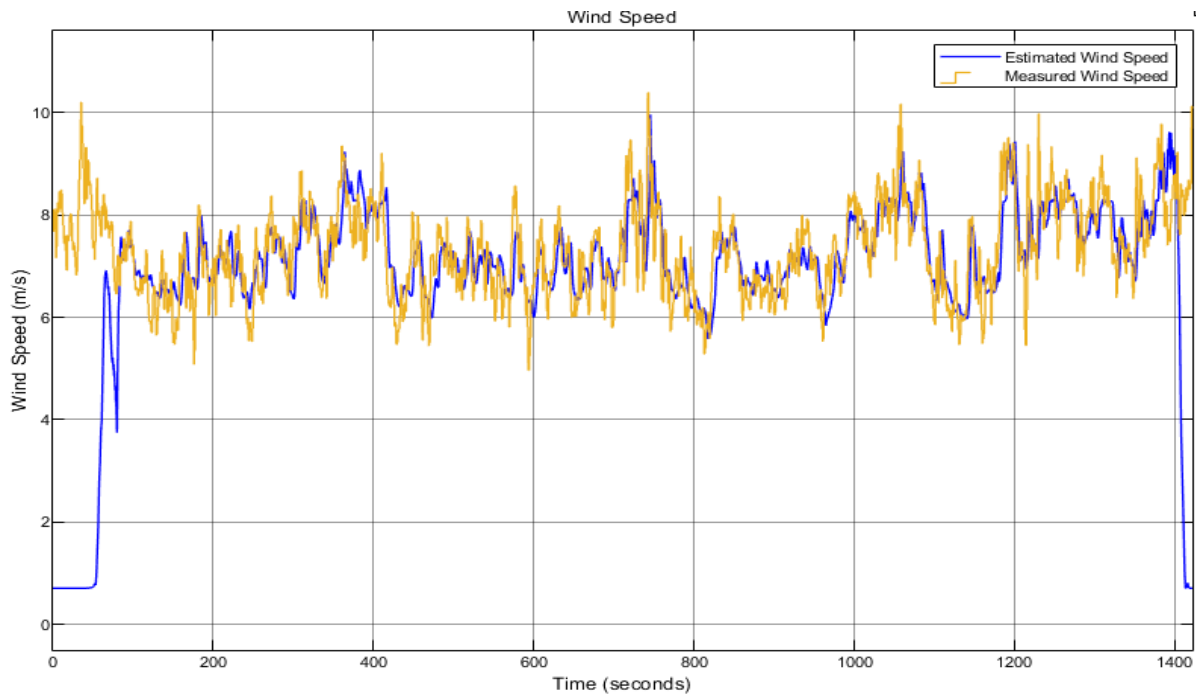


Figure 2-17: measured and estimated wind speed

Figure 2-18 below shows the measured and estimated wind power. The measured power is calculated by multiplying the measured DC voltage and DC current sensed with the help of sensors and provided in the data file. The estimated power is the estimation made using the Simulink code. Same as the available and measured wind speed, the power curves follow the same path often overlapping each other. Initially the estimated and measured power should be zero because of the fact that there should be enough wind to start producing power from the turbine and it is evident from the plot as well.

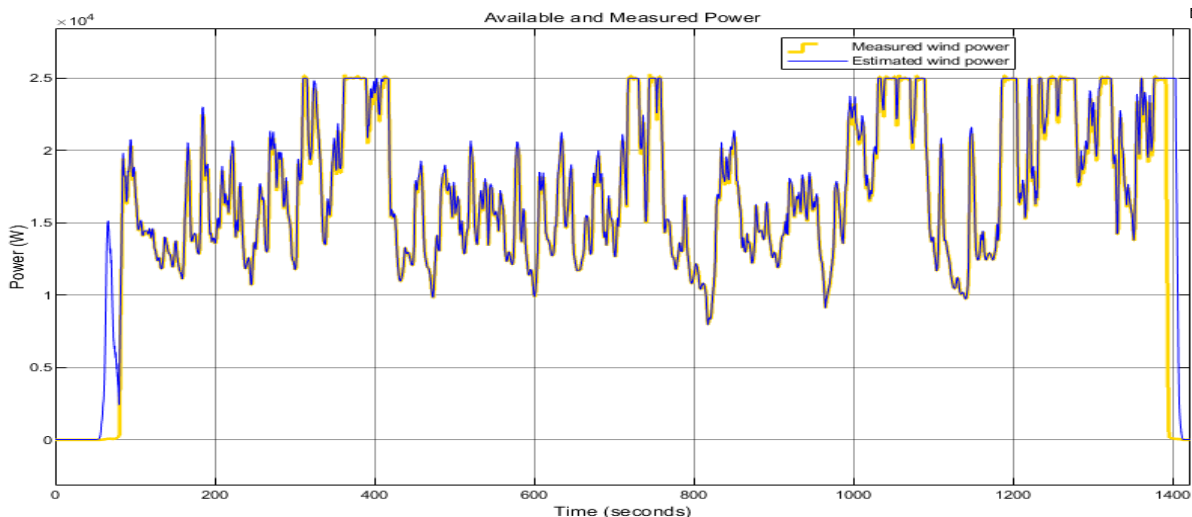


Figure 2-18: measured and estimated wind power

The figure 2-19 below present a comparison of the measured power and the simulated power. As discussed previously the measured power is calculated in MATLAB code using the readings from sensors provided in the text file while the simulated power is the electrical power at the output of the simulation. The simulated power is a bit less in magnitude at some points as shown in the plot but both curves follow the same pattern. It's enough to conclude that our

simulation is working in a desirable manner as the output of the simulation that is simulated power is somewhat similar to the measured power from real wind turbine.

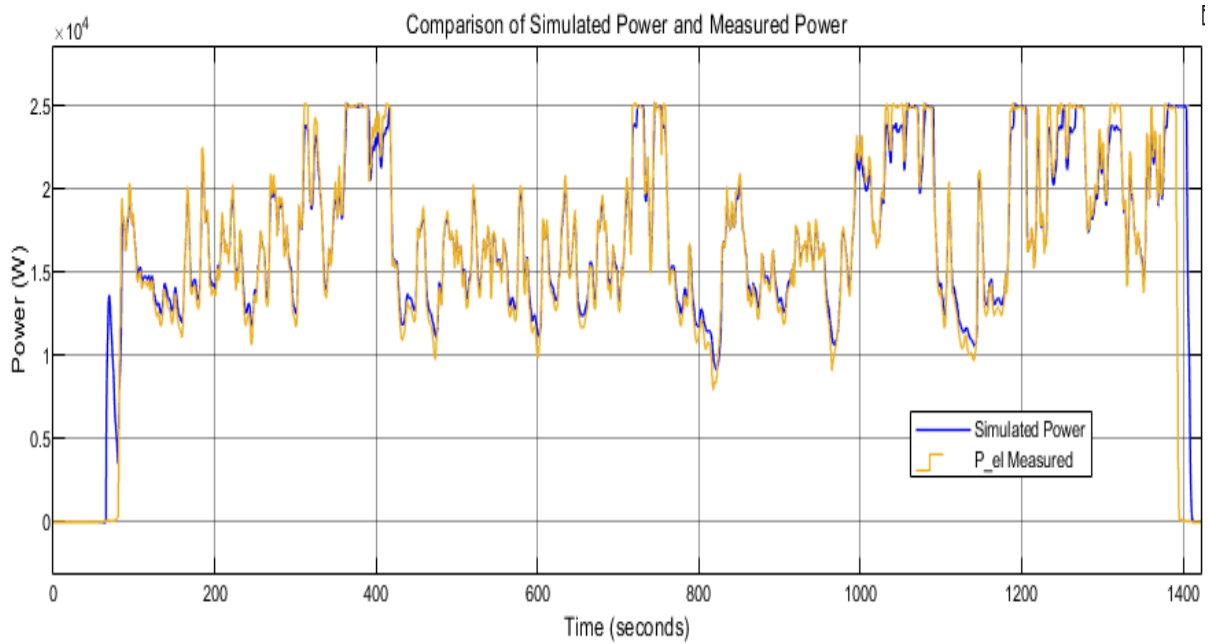


Figure 2-19: comparison of the measured power and the simulated power

In order to further verify the fact that the simulation is working in a desirable manner imitating the real wind turbine, the blade angle and the turbine speed both measured and simulated are provided respectively in the figures 2-20 and 2-21 below. It is evident from the plots that the simulated results are following the measured results. Another observation important to be mentioned is that during initial 100 seconds the measured and simulated values deviate significantly for the fact that this is the time during which the power plant starts, and it needs wind strong enough to produce power. Once the wind is appreciable enough to run the wind turbine and turbine achieves a normal running status the simulation results start following the measured results.

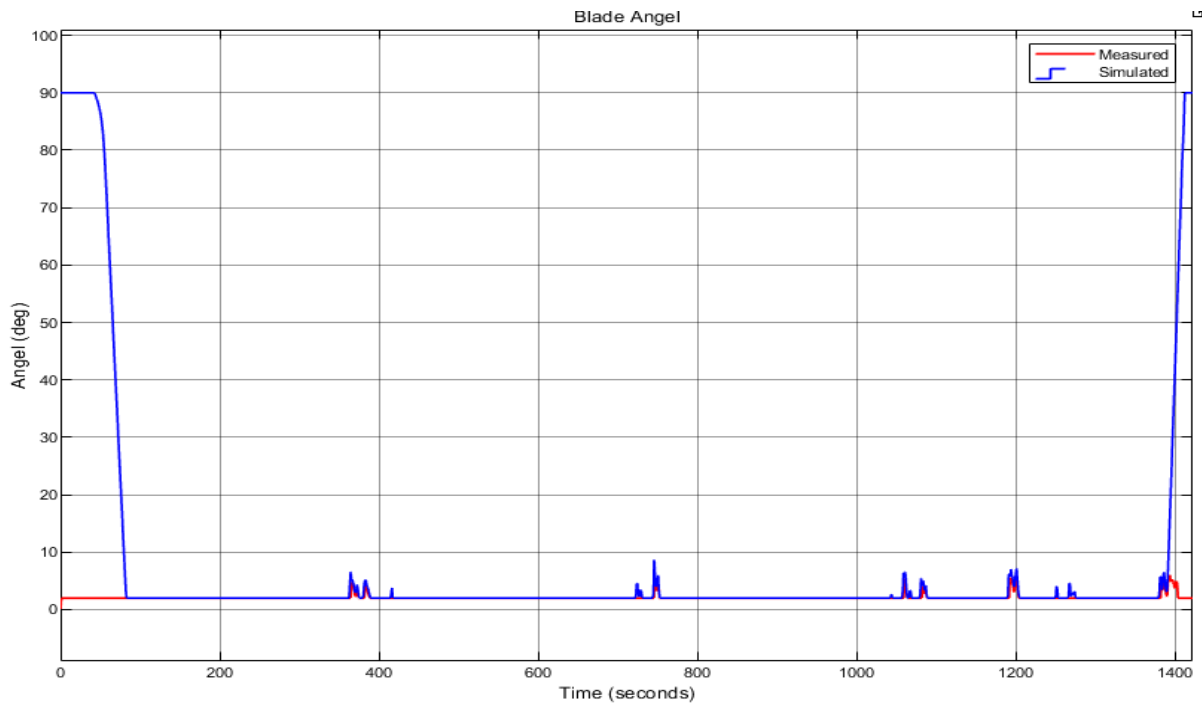


Figure 2-20: measured and simulated blade angle

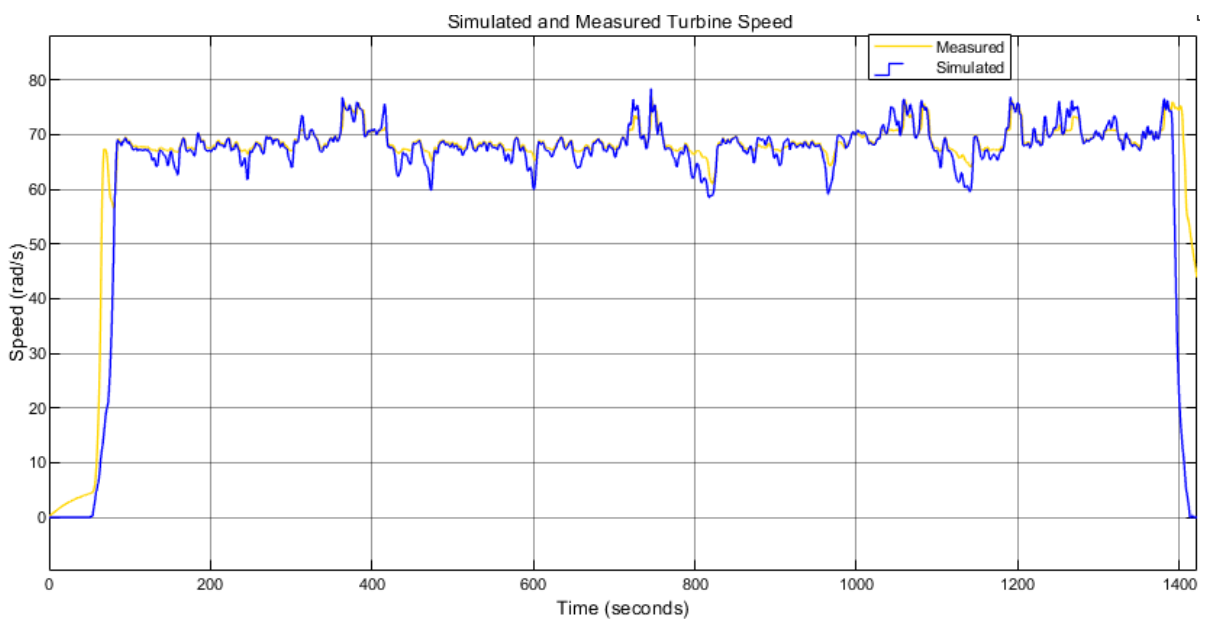


Figure 2-21: measured and simulated turbine speed

2.6.2 Results for 24 Hours Simulations

After verifying the fact that our model is behaving like the real wind turbine, in this section we present the results when the wind turbine model was run with measured wind speed data for 24 hours. Unlike the previous section, instead of estimated wind speed and wind power, measured wind speed was used to run the turbine model. As we didn't have the measured value for wind power, rotor speed and blade angle for 24 hours because the wind turbine only runs for a very short period of time which is 23 minutes approximately and not for the whole day. So first we ran our model for 23 minutes and compared our results with the measured

values of wind power, rotor speed and blade angle to verify our model. The model was verified so now we use the same model and get the wind power produced, rotor speed and blade angle during 24 hours of the day. In each plot the x-axis is the time in seconds from 0 to 86400 as there are 86400 seconds in 24 hours and our runtime for simulation is 86400 seconds.

Figure 2-22 below gives a plot of the wind power produced through the wind turbine over a period of 24 hours. It can be seen that the time period when the wind speed was high, more power is produced, and the maximum power produced during this time is not more than 25kW. The wind power keeps increasing and decreasing following the available wind but there are not very sudden harmonics or fluctuations making the whole model more stable and reliable.

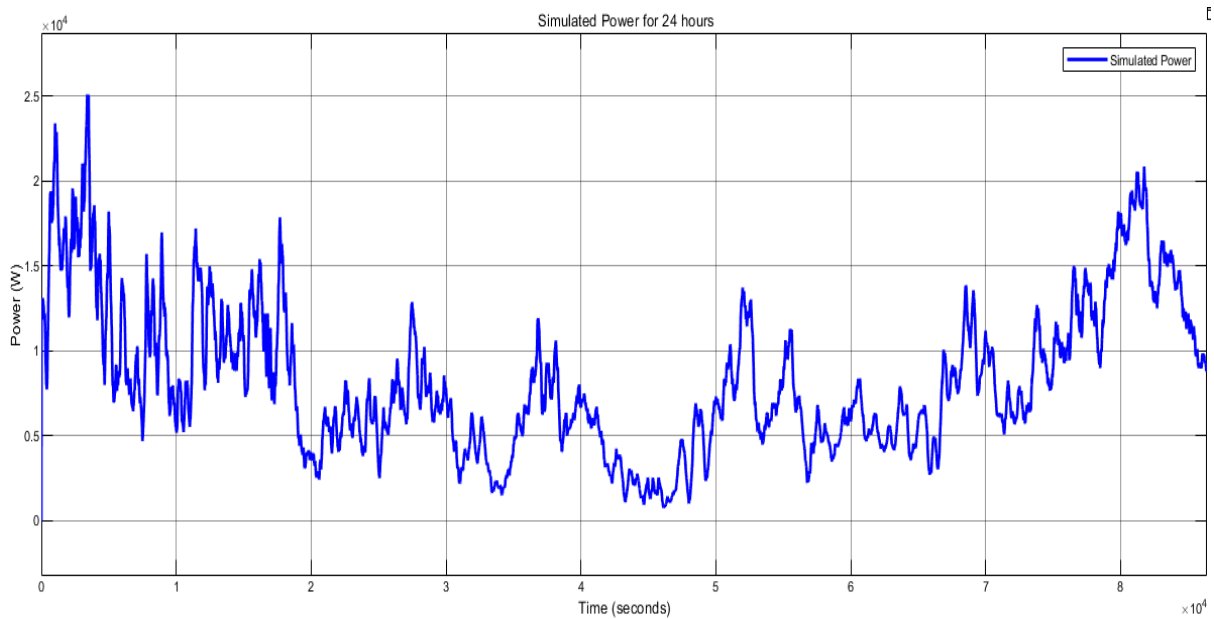


Figure 2-22: simulated power for 24 hours

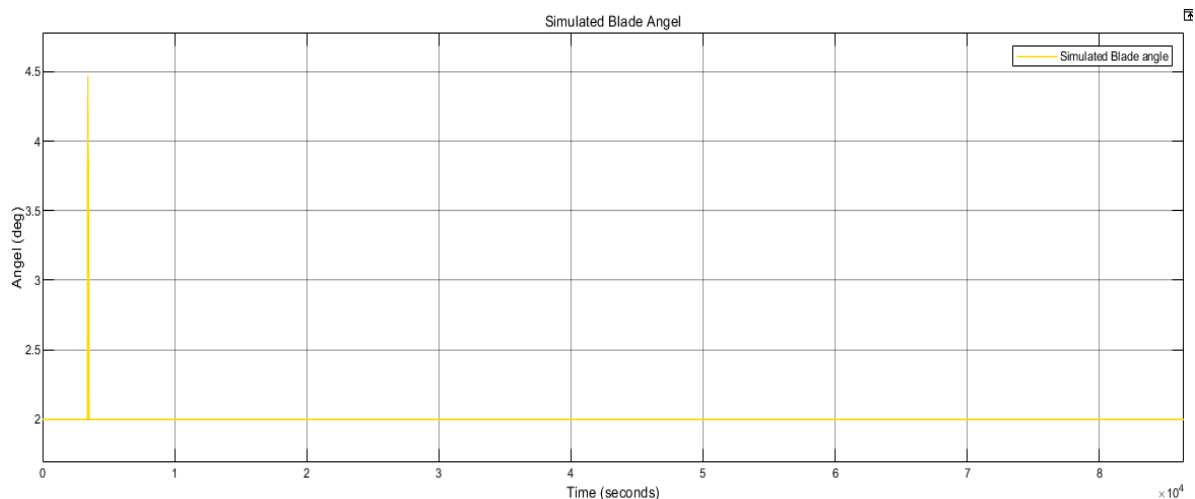


Figure 2-23: simulated blade angle

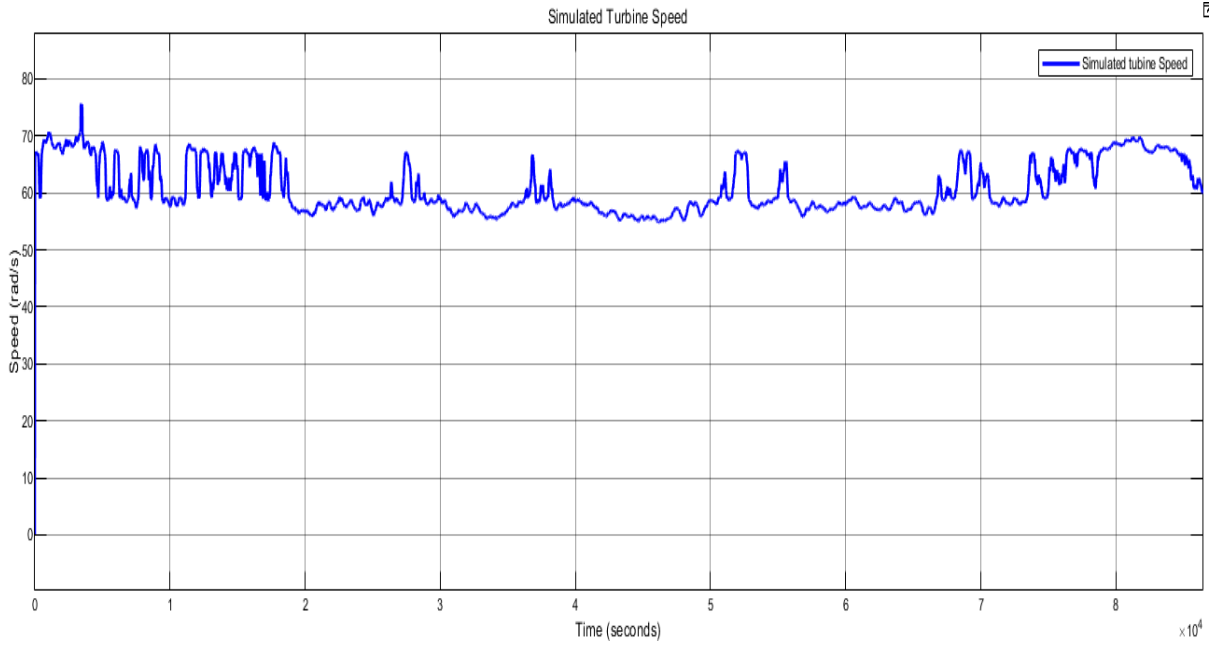


Figure 2-24: simulated turbine speed

3 Solar Power

This chapter gives a brief overview of how the solar radiations are converted to electrical power using photovoltaic effect. The chapter also bring into the light the sensors which are used to measure solar irradiance. Furthermore, the chapter covers the modelling and simulation of photovoltaic array in Simulink MATLAB. At the end of the chapter a detailed analysis of results of solar power model is provided.

3.1 Introduction

The sun radiates a large amount of energy in a day which is more than the total energy utilized by the world in a year [28]. The sun is a large sphere composed of hydrogen and helium gases [27]. Energy production occurs in the sun's inner core through a process called nuclear fusion. Solar radiations travel at approximately same the speed of light [24]. Just a fraction of visible radiant light emitted by the sun reaches the earth which is sufficient to meet our energy requirements [5]. In solar power setup, the basic components are solar cells that convert solar energy into electrical power. When number of solar cells are combined together, are called a solar module or solar panel. Similarly, Series of connected panels form a string and when Multiple strings combined together these form a basic solar power generating system.

3.2 The Photovoltaic Effect

The ability of certain materials to generate electric current when illuminated by sunlight is known as the photovoltaic effect. The solar radiations carry photons and these photons are absorbed when solar radiation strikes on the surface of the solar cell and transfer their transfer to the electrons of the semiconductor material [27]. Due to this, electrons move freely after getting the energy from the photons and these movements of electrons establish the electric current.

3.3 Solar cell or Photovoltaic cell

A solar cell changes sunlight into electrical energy. A solar cell is the basic element of a solar power system. When solar radiation falls directly, the solar cells produce more electrical energy. The solar cells reduce the dependence on fossil fuels and reduce environmental effects.

3.4 Solar Sensors

The solar sensors are used to measure the different aspects of solar radiation for solar power generation, weather monitoring and environmental research studies. There are two main types of solar radiation shown in figure 3-1: (i) Direct Solar Radiations, which directly reach the surface of earth without being scattered. These are the most intense and are the cause of brightness and sunny days on earth, and (ii) Diffused Solar Radiations, which are scattered by particles, gasses, filtered by the clouds in the atmosphere. or reflected by the ground surface. Diffuse radiation adds to the overall brightness of the sky, especially when

direct sunlight is blocked by clouds etc.

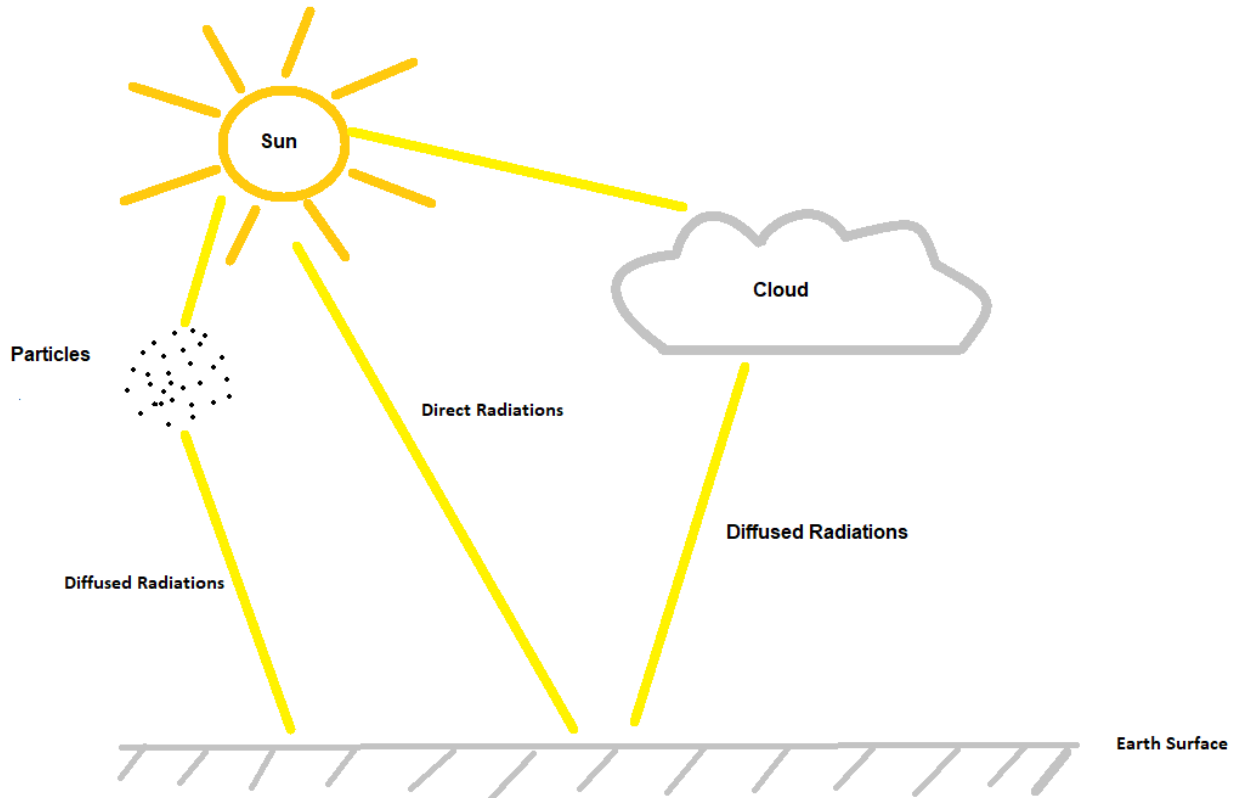


Figure 3-1: different types of solar radiations

3.4.1 Pyranometer

Pyranometer is used to measure the solar irradiance at certain places. Figure 3-2 shows the basic illustration of a pyranometer. Pyranometers are used in parallel, sloping and inverted alignments [29]. A pyranometer has a 180-degree field of view angle. This combination of glass and coating also has a flat spectrum response in the range of 300 to 3000 nanometers [1]. The solar radiation is transmitted by the pyranometer glass dome and is observed by a black coating where it is converted into heat. Inside a pyranometer you can find a very temperature difference sensor called a thermopile. Thermopiles do not require any power supply. A pyranometer has the following main components:

3.4.1.1 Thermopile

It is used to convert the solar radiations into an electrical signal to measure the intensity of solar irradiance. Thermopile calculates the temperature difference. Due to gradient of temperature between surfaces a potential difference is created. The potential difference is measured with the help of a volt meter.

3.4.1.2 Glass Dome

Glass dome in the pyranometer is used to protect the thermopile from rain, wind and other environmental effects. The glass dome consists of two glass covers. The second glass in the glass dome gives extra protection to the inner dome and thermopile which helps to reduce error during measurements.

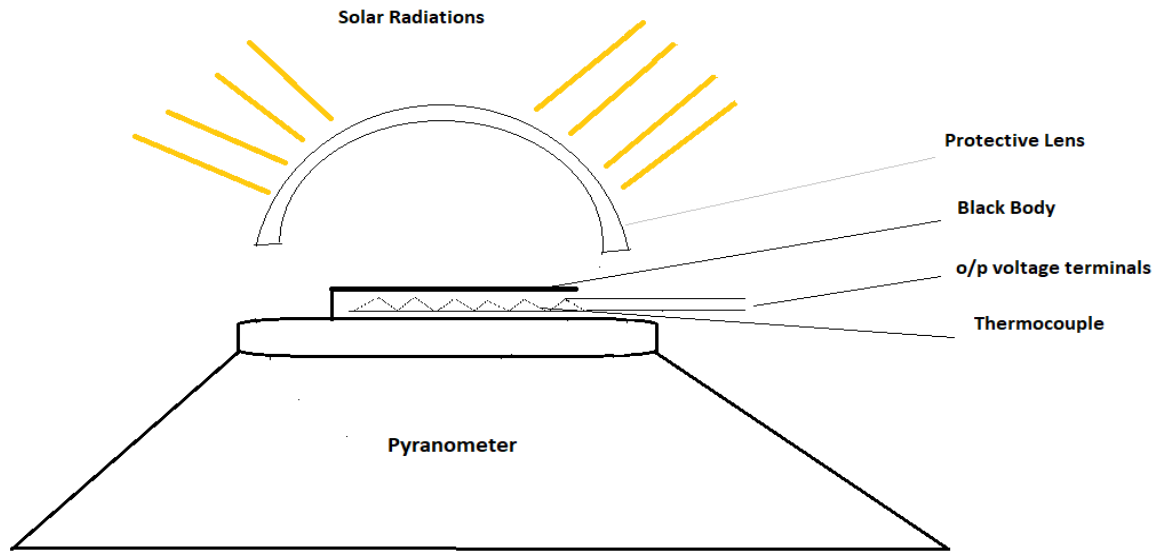


Figure 3-2: pyranometer

3.5 Equivalent Circuit of Solar Cell

Figure 3-3 represents the equivalent circuit of a solar cell. It contains a current source, a diode, a series resistor and a parallel resistor

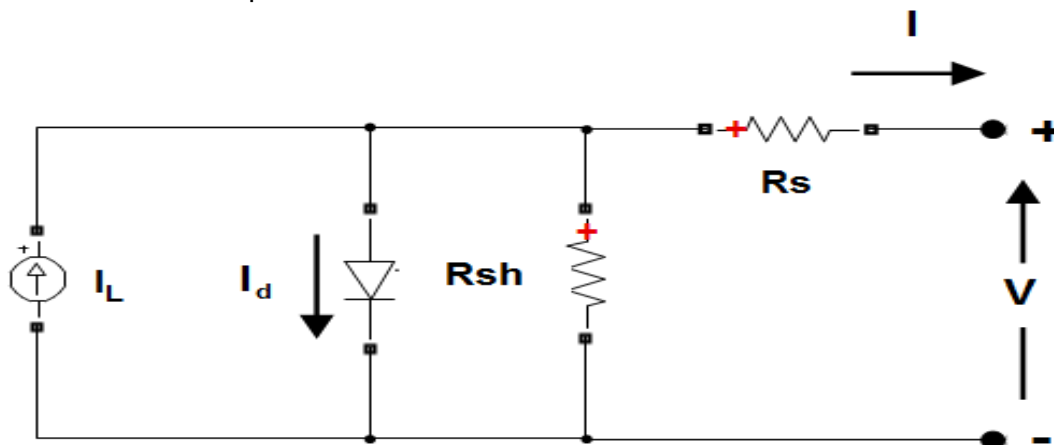


Figure 3-3: the equivalent circuit of a solar cell

The current source generates the current which is called photo generated current and is generated as a result of receiving solar irradiance. This I_{ph} is directly proportional to Irradiance (the intensity of solar radiations) that is the power in the solar cell. The small part of photo generated current I_{ph} flows through the diode which is called diode current I_d and the remaining current will flow out from the cell which is denoted by I_{sc} . The current flowing out of the solar cell is given as:

$$I_{sc} = I_{ph} - I_d - I_{Rs} \quad (3-1)$$

$$I_{sc} = I_{ph} - I_o \left(e^{\frac{qv}{\alpha KT}} - 1 \right) - I_{Rs} \quad (3-2)$$

$$I_{sc} = I_{ph} - I_o \left(e^{\frac{q(v+IR_s)}{\alpha KT}} - 1 \right) - \frac{v+IR_s}{R_{sh}} \quad (3-3)$$

Where,

I_{ph} is photon current

q is charge on an electron

α is the diode ideality factor

K is Boltzmann constant

T is temperature in kelvin

I_o is diode saturation current

When there is no solar radiation that is under dark condition in that I_{ph} will be zero there will be no photon current or solar irradiations under that condition the diode will be reverse biased so the current flowing through the diode will be reverse saturation current.

$$I_d = I_o \left[\exp\left(\frac{V_d}{V_T}\right) - 1 \right] \quad (3-3a)$$

3.6 MATLAB Simulation of Solar Array

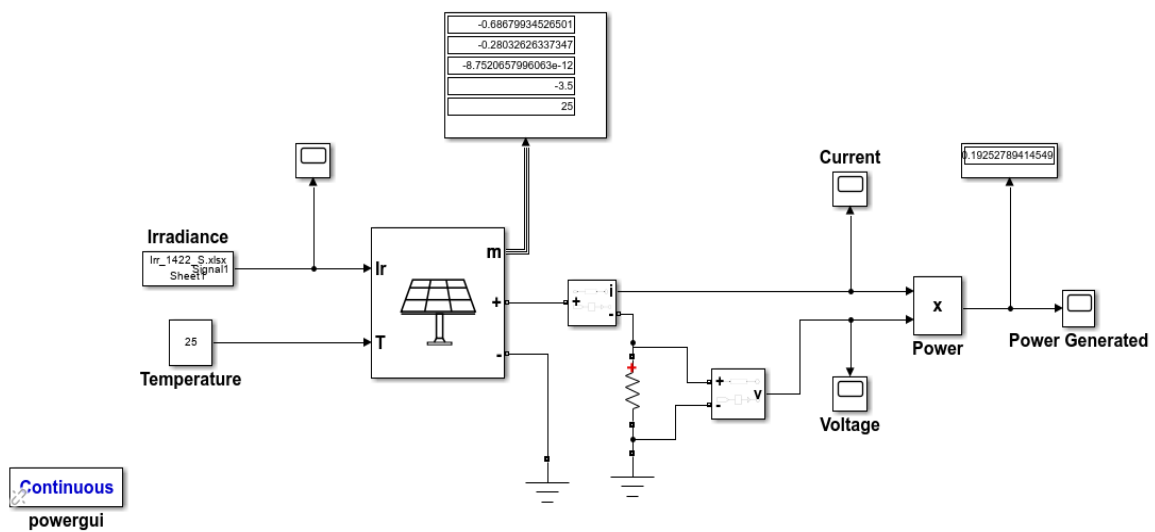


Figure 3-4: solar power model

From the figure 3-4, it can be seen on the left side of the PV array, there are two input ports one is I_r which stands for solar irradiance and other is T which stands for temperature. On the right side of the PV array, it has three ports. The positive and negative are used to connect it with other components and at top there is a measurement port represented by symbol m . From this measurement port, we can measure voltage, current, irradiance, temperature and diode current respectively. When we double click the PV array, the block parameters are displayed which gives useful and important information about the PV model. During the module section of the block parameters, there are a large number of standard modules of PV array by different companies available. In the module parameter section of the PV array, it provides basic parameter values of the model namely light-generated current I_l , diode saturation current I_o , diode ideality factor α , shunt resistance R_{sh} and series resistance R_{se}

respectively. Another important section of this model is the display of Current-Voltage (I-V) and Power-Voltage (P-V) characteristics at different temperatures and solar irradiances. To see the current- voltage and power-voltage characteristics of the model of PV array we will have to click the plot on the block parameters. To design the PV module of desired power rating, the module data section will provide a special feature to design PV array modules by user defined values. By clicking on the user option, we can insert the various parameter values. But we have used Module Advance Power API-M360 with adding 8 parallel strings and 6 series connected modules per string for delivering output power. The model parameters are as under:

Table 3-1: parameters for solar model API-M360

Parameter	Symbol	Value	Unit
Maximum Power	P	359.752	W
Cells per Module	N_{cell}	72	Nos
Parallel strings	-	8	Nos
Series-connected modules per string	-	6	Nos
Open circuit voltage	V_{oc}	47.6	V
Short Circuit Current	I_{sc}	9.99	A
Voltage at maximum power point	V_{mp}	38.6	V
Current at maximum power point	I_{mp}	9.32	A
Temperature coefficient of Voc	-	-0.282	%/deg.C
Temperature coefficient of Isc	-	0.04200	%/deg.C
Light generated current	I_l	10.0116	A
Diode saturation current	I_o	1.5X10e-11	A
Diode ideality factor	-	0.94719	-
Shunt resistance	R_{sh}	180.3189	Ω
Series Resistance	R_{se}	0.39053	Ω

3.7 Characteristics of Solar Cell

A solar cell has two characteristics (i) the Current versus Voltage characteristics and (ii) the Power versus voltage characteristics. So, both characteristics are drawn against voltage.

3.7.1 I-V Characteristics of Solar Cell

From figure3-5, it can be seen that the voltage varies from zero to its maximum value. When we get zero voltage across the diode, we have to short circuit output terminals because voltage across the short circuit is always zero so maximum current will flow across the terminals because of zero resistance. Maximum value of voltage is obtained when terminals of the solar cell are open circuited. Corresponding to the open circuit, the voltage will be maximum and is denoted by V_{oc} .

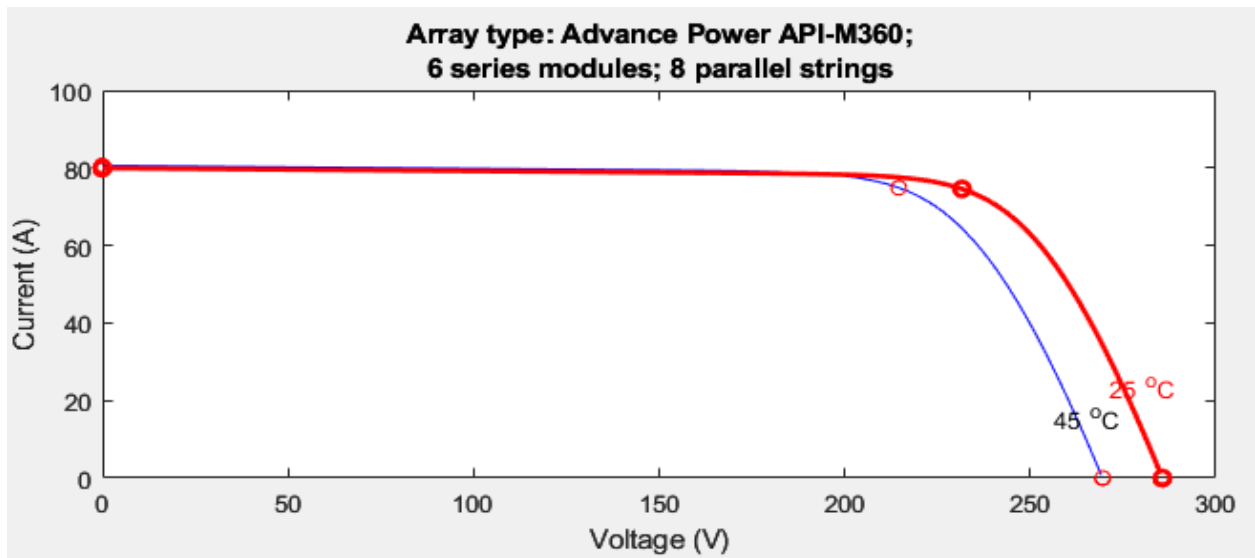


Figure 3-5: current-voltage (IV) characteristics

3.7.2 P-V Characteristics of Solar Cell

Figure 3-6 shows the P-V characteristics of a solar cell and from the figure it can be seen how output power varies with voltage. In the graph of the P-V curve there is a maximum power point P_{max}. At P_{max} the solar cell works efficiently by extracting maximum power from the solar radiation. Overall solar irradiance, temperature and load affects the shape of the P-V curve.

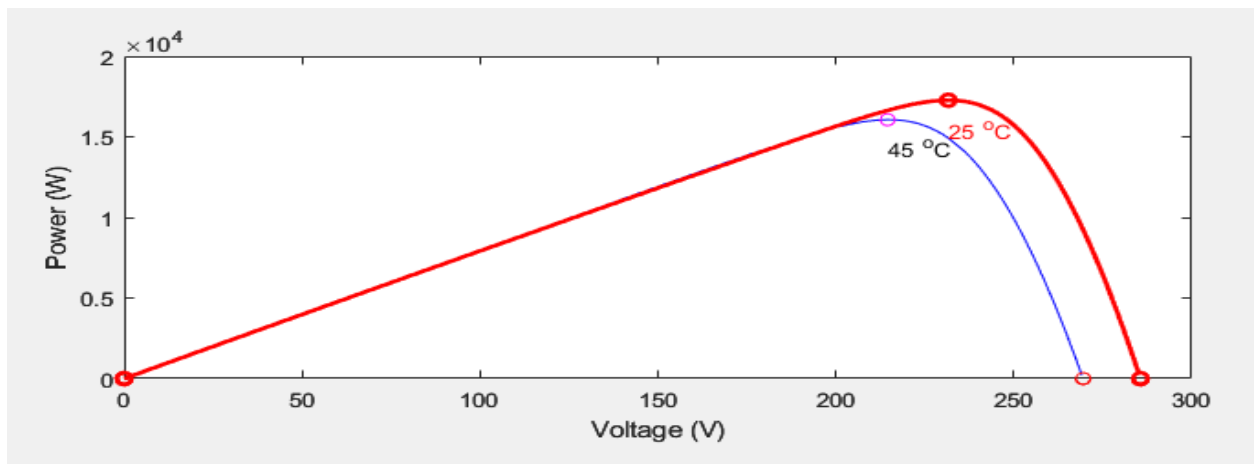


Figure 3-6: power- voltage (PV) characteristics

3.8 Short Circuit Current

Maximum current that flows from a solar cell when the terminals are short circuited is called Short Circuit Current. The short circuit current mainly depends on solar irradiance whereas the variation of short circuit current with temperature has low effect so it can be neglected.

3.9 Open Circuit Voltage

It is defined as the maximum voltage across the terminals of solar cell when terminals are short circuit is called open circuit voltage. The open circuit voltage varies little with temperature and too much with respect to solar irradiance.

3.10 Results of Solar Power

Figure 3-7 denotes the solar irradiance of a full sunny day 17th March 2024. The data is taken from the solar sensor installed at Chalmers Research wind turbine at Björko. The X-axis represents time and Y-axis shows solar irradiance. It can be seen that between 0 to 25200 seconds, the solar irradiance is zero. From 25200 seconds solar irradiances start increasing and go to maximum value in 45000 seconds. From 45000-55800 seconds solar irradiance starts decreasing. From 55800-64800 seconds, solar irradiance drops too much due to passing of clouds. Finally, solar irradiance goes to zero from 64800-86400 seconds due to sunset.

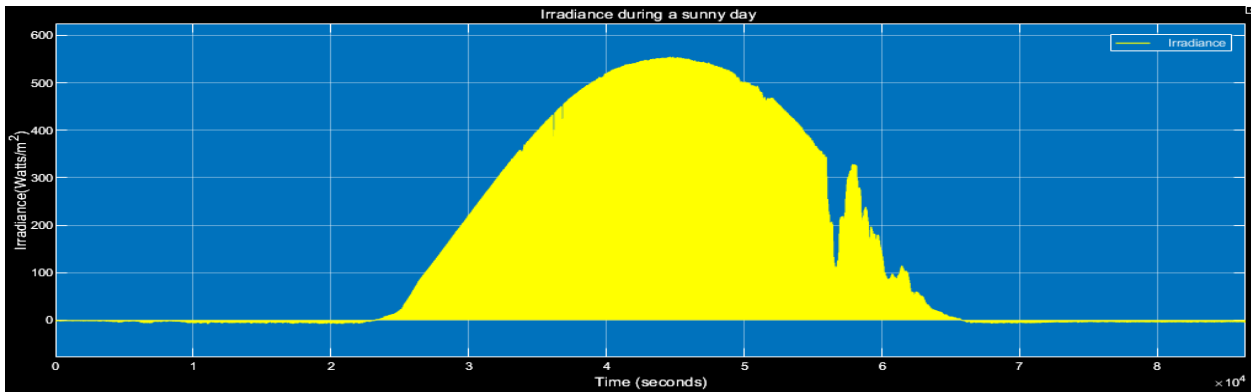


Figure 3-7 : solar irradiance during a sunny day

Figure 3-8 represents output of the power generated during the same day 17th March 2024. The horizontal axis denotes time, and vertical axis shows power generated. Up till 25200 seconds there is no solar irradiance. From 25200 seconds solar power starts increasing and goes to its maximum value of 5400 watts at 45000 seconds. From 45000-55800 seconds power starts decreasing. From 55800-64800 seconds power drops too much due to passing of clouds. Finally, solar power goes to zero from 64800-86400 seconds due to sunset.

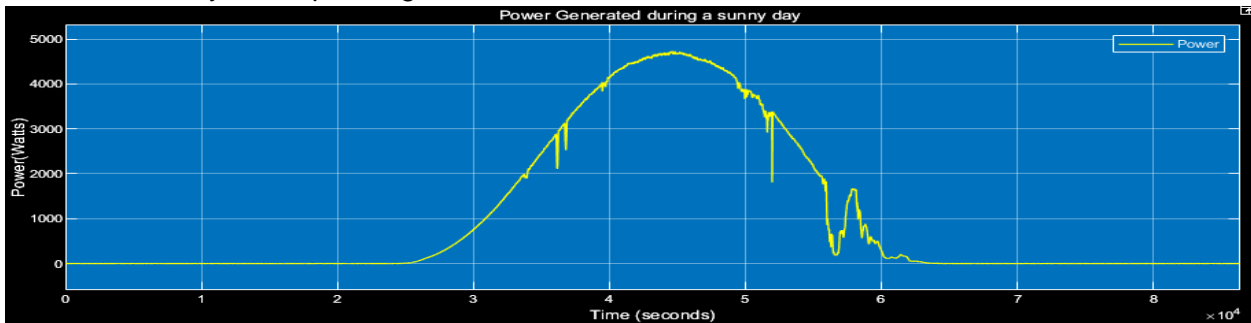


Figure 3-8: power generated during a sunny day

Figure 3-9, shows the solar irradiance on a cloudy day. The data was taken from solar sensors installed at Chalmers research wind turbine at Björko on 16th March 2024. The figure indicates that the time is shown on x-axis and irradiance is shown on y-axis. Until 25200 seconds, the solar irradiance is zero. From 25200 seconds solar irradiance starts increasing and goes to their maximum value in 49000 seconds. From 49000 onwards solar irradiance start to decrease until 52000 seconds and further drops due to passing of clouds. Finally, solar irradiance starts to increase and then goes to zero from 64800-86400 seconds due to sunset.

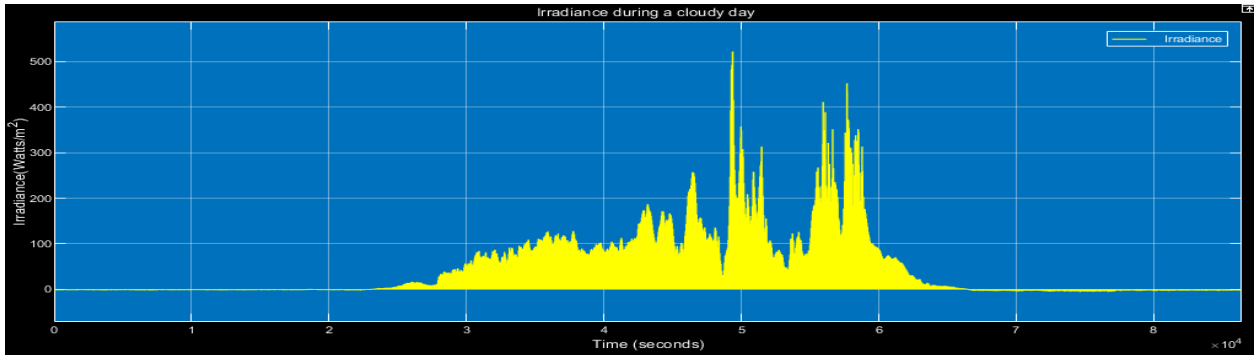


Figure 3-9: solar irradiance during a cloudy day

Figure 3-10 represents output of the power generated on the same day. The X-axis shows time whereas Y-axis denotes power generated. Up till 25200 seconds, the power is zero due to the non-availability of solar radiation. Solar power starts growing from 25200 seconds and reach to maximum value in 49000m seconds. Due to cloudy day, output power generated is not meeting load requirements.

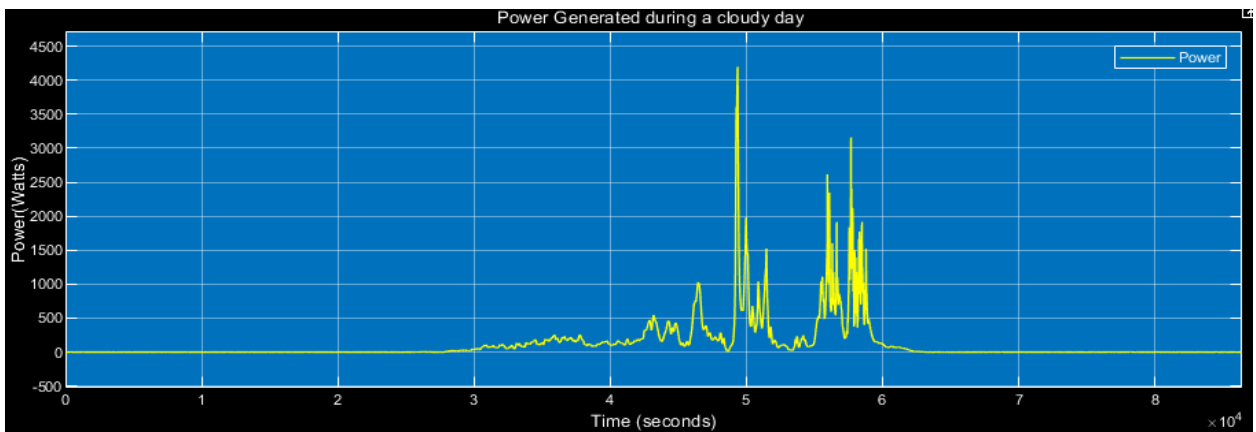


Figure 3-10: power generated during a cloudy day

3.11 New Solar Model

The Previous solar model was built on MATLAB Simulink and provided good performance when functioning independently to generate power based on solar irradiance input. However, difficulties occurred when integrating this model with wind and battery models. Upon identifying the root cause of these integration errors, it was found that the solar model operated on a variable-step solver with a fundamental sample time of 0.05 seconds, whereas the wind and battery models were configured to use a fixed-step solver. To mitigate this issue and to ensure interaction within the system, a new solar model was developed to align with the fixed-step solver settings utilized by the wind and battery models. This updated solar model dynamically adjusts its time steps, thereby facilitating synchronized operation and seamless communication among the interconnected components. The transition to a variable-step solver for the solar model not only resolved the integration issues but also optimized the overall performance of the integrated renewable energy system.

The new solar model in MATLAB Simulink utilized the dataset of solar radiation levels over a full day in March 2022 in seconds to simulate solar energy patterns at the location of the Chalmers research wind turbine site. This dataset provided the model to work accurately when

sunlight radiation varied throughout the day of that specific month. The utilization of solar irradiance inputs provided the model's capability to simulate realistic solar energy generation scenarios, which is essential for comprehensive energy system analyses and optimization. Solar irradiance values are inserted from the dataset whereas 25 centigrade temperature is taken as a reference value for making calculation simple and easier.

3.11.1 Mathematical Modeling of a Solar Array

The simulation block diagram of a PV array as shown in figure 3-11, includes solar irradiance as an input parameter along with fixed values for temperature T , diode saturation current I_0 , diode ideality factor α , and series resistance R_s . The model used 6 series and 8 parallel cells and is shown in below diagram:

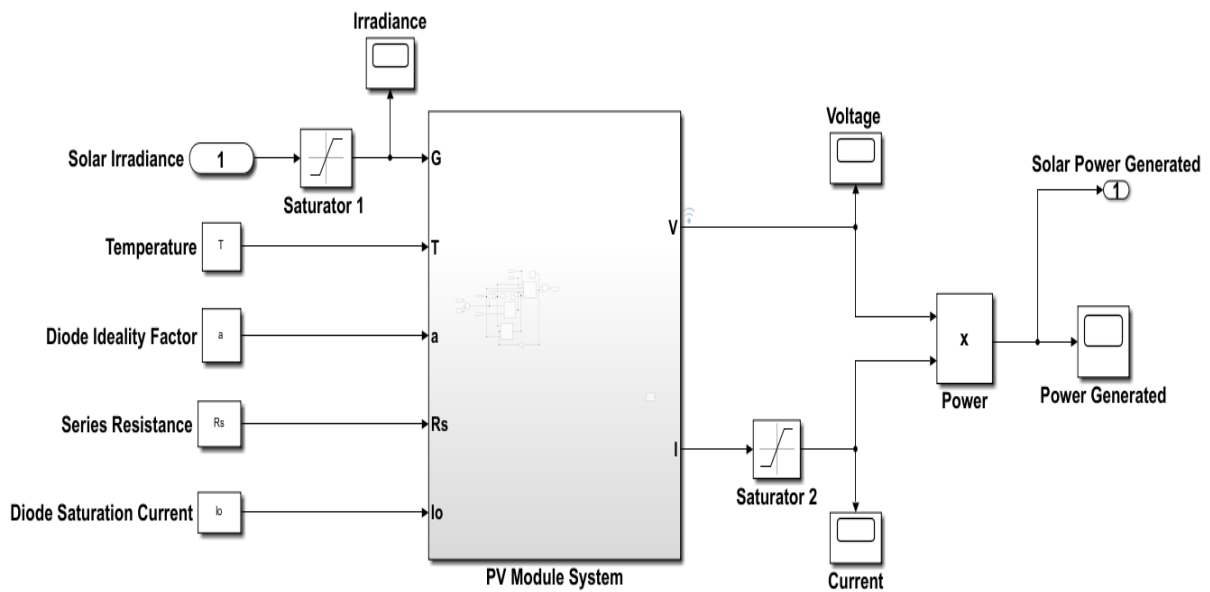


Figure 3-11: solar model on Simulink

The subsystem of the solar model is shown in figure 3-12:

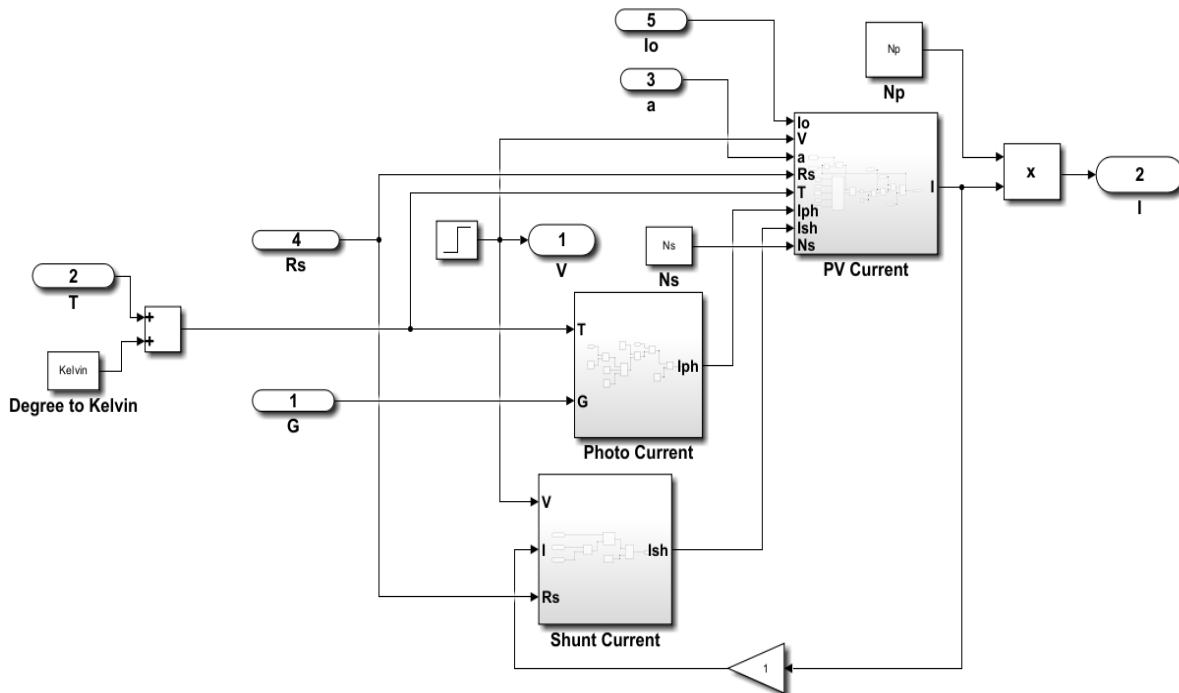


Figure 3-12: sub systems for solar model

Following equation is used to calculate the photocurrent:

$$I_{ph} = \frac{[(T - T_{ref})K_{sc} * I_{sc}] * G}{1000} \quad (3-4)$$

The above equation is used to calculate the Photo current I_{ph} generated by the photovoltaic cell. It first calculates the temperature difference $T - T_{ref}$ multiplied by the temperature coefficient of short-circuit current K_{sc} and the short-circuit current I_{sc} . This product is then multiplied by the solar radiation intensity G and then is divided by 1000.

The mathematical representation of the photocurrent model is illustrated in figure 3-13 below.

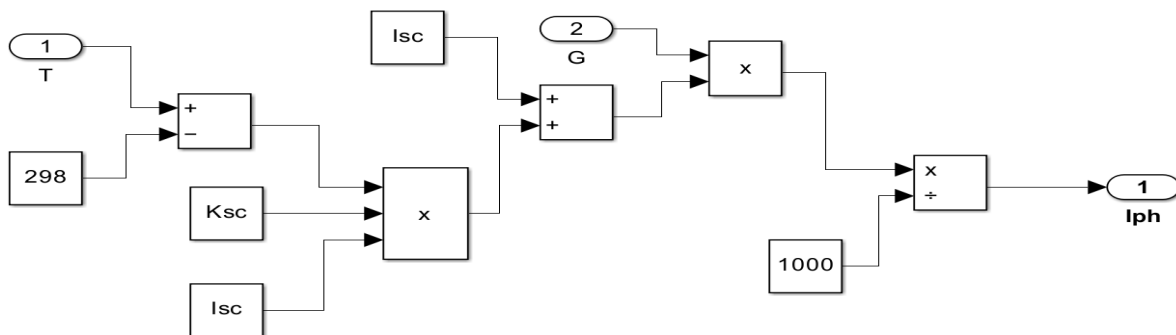


Figure 3-13: modelling of photo current

We used the following equation to calculate the shunt current.

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \quad (3-5)$$

The mathematical representation of this shunt current model is shown in figure 3-14 below:

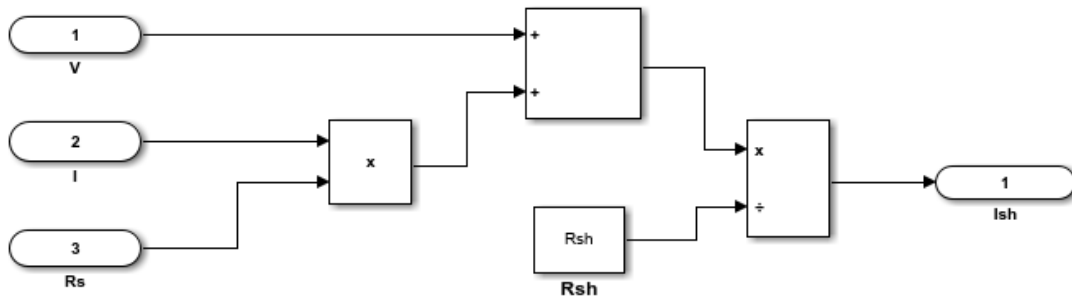


Figure 3-14: mathematical modeling of shunt current

For calculating the output current I , the following equation was used.

$$I = I_{ph} - I \left(e^{\frac{I_{sc} * R_s}{vT}} - 1 \right) - \frac{I_{sc} * R_s}{R_{sh}} \quad (3-6)$$

Figure 3-15 shows the mathematical representation of output current.

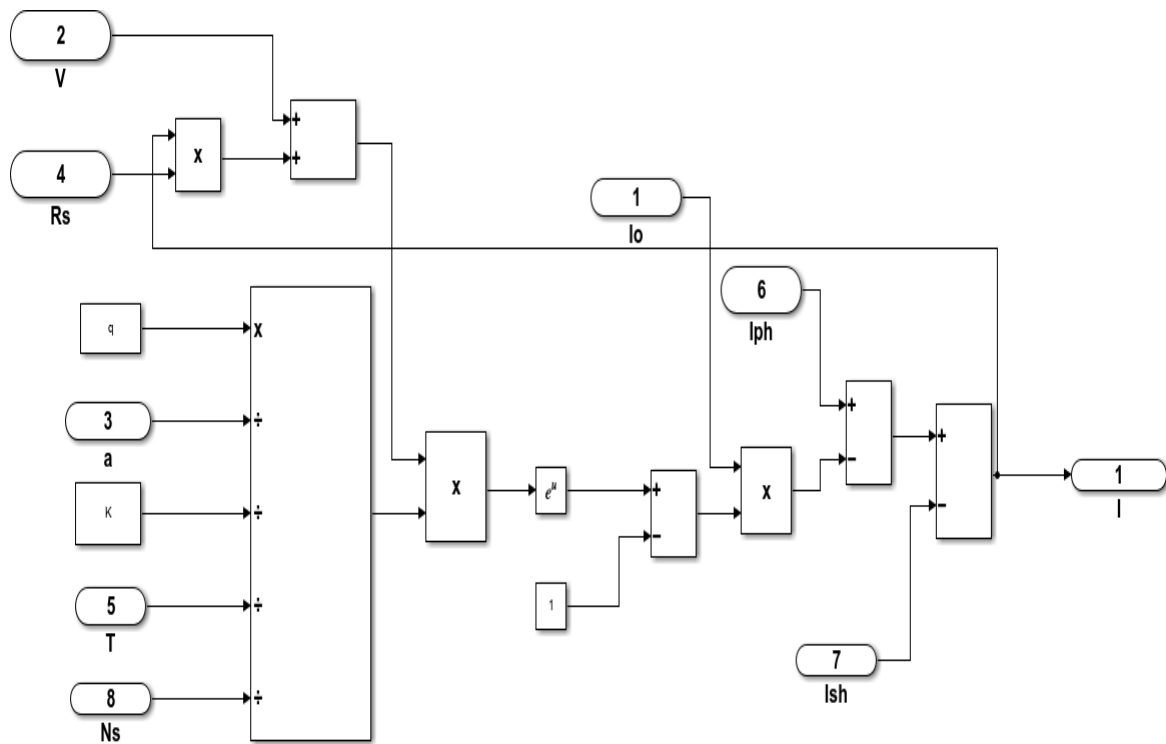


Figure 3-15: modelling of PV output current I

Other parameters for modeling are shown in table 3-2:

Table 3-2: parameters of solar model

Parameter	Symbol	Value	Unit
Temperature	T	25	Degree Celsius
Diode Ideality Factor	$Alpha$	1.5	-
Series Resistance	R_s	0.39053	Ohm
Diode Saturation Current	I_o	5×10^{-8}	A
Number of cells connected in parallel	N_p	8	Nos
Short circuit Temperature coefficient	K_{sc}	0.0032	J/C
Short Circuit Current	I_{sh}	9.99	A
Shunt Resistance	R_{sh}	180.3	Ohm

3.12 Results of Solar Model

Figure 3-16 shows solar irradiance for 1422 seconds. The x-axis represents time in seconds whereas y-axis shows solar irradiance. From 0 to 400 seconds, the solar irradiation is at its peak. From 400 to 780 seconds solar irradiance start decreasing. Between 780 and 950 seconds, the solar irradiation drops down too much due to passing of clouds and increase when clouds pass. After this period of sudden decrease and increase, the irradiance continues to decrease further and goes to zero between 1250 to 1422 seconds.

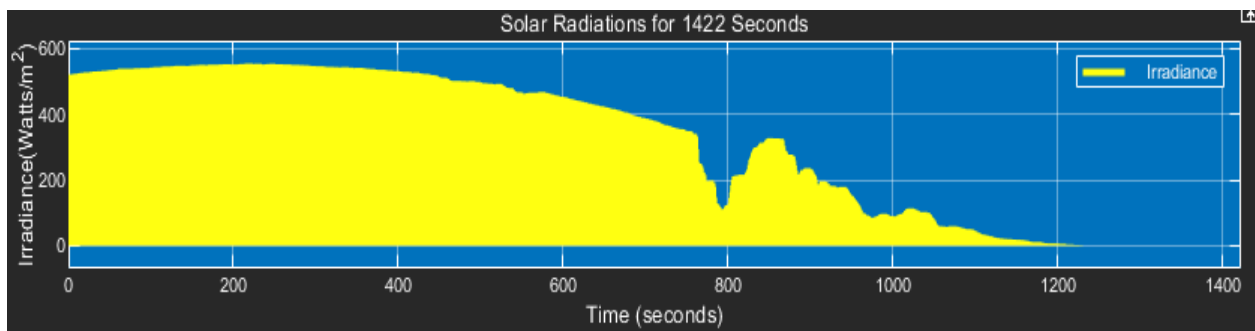


Figure 3-16: solar irradiance for 1422 seconds

The graph in figure 3-17 illustrates the power generated over a time interval from 0 to 1422 seconds. The horizontal axis denotes time in seconds whereas vertical axis shows solar irradiance in watts per square meters. By examining the graph, we can identify distinct patterns in power generation. Initially, from 0 to 400 seconds, the solar power reaches its peak, indicating the maximum power available during this interval. After this peak, the power begins to decline steadily from 400 seconds to 780 seconds. Between 780 and 950 seconds, solar power shows fluctuations, possibly due to transient factors such as passing clouds. Following this period of fluctuation, the power continues to decrease and eventually drops to zero from 1250 to 1422 seconds. This final drop to zero suggests a complete absence of solar radiation, likely corresponding to the setting of the Sun.

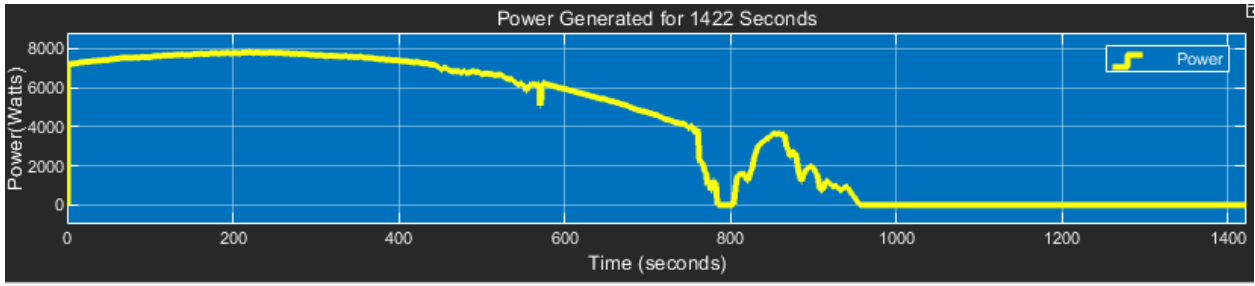


Figure 3-17: solar power generated for 1422 seconds

Figure 3-18 denotes the solar irradiance of a full day. The solar irradiance is represented by y-axis and time is shed in x-axis. Up till 25200 seconds, the solar irradiance is zero. From 25200 seconds starts increasing and goes to its maximum value in 45000 seconds. Between the interval 45000-55800 seconds solar irradiance starts decreasing. From 55800-64800 seconds, solar irradiance drops too much due to passing of clouds or due to rain. Finally, solar irradiance goes to zero from 64800-86400 seconds due to sunset.

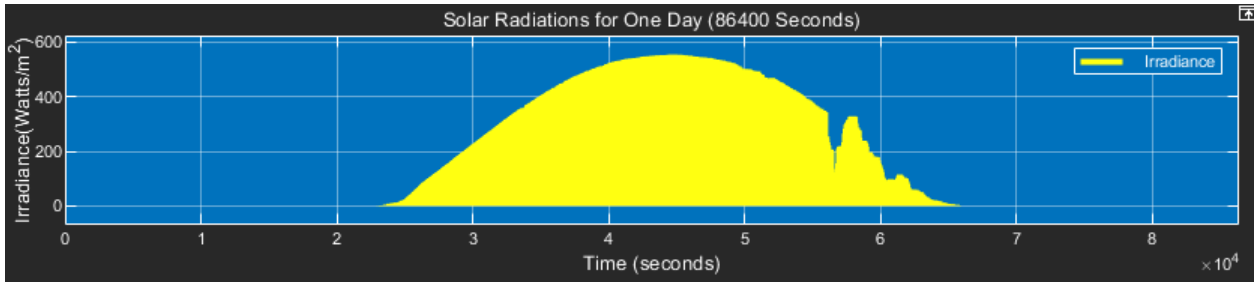


Figure 3-18: solar irradiance for 24 hours

Figure 3-19 shows the output power generated during a day with x-axis denotes time and y-axis shows power generated in watts. From 0-25200 seconds, the output power is zero. From 25200 seconds solar power starts increasing and goes to its maximum value i.e. 7800 watts at 45000 seconds. From 45000-55800 seconds power starts decreasing. From 55800-64800 seconds power drops too much due to passing of clouds. Finally, no solar power is generated between 64800-86400 seconds due to complete sunset.

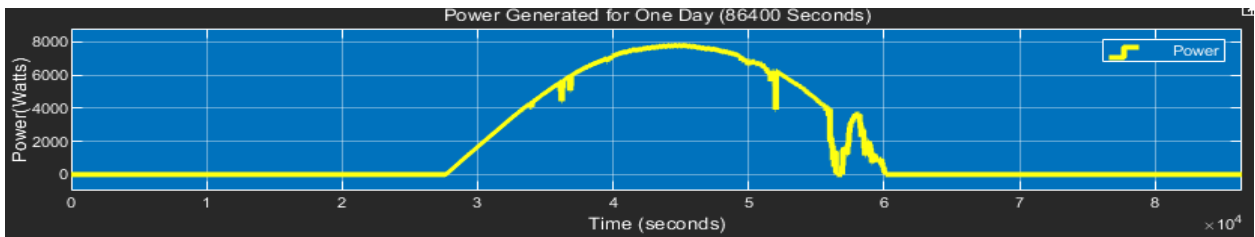


Figure 3-19: solar power generation for 24 hours

4 Battery

This chapter presents the brief introduction of the battery and its components. The chapter also introduces the basic concepts of state of charge and charging rate. After developing an understanding of fundamental concepts of battery the chapter illustrates the modelling and simulation of battery in MATLAB Simulink. Moreover, the results of the battery model are also presented and analyzed.

4.1 Introduction

Due to intermittent nature of wind and solar powers and to maintain stable and reliable islandic operation, lithium-ion batteries are the perfect solution. During the charging, the battery converts electrical energy into chemical energy and during discharging it converts stored chemical energy into electrical energy [8]. For the last thirty years, an outstanding improvement has occurred in both commercial and academic research on lithium-based batteries. During this period, advancements in electrochemical processes, developments in new electrode materials, improvements in battery performance have been made. In 1979, Professor John B. Goodenough and his colleagues have used lithium cobalt oxide (LiCoO_2) as a positive-electrode material in rechargeable lithium-ion batteries [8]. This discovery made a significant advancement in battery technology, for enhancing energy density and stability as compared to previous electrode materials. In 1982, researchers Rachid Yazami and Michel Touzain [8] carried out a successful experiment in the development of lithium-ion battery technology that explained how lithium ions are inserted and removed from graphite electrode through electrochemical process. In 1987, Akira Yoshino invented the first practical lithium-ion battery by using a "soft carbon" material for the battery's anode along with Goodenough's previously reported LiCoO_2 cathode and carbonate ester-based electrolyte which was commercialized by a Sony and Asahi Kasei team led by Yoshio Nishi in 1991 [9].

4.1.1 Anode

It is a negative electrode. Anode material is called graphite due to good electric conductivity, scalability to enhance performance and longevity [23].

4.1.2 Cathode

It is a positive electrode. Cobalt Oxide, Lithium Manganese Oxide, or Lithium Iron Phosphate are used as cathode materials [10].

4.1.3 Electrolyte

Electrolyte gives path to move lithium ions from anode to cathode and vice versa. The most commonly used electrolyte is LiPF_6 in ethylene carbonate (EC) solvent [23].

4.1.4 Separator

A separator in a battery separates anode and cathode to avoid short circuit and allows the flow of lithium's ions for providing electrochemical processes. The separators common types are microporous, non-woven, electro spun and composite membranes [23].

4.1.5 Binders

In a Lithium-Ion battery, the binders help to stick together the active material like lithium cobalt oxide in the cathode or graphite in the anode, along with conductive additives, so they stay connected and in place. The binder also sticks these components onto the aluminum foil for cathode or copper foil for anode that acts as the current collector. Essene binder plays a crucial role in keeping everything organized and connected inside the battery electrode, ensuring efficient electron flow during charging, and discharging. Polyvinylidene Fluoride (PVDF) is the most common binder for LIB [23].

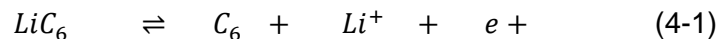
4.1.6 Conductive Additives

These provide electron transport throughout the electrode and also assist in maintaining uniform current distribution and preventing the formation of localized hotspots. Most commonly used conductive additives are carbon based with different morphologies.

4.2 Charging and Discharging of Lithium-ion Batteries

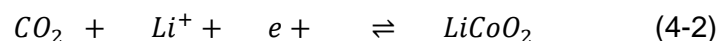
Lithium ions go from cathode to anode while the charging and are stored at anode material. Similarly, during discharging reverse process occurs, lithium ions move back from anode to cathode and are stored at cathode terminal.

During the discharging, the stored chemical energy in the battery is being converted into electrical energy [11]. The equation for chemical reaction at Anode (Graphite) during discharging and charging of lithium-ion battery is [12]:



From Left to Right \longrightarrow Discharging and from Right to Left \longrightarrow Charging

The equation (4-2) is the equation for chemical reaction at Cathode (Lithium Cobalt Oxide $LiCoO_2$) in discharging and charging of lithium-ion battery [12]:



From Left to Right \longrightarrow Discharging and from Right to Left \longrightarrow Charging

4.3 Charging/discharging Rate (C-Rate)

The C-rate is defined as the speed which shows how battery is charged or discharged is called C- rate. Higher values show fast charging and discharging time. Whereas lower values indicated slow charging and discharging times [12].

Following are the different c-rate values;

- 1 C Rate => Discharge or Charge in 1 hour
- 2 C Rate => Discharge or Charge in ½ hour
- 5 C Rate => Discharge or Charge in 12 minutes
- 0.1 C Rate => Discharge or Charge in 10 hours

4.4 State of Charge (SOC)

The charge left in a battery with respect to its full capacity is called state of charge. The state of charge gives information about health of battery.[13]. Various methods, for example voltage-based calculations, coulomb count and modern algorithms are used to estimate the soc.

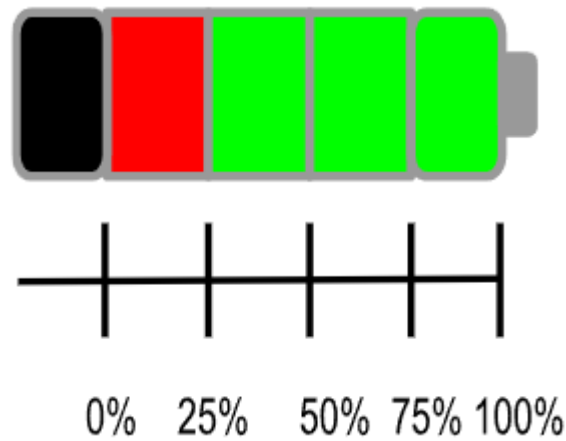


Figure 4-1: state of charge (SOC) of a battery

4.5 Battery Model

The chapter focuses on the modelling of the battery in Simulink. The model of the battery is quite simpler. While designing the battery model the basic idea of storing the charge over time was kept in mind which can be implemented in the model through a limited integral block. Depending on the availability of wind, the energy produced by the wind is intermittent in nature thus a battery may act as an energy storage during the period of high winds and supply energy to load during periods of low wind. In the time when wind and solar both are available, wind power will primarily be used to supply the load while solar power will along with excess wind will be used to charge the battery. For our system, we selected a small size battery with a rating of 5 kWh. The reason behind choosing a small size battery for the simulation process was the focus in the project to meet the load demand directly from available wind power and to -charge the battery from the energy more than the demand [30]. The battery size is normally chosen in accordance with the load demand. It should be large enough to meet the load requirements when there is not enough energy provided by the main energy source and it should be charged when the available energy is more than the load demand. The small-sized battery can be cost effective as well, making the overall system less expensive and reducing the initial cost. A small size battery can be easy to maintain, and the replacement cost of the battery is also not as high as a large battery.

The battery stores the charge over time and then makes the charge available to be used by the load. The charge to be stored in battery is provided in the form of current. The basic equation which correlates the charge and current is given as below

$$Q = I * t \quad (4-3)$$

Where Q is charge stored in battery in Ampere seconds, I is Current in Amperes and t is time in seconds. Q represents the quantity of the charge which can be stored in the battery and

determines the battery capacity. The capacity of the battery is usually represented in Ampere hours (Ah). To convert the battery capacity to charge we need to convert it from ampere hours to ampere seconds as one ampere second is equal to one coulomb and thus the exact charge stored in the battery can be assessed.

The energy stored in the battery can be estimated by the equation given as follows.

$$E = Q * V \quad (4-4)$$

Where E is energy stored in battery in joules, Q is charge stored in battery while V is voltage in Volts.

As already explained above, current is needed to charge the battery, and in the model the charging current is given by wind and solar power [30]. The wind and solar power are primarily used to meet the load demand, and the excess of wind and solar power is directed to charge the battery by controller. In the model the battery voltage is considered to be 500V, which is indicated through a constant block in the model. The wind and solar power excess of load is directed to the battery and power divided by voltage will give us current. This current is directed toward the battery to charge it. To imitate the battery in the model we used an integrator block. The integrator block keeps integrating the input value which is current thus indicating that the charge is accumulating in battery over time. As the battery has a specific capacity, and we cannot overcharge the battery beyond the maximum limit so to imitate this behavior of battery we had to use a limited integral with an upper saturation limit. As discussed above initially, we chose to design the battery with a capacity of 5kWh and a battery with the capacity of 5kWh the maximum charge it can store is 36000As in one hour, so we chose the upper limit of the limited integral to be 36000. It means when the integrator keeps integrating the current and the integral reaches 36000, the battery is 100 percent charged. The SoC indicator will indicate that the battery is 100 percent charged and available to use. SoC is the state of charge of battery which indicates the amount of charge available in the battery compared to its full capacity. The integrator block is executing the equation given below:

$$Q = \int_0^{36000} i * t \quad (4-5)$$

Where i is calculated from the power which is excessive of load

$$i = \frac{P_{excess}}{V} \quad (4-6)$$

Now when the battery starts getting charged, it means it has charge available to be used in the form of current. The charge is then converted to current by using the equation below:

$$i = \frac{Q}{t} \quad (4-7)$$

Now the battery has available current, and the battery is ready to discharge. Using the available battery current and voltage, the power available from battery can be assessed following the equation below:

$$P = V * I \quad (4-8)$$

The Simulink model displays the battery's state of charge and available power as outputs. The input to this model block is the excess power from solar module which charges the battery. Another input to this block is power which is either more than demand or less than demand. When available power is more than demanded, the other input (power less than demand) is zero and this power is added with excess solar power generating a positive value of power which is used to charge the battery. When power is less than demand then the other input (power more than demand) is zero and in this scenario, there is no excess power available from solar thus this addition will generate a negative value of power which is then used to discharge the battery. In this manner we created a battery model which is charging and discharging depending upon the input power either positive or negative. It can be seen from the model that the model is dependent upon input power. When input power is positive the battery will get charged. The Simulink model of the battery can be seen in the figure 4-2 below.

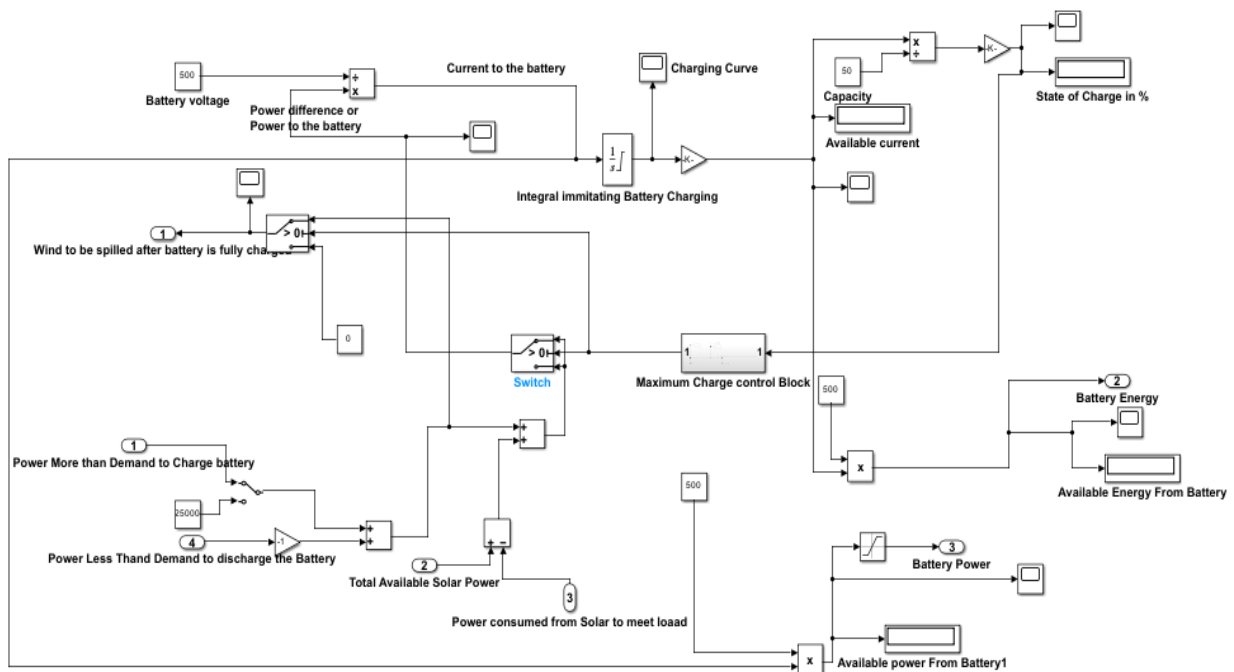


Figure 4-2: battery model

We need to take into consideration that two important parameters must be observed carefully, one is input power, and the other is charging time. The battery charging depends on input power. When the input power is high the battery will get charged quickly and less time is required for the battery to reach its full charged capacity. When input power is low, the battery will take longer time to get charged fully thus charging time is increased.

One important point to keep in mind is that the initial state of charge of battery and depth of discharge of the battery are ignored in the model. It is assumed that every time the simulation runs the battery starts to charge from 0% and reaches 100%. While discharging, the battery will start discharging from 100% and will discharge until it reaches 0%. So, the depth of discharge and initial state of charge is neglected in simulation which is not the case with real time system.

In our simulation we study two cases: case one refers to simulation running around 1400 seconds, with the data of estimated wind speed and solar irradiance available from Chalmers wind turbine site, while case 2 refers to simulation running for 24 hours with the real time data of both wind speed and solar irradiance during a period of 24 hours. The battery charging and discharging in both cases is shown in the figures below where the SoC level can be clearly seen varying with the time. When there is excess power available to charge the battery, the battery charging curve can be seen going up, indicating that the charge is being accumulated. And when the system needs the energy from the battery the charging curve starts going down indicating that the battery is being discharged.

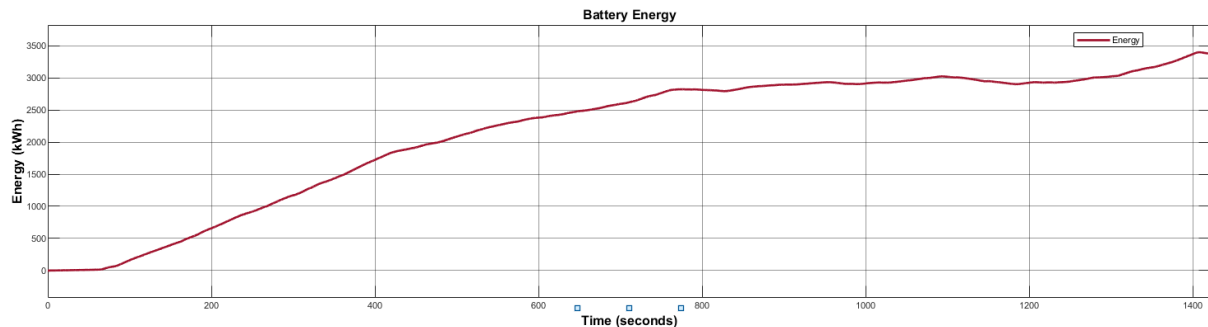


Figure 4-3: battery energy for 1422 seconds

The figure 4-3 above refers to case 1 where the simulation runs for approximately 1400 seconds. Firstly, there was no power available to charge the battery, so the state of charge remains zero and battery energy is zero as well, but around 150th second, there is power available more than the load which is directed toward the battery and the battery energy start to increase and keep rising around the 1000th second. After this we see a bit of a drop in the energy which indicates that the power was being consumed at this instant of time. The consumption of power from battery is very small so there is a very small dip which is unnoticeable. This dip is discussed in detail in the subsequent chapter 7 later. After this discharge dip, it can be seen that the battery starts charging again, the SoC and energy level starts rising again until the end of simulation runtime.

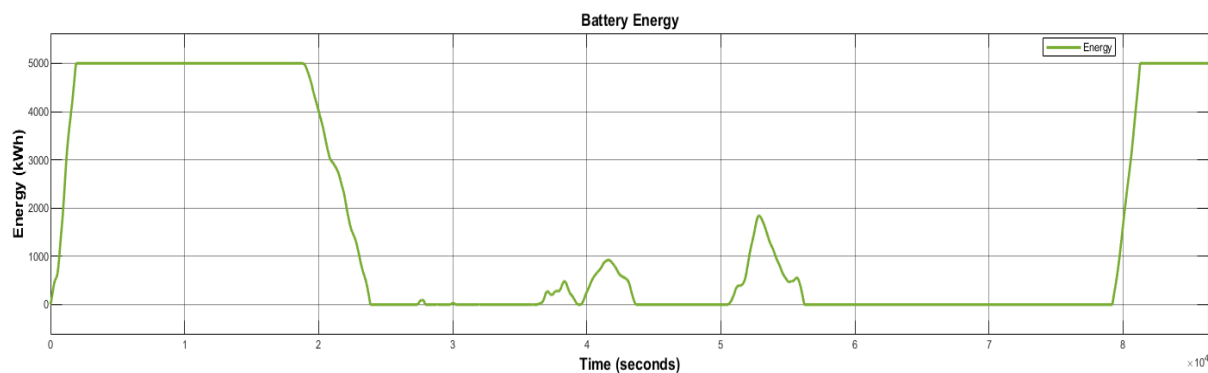


Figure 4-4: battery energy for 24 hours

Figure 4-4 above refers to battery energy levels for case 2 where the simulation imitates the system for 24 hours. It can be seen that battery starts getting charged from the start of simulation and reaches the maximum level and maintains its SoC to 100% as no power is being consumed. During this time period of battery maintaining its SoC to full, we can see few dips at different intervals which indicates that battery was being consumed, it was discharged a fully but again started charging because of availability of excess power. Then as we proceed

further, it can be observed there is huge dip and battery is fully discharged. After being fully discharged the battery SoC remains zero for intervals between 58000 sec to 78000 sec. This indicates that battery was fully discharged, and load exceed the available power so there is no power available to charge the battery after it being fully consumed. This is the time where the available power sources are not able to meet the load demand and load shedding will be required, or we need other means to meet the load (increasing the battery size) which are discussed in detail in results chapter 7 later. At around 78000th second, the battery starts getting charged again and achieves its 100% SoC and is available to be consumed by the system to meet load demand.

When the battery is fully charged and the power from battery is not consumed, then energy is stored in the battery. If wind and solar power is still available, the system is designed in such a way that the excess power after meeting the load and charging the battery will be sent to a wind spilling system.

5 Load

In this chapter modelling and simulation of electrical load is covered on hourly basis.

5.1 Load Modelling

In this chapter, the load model was built on MATLAB Simulink software. The load model consists of three key components such as a variable load resistor, signal builder and a Ps-to-Simulink converter and are explained one by one as under:

5.1.1 Variable Load Resistor

A variable load resistor is an electrical component which allows us to adjust the resistance within the electrical circuit according to our requirement. The main purpose of variable load resistors is to regulate the electric power within a circuit. By increasing or decreasing the resistance value, we can control the flow of the power within the circuit. In this load model, the adjustment is made through the slider.

5.1.2 Signal Builder

To define the variable load resistor values, we use a signal builder which gives us information about the different values of load resistance at different intervals of time according to required load by using equation 5-1.

5.1.3 Simulink-to-Ps Converter:

To convert the Simulink to PS converter we used Simulink-to-Ps Converter. It acts as an interface to transfer simulation data from Simulink model to power system.

5.2 Load Model Diagram

We studied how the load in different residential or commercial buildings varies for 24 hours a day, we studied the peak demand and low demand hours. On the basis of our study, we defined a load for the island as we didn't have the load data available. The following image 5-1 indicates the load model diagram and it contains variable load resistor, signal builder and Ps to Simulink converter.

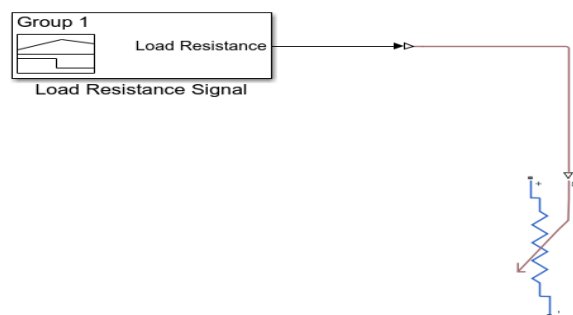


Figure 5-1: load model

For the load data model, the realistic values of load parameters for island operation are selected as shown in Table. 5-1. With the help of a signal builder, we inserted the values of resistance inside the variable load resistor. Signal builder is used to generate a signal which imitates resistance values. The signal is divided into 24 different sections with each section

representing the value of resistance during 24 hours of the day. By setting the constant value of voltage i.e. 230 volt we calculated the values of hourly load power consumption. The hourly power consumption is calculated by the following formula:

$$P = \frac{V^2}{R} \quad (5-1)$$

5.3 Peak Load

In this 24-hour load profile analysis, the peak load is 19100 W power consumption. This maximum power consumption load appears between 20:00 to 21:00. During this time frame power goes to its highest-level rate. This peak demand occurs during evening hours when households use electrical appliances, lighting and other energy consuming devices.

5.4 Minimum Load

In the analysis of the 24-hour load profile, there is a phase characterized by the minimum load between 03:00 to 04:00. Within this time frame power consumption remains at level 4000 W. This interval stands to illustrate the system's ability to sustain operation during the time of minimum load demand.

Table 5-1: Load Parameters

Time (h)	Power (W)	Resistance (Ω)	Voltage (V)
00:00 – 01:00	6500	8.1	230
01:00 – 02:00	5500	9.6	230
02:00 – 03:00	4500	11.8	230
03:00 – 04:00	4000	13.2	230
04:00 – 05:00	6000	8.8	230
05:00 – 06:00	7500	7.1	230
06:00 – 07:00	10000	5.3	230
07:00 – 08:00	11000	4.8	230
08:00 – 09:00	9000	5.9	230
09:00 – 10:00	12000	4.4	230
10:00 – 11:00	14000	3.8	230
11:00 – 12:00	12000	4.4	230
12:00 – 13:00	13000	4.1	230
13:00 – 14:00	15000	3.5	230
14:00 – 15:00	13500	3.9	230
15:00 – 16:00	14000	3.8	230
16:00 – 17:00	16800	3.1	230
17:00 – 18:00	18000	2.9	230
18:00 – 19:00	18300	2.9	230
19:00 – 20:00	19000	2.8	230
20:00 – 21:00	19100	2.8	230
21:00 – 22:00	16400	3.2	230
22:00 – 23:00	8500	6.2	230
23:00 – 00:00	7000	7.6	230

Load Power Consumption for 24 Hours

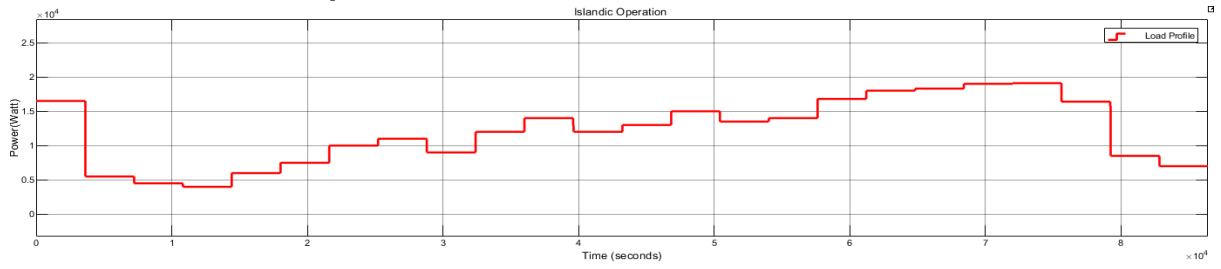


Figure 5-2: load consumption for islandic operation for 24 hours

6 Controller

In this chapter, modelling and simulation of controller is carried out. This chapter also explains the working principle of the controller.

6.1 Introduction

The effective management of the load during the islandic operation is only possible when the energy source is chosen wisely depending upon the availability of the power source. Until now we have discussed all the power sources which include power generation from wind turbine, PV panels and energy storage in the form of battery. Now in order to integrate all these energy sources and manage the load efficiently, it is required to design a robust control system that could effectively meet the load demand keeping in view the available power to ensure the continuity of power supply and system reliability. One of the major challenges with this islandic operation is the intermittency of power from renewable sources. The renewable energy is greatly dependent upon the availability of the natural resources such as wind and solar irradiance in our case. These natural resources are intermittent in a way that at nighttime there is no solar radiation similarly there are times when wind is very slow or very high thus causing no wind power generation from the turbine. In such a case the controller is very important as it should be intelligent enough to choose which of the sources is available at the moment to meet the load demand, and to estimate if the power generated is more or less than the load demand. The controller must be able to make the decision about which of the available sources alone or combination of the sources would be used to maintain the continuous supply of electricity. The controller is responsible for managing the available energy and ensuring the stability of the system. The controller is responsible for integration, optimization, battery management and load management.

In this thesis work we designed a controller model for managing the islandic operation of wind turbine in MATLAB Simulink with the help of different logic gates who check the availability of the sources and then evaluates if the available source is enough to meet the load demand or not. The controller has two basic functions, the first one is that it evaluates the amount of energy available from different sources and secondly it makes a comparison with the load to ensure that if the available energy is enough to meet the load or not. If there is enough energy available to meet the load from primary power source(wind), then the secondary source(solar) is being directed to storage (battery). This deciding power of the controller is very crucial for optimizing the utilization of available power from different sources and successful islandic operation of power plant. The whole logic of the controller is further discussed in the subsection of this chapter.

6.2 Simulink Model of Controller

Figure 6-1 below gives an overview of the controller model designed in Simulink. The model mainly comprises of 4 sub blocks. The controller block has 4 inputs. It takes wind power, solar power, battery power and load as input. As discussed above the controller is the brain of the system, and its decisive power is based on the real time availability and capacity of the power from different sources. In order to ensure the capacity and availability, all available power values are fed as input to this block. The controller then makes assessment on the basis of the dynamic values fed to it. It performs a comparison of the dynamic values of the power

available from wind and solar source and decides if the wind alone or in combination is enough to meet the load demand. If the available wind power alone is enough to meet the load demand, the available solar power is directed to charge the battery. If the available wind power is in excess than the load, then this extra wind power is added to the solar power and is directed to charge the batteries. During the time of the day when the wind is approximately zero but there is solar irradiance available, then the controller decides to meet the load with the help of solar power instead of charging the batteries. If the solar alone is not sufficient, then the available power from battery storage is added to solar power to meet the load. The batteries participate in meeting the load until they are fully discharged. On some days during the daytime there is enough solar available while on other days the solar irradiance is not strong enough to produce power, the controller must take into account all these scenarios. All this logic is implemented in Simulink with the help of conditional statement and logic gates. The controller can be beneficial in terms of cost cutting as it saves the extra expense of backup power plans.

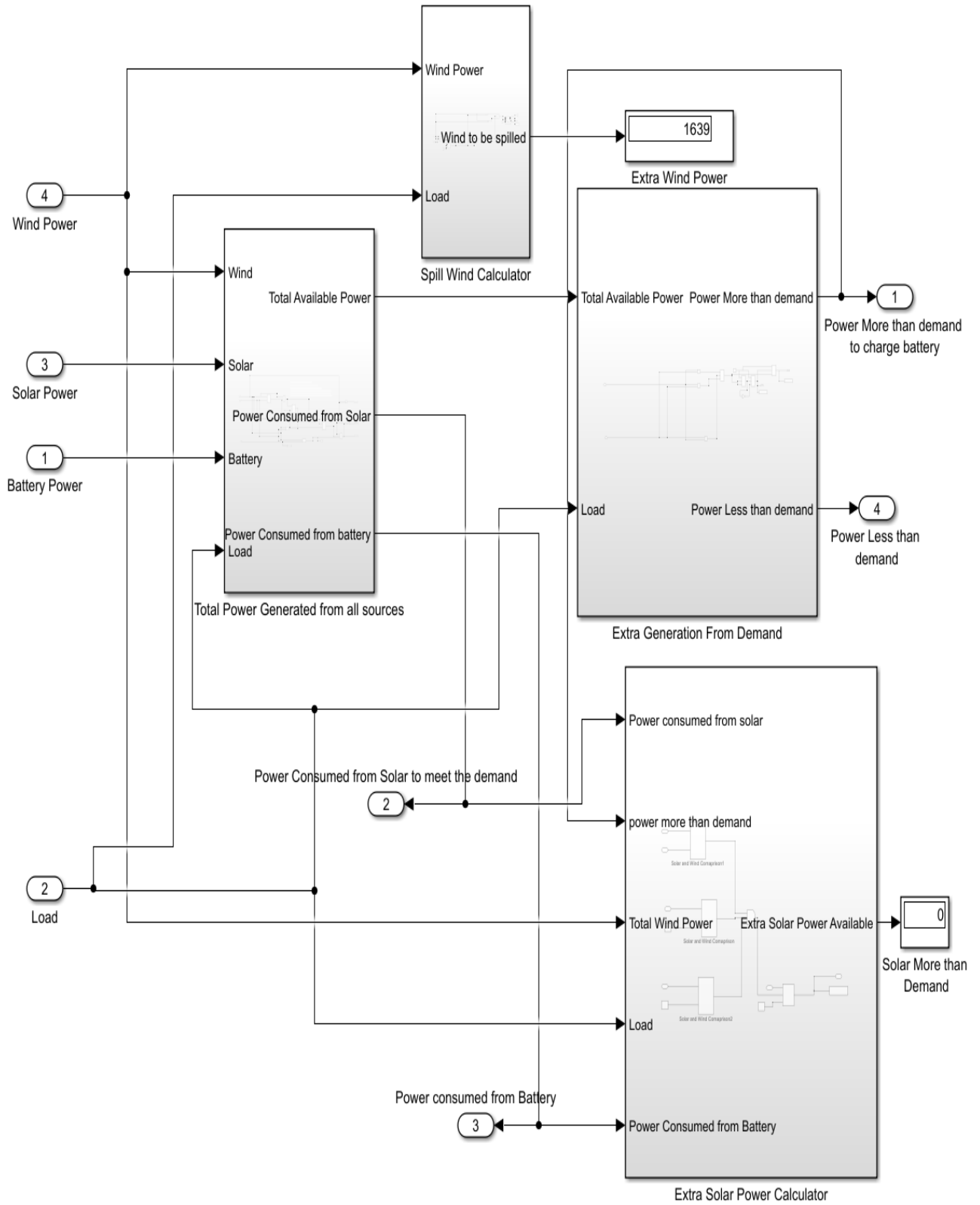


Figure 6-1: the block diagram of the controller

After integrating all the blocks and systems, the simulation imitating the full system controlling the islandic operation of wind turbine is provided in appendix3. The image 6-2 below gives a block diagram of how the islandic system is working.

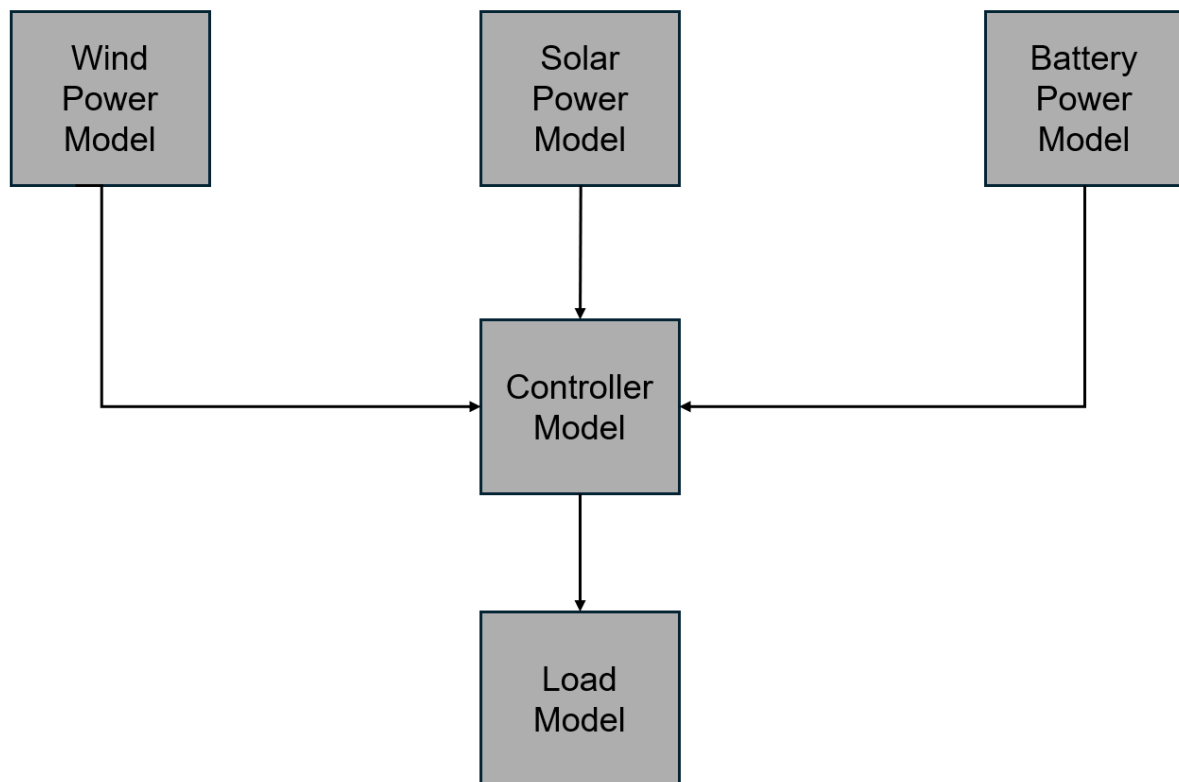


Figure 6-2: block diagram of the islandic operation of wind turbine

7 Results and Discussion

This chapter presents and analyzes the results obtained from simulation for islandic operation. There are two cases of simulation for analyzing the results.

7.1 Case 1

In the first case of the simulation, we have used a dataset covering a duration of 1422 seconds. This dataset is realistic and is taken from the Chalmers wind turbine site, to simulate power generation from different sources. By employing these realistic values, the simulation produces results that closely align with the actual circumstances, which in result provides a comprehensive understanding of the system's performance. The data is taken from wind sensors, sensors of wind turbine and solar model. The graphs for wind power generation, solar power generation, load profile and energy stored in the battery, are as shown in figures from 7-1 to 7- 4 below:

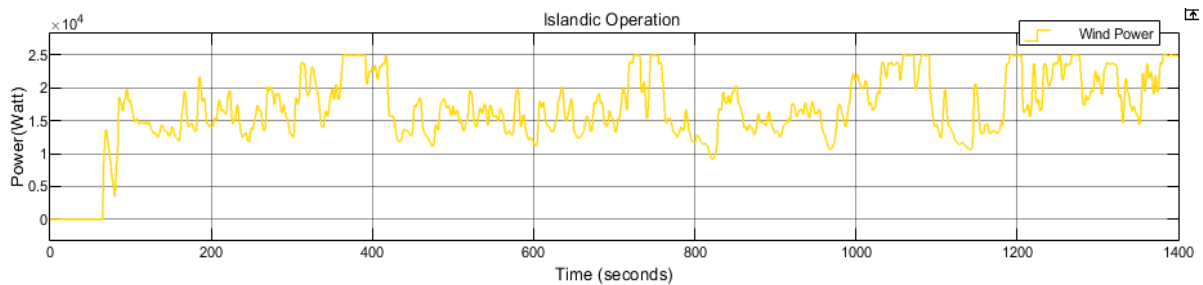


Figure 7-1: wind power generation for 1422 seconds

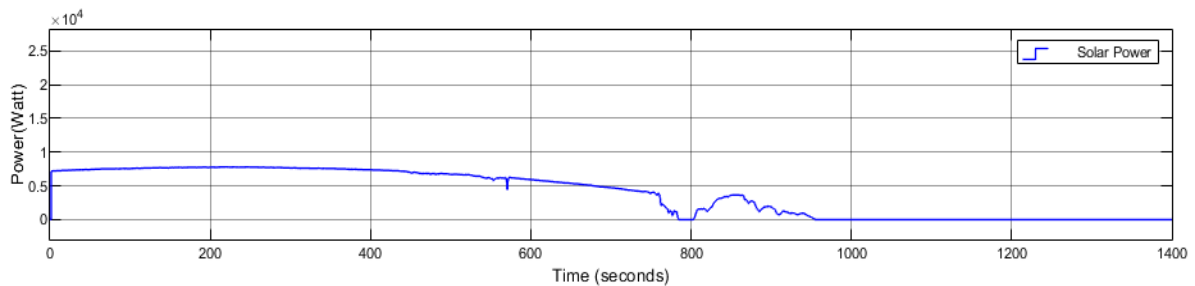


Figure 7-2: solar power generation for 1422 seconds

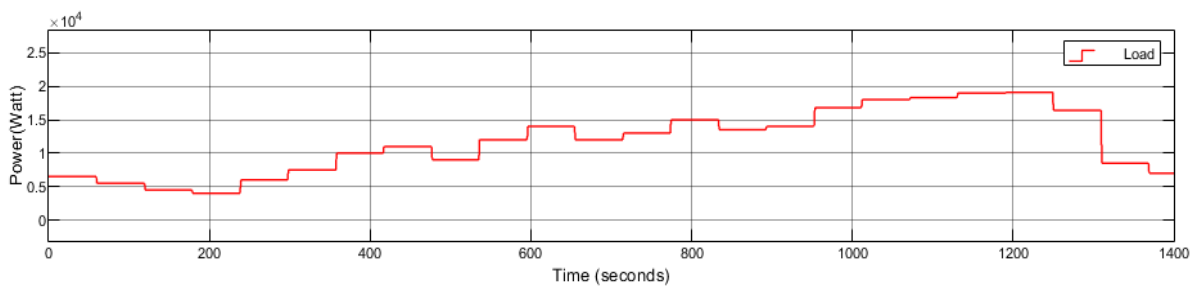


Figure 7-3 : load profile for 1422 seconds

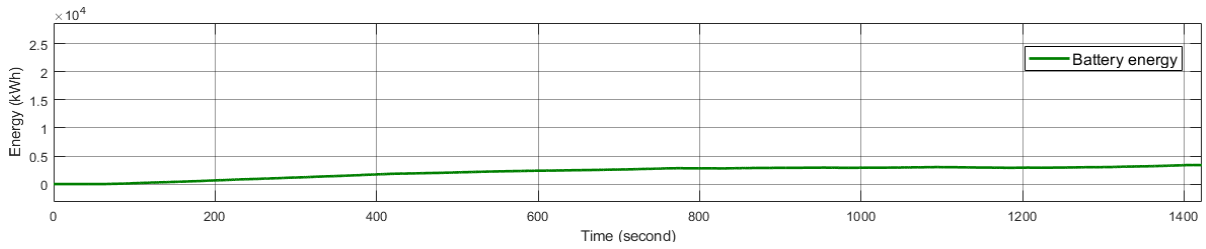


Figure 7-4: energy stored in the battery for 1422 seconds

From the graphs in figure 7-5 below it can be seen that, in the Islandic operation the primary source of power supply is wind turbine. When low power is generated from wind turbine and load is increased then solar power or energy stored in the battery is used to meet the load. From the period between 75-90 seconds and from 590-640 seconds, the wind power is reduced, therefore solar power is also used to meet the load demand. In the time intervals from 780 seconds to 1240 seconds, load is increased so energy stored in the battery is used to meet the load requirements. This system ensures that load demands are consistently fulfilled by the most available and efficient energy sources at the given moment by primarily relying on power from wind turbines. However, when wind power generation is reduced or load demand increases, the controller directs the system to utilize solar power or from the energy stored in the battery. This strategic and responsive approach guarantees a reliable and uninterrupted power supply in the islandic operation.

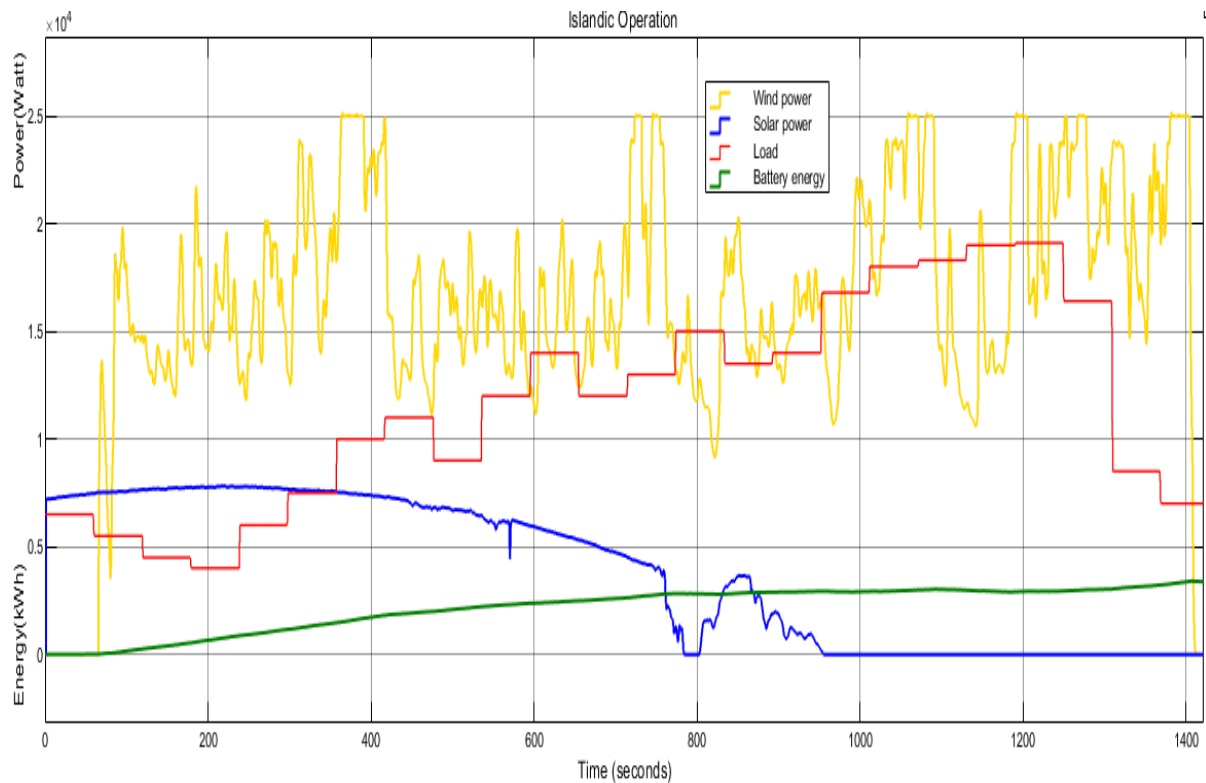


Figure 7-5: wind, solar and battery energy along with load profile for 1422 seconds

7.2 Case 2

For case 2 of the simulation, the data for 24 hours was used. This data is taken from the Chalmers wind turbine site, to simulate power generation from different sources. By employing these values, the simulation produces results that closely align with the actual circumstances

for one complete day, which as a result provides a comprehensive understanding of the system's performance. The graphs for wind power generation, solar power generation, load profile and battery state of charge of the battery are provided in the figures from 7- 6 to 7-9 below.

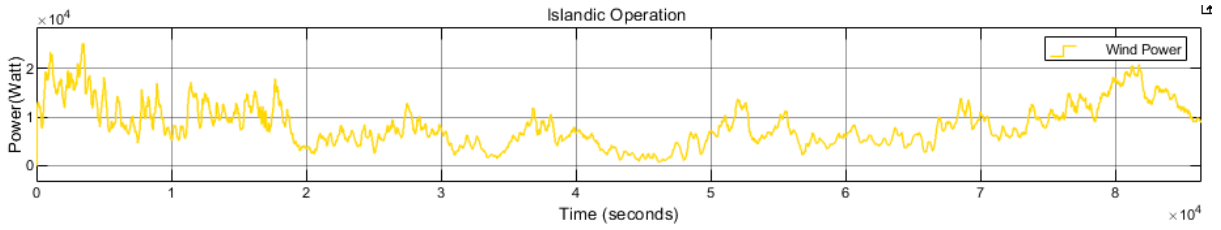


Figure 7-6 : wind power generation for 24 hours

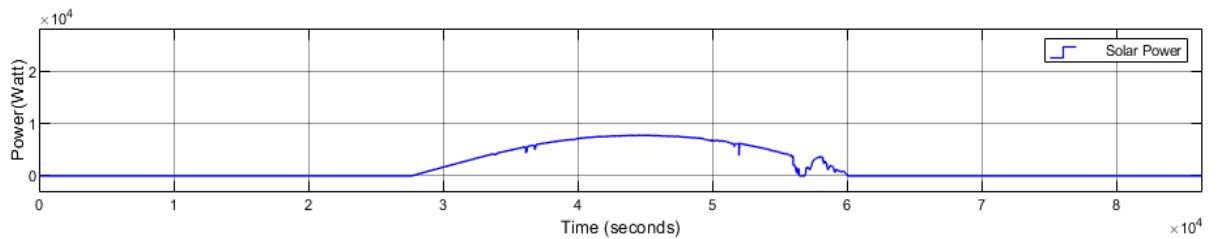


Figure 7-7 : solar power generation for 24 hours

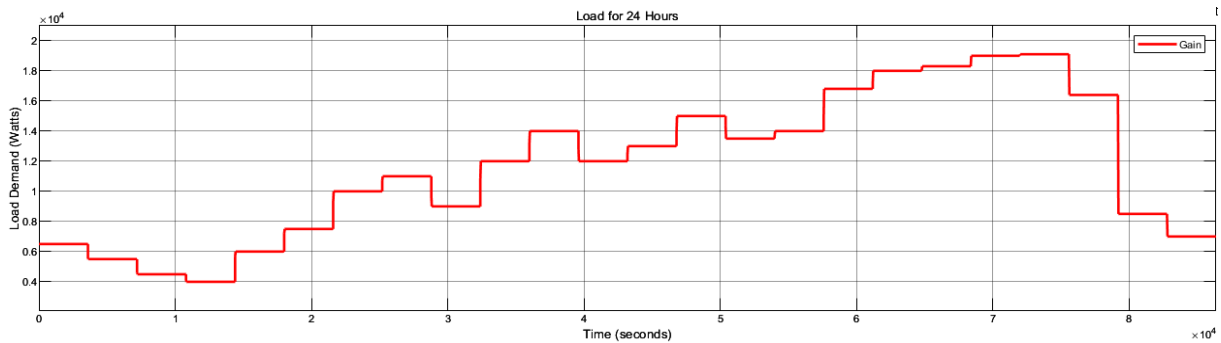


Figure 7-8: load profile for 24 hours

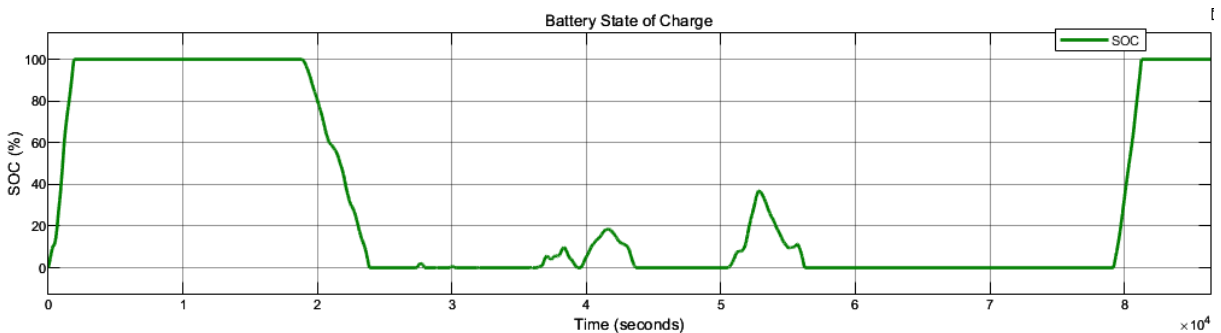


Figure 7-9: battery state of charge (soc) 24 hours

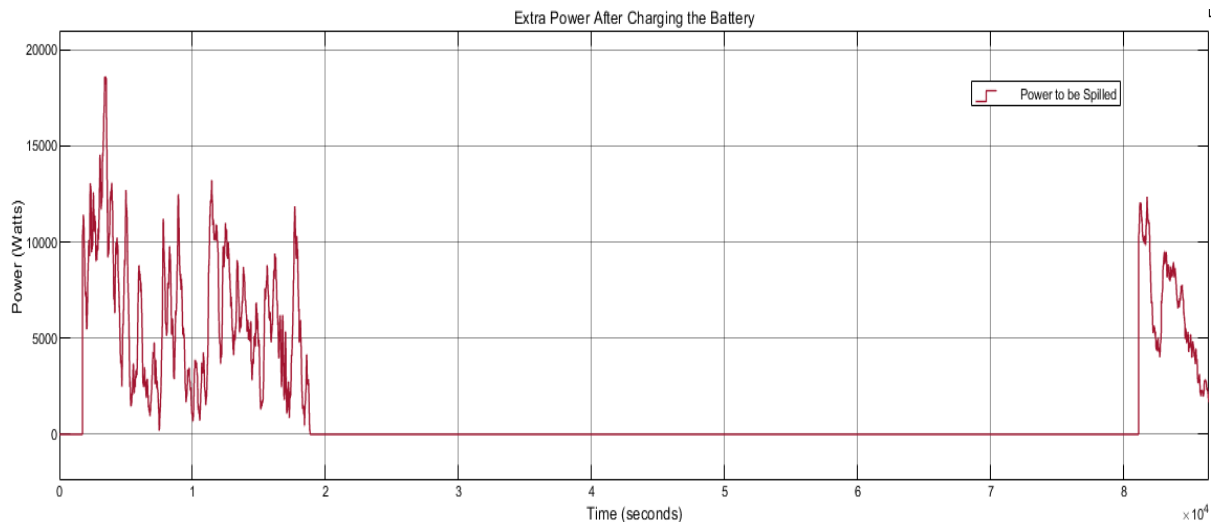


Figure 7-10: power to be spilled after fully charging the battery

From the figure 7-10, it can be seen that when the battery is fully charged then extra available power is spilled by a system called wind spill. Battery charging is dependent on input power from wind and solar. Battery remains discharged when there is no input power from wind and solar is available. Therefore to keep the battery charged for a longer period, it is necessary to increase the capacity of the battery. But it should be noted that a larger size of battery will require more time and more input power to be fully charged. When the capacity of the battery is higher it can support the load for a longer time and takes more time to discharge thus the reliability of the system is increased. The cost efficiency of the system would be compromised by choosing a larger battery. But cost control is not the aim of this project.

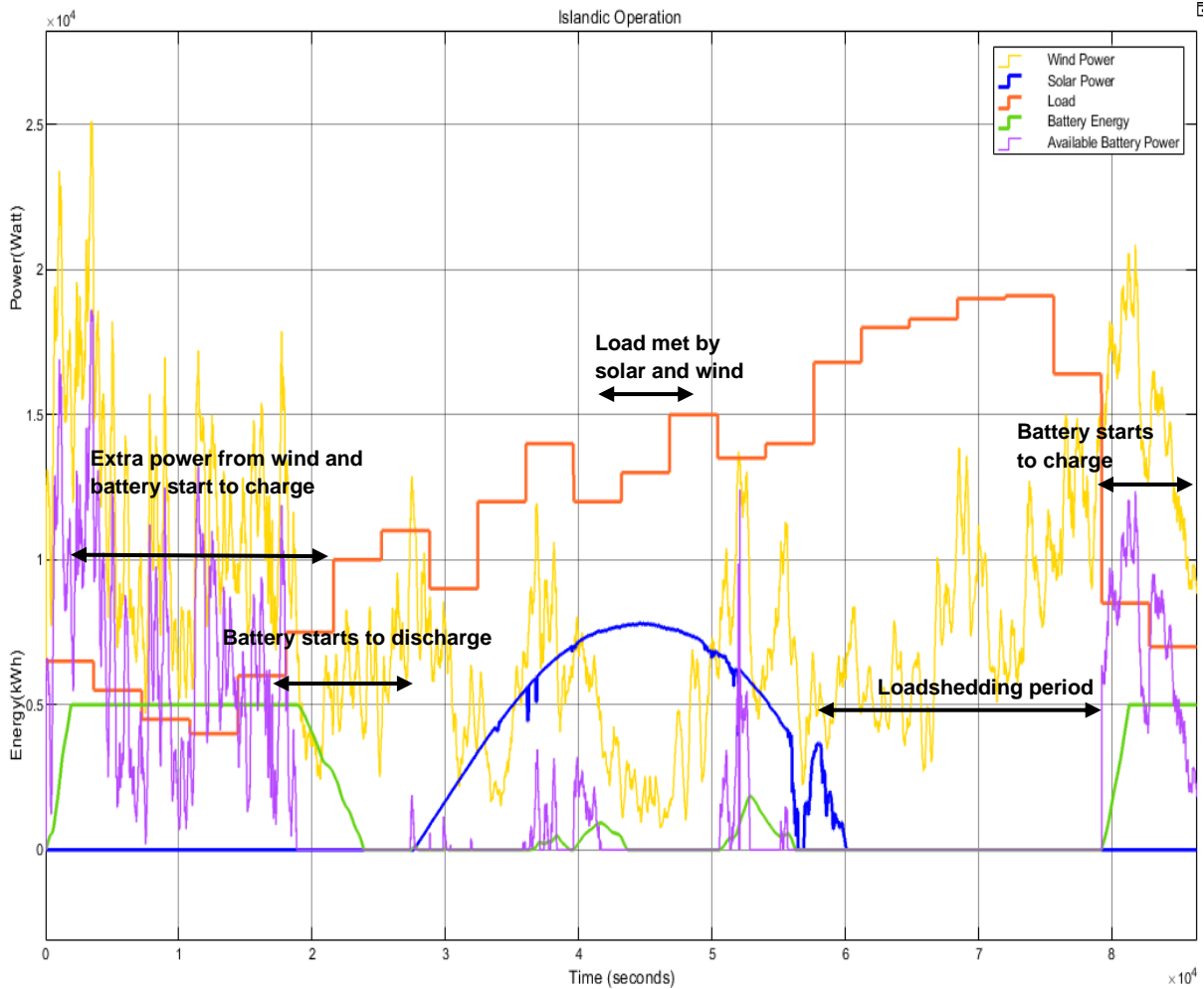


Figure 7-11 : islandic operation with battery capacity of 10 Ah (5kWh)

Figure 7-11 shows that enough wind power is available from the time periods 3713-18685 seconds and from 79200-86400 seconds. So electrical load is met by wind power only. After meeting the load, the remaining power is used to charge the battery and after charging the battery the extra power is spilled by wind spilling system. From 18000-25200 seconds the power from wind and battery power is used to meet the load. From 25200-57600 seconds, power from wind and solar along with power from energy stored in the battery is used to meet the load. From 57600-79200 seconds, wind power is reduced and there is no solar power and battery is fully discharged. The load is maximum, and wind power cannot meet the load, so there is a power outage. In order to sidestep the outage, we will have to increase the capacity of the battery. To verify this, battery capacity is increased from 10Ah-30Ah. The SOC of 30Ah battery is as shown in figure 7-12.

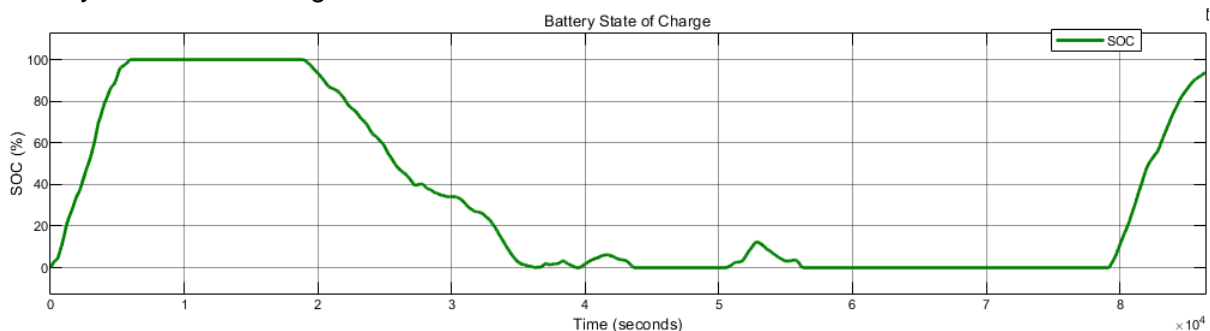


Figure 7-12: battery state of charge of battery capacity of 30Ah (15kWh)

The results of Islandic operation at the same wind power, solar power and load conditions with an increased battery capacity for 24 hours are given in the figure 7-13 below:

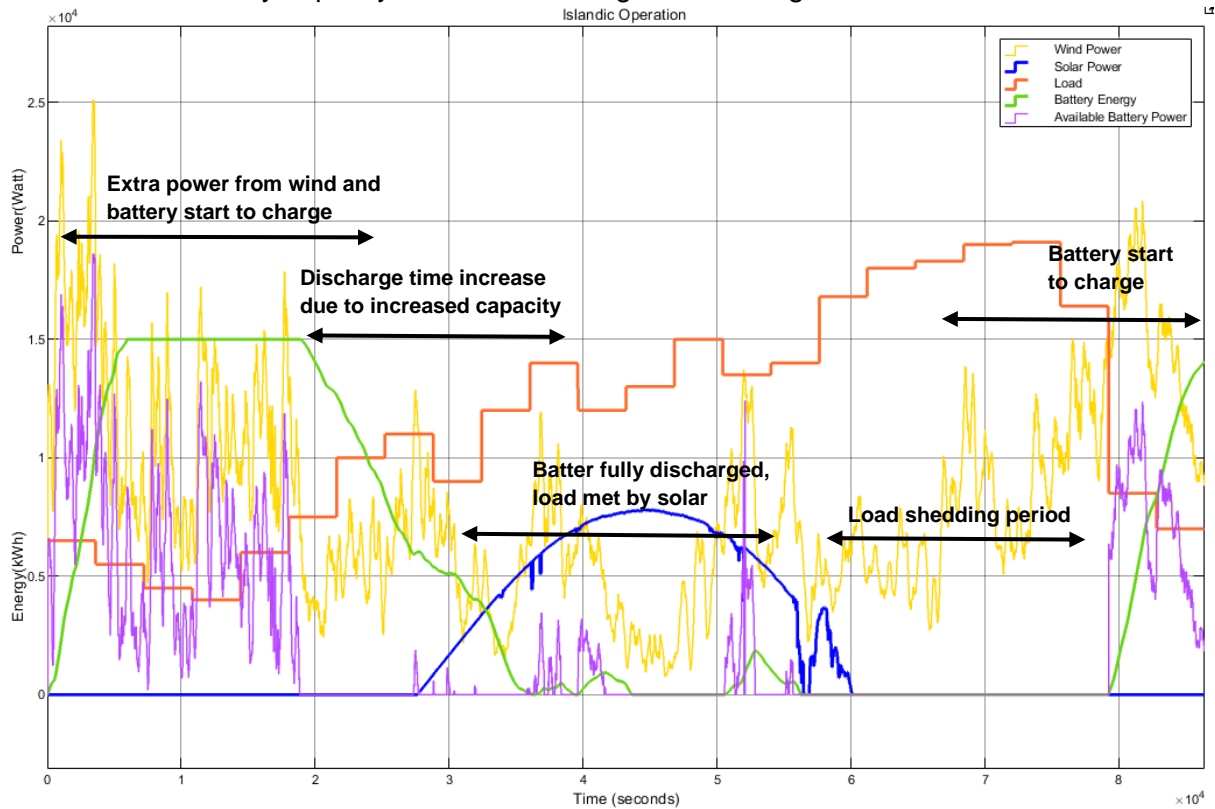


Figure 7-13: islandic operation with battery capacity of 30Ah (15kWh)

From the above graph in figure 7-13 it is concluded that when battery capacity is increased, it can be seen that battery discharge time is increased and support the load for longer period making battery available for longer period. The increased battery capacity increases the system reliability. But there is still power outage, avoid this outage, the capacity of the battery is further increased to 25kWh. The state of charge of 50 Ah battery is shown in Figure 7-14

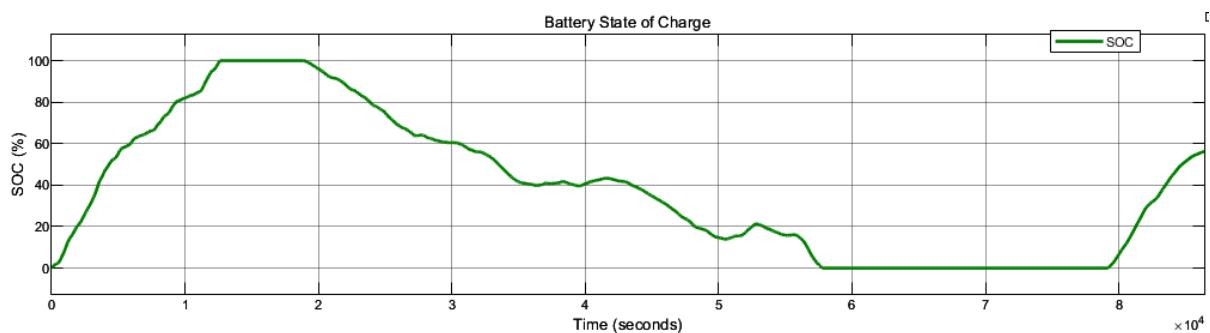


Figure 7-14: state of charge of battery of capacity of 50Ah (25KWh)

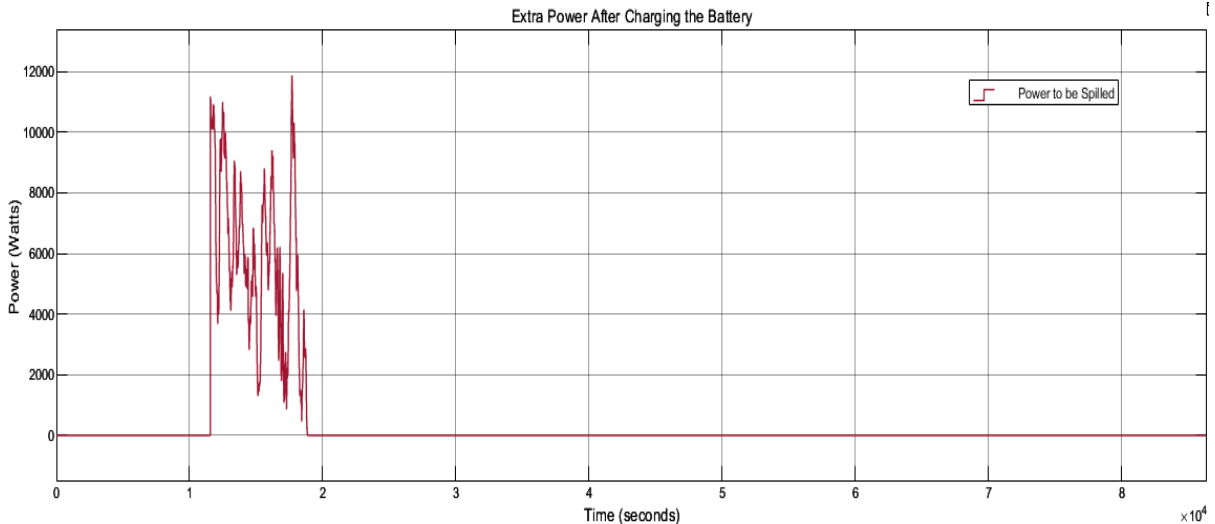


Figure 7-15: power to be spilled after fully charging the battery

From the figure 7-15, it can be seen that when the battery is fully charged then extra available power is spilled wind spilling system.

For the same values of the wind power, solar power and load conditions with an increased battery capacity of 50 Ah for 24 hours the results are given in the figure 7-16 below:

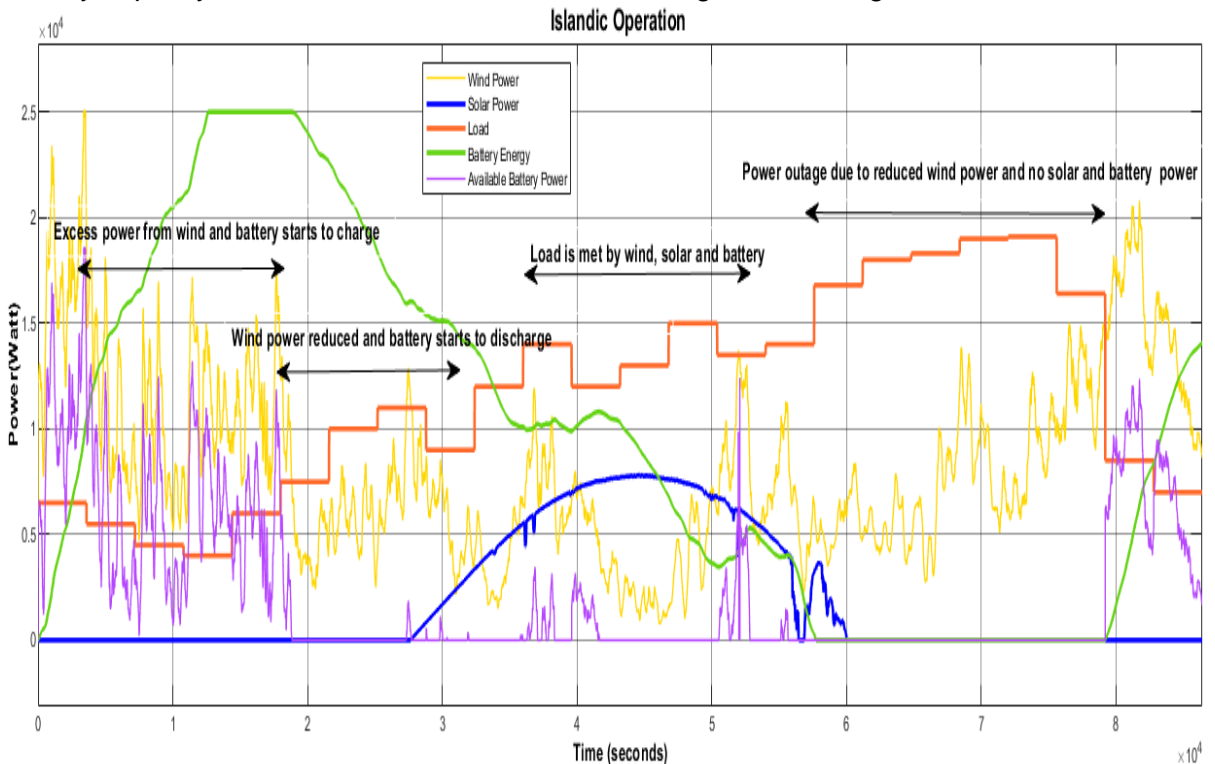


Figure 7-16: islandic operation with battery capacity of 50Ah (25kWh)

From the above graph in figure 7-16 when battery capacity is increased to 25kWh, the battery discharge time is further increased, and battery can support power for longer period. Thus, making the system more reliable and stable for islandic operation.

It can be concluded that increasing the battery size results in longer charging times and higher input power to fully charge the battery. When the capacity of the battery is higher it remains

charged for a longer period of time and can support the load for a longer time and thus takes more time to discharge thus increasing the reliability of the system. Although the larger battery would increase the cost of the system, cost control is not the focus of this project.

7.3 Conclusion

The Simulink model for islandic operation was successfully designed. The model works well during different scenarios under various load conditions in islandic operation. The designed controller is efficiently estimating the power available from different sources and prioritizing their use based on source availability and load demand. The controller manages to make power balance in different scenarios. When there is sufficient wind power available, it meets the load demand effectively. If the power produced from the wind is more than the load demand, then the controller directs the wind power to charge the battery. After charging the battery the extra power is spilled. When the wind power is reduced the controller combines wind power and solar power to meet the load demand. If the wind power is further decreased, then the load demand is met by power from wind, solar and energy stored in the battery. With no solar power available, the load is fed by wind power and energy stored in the battery. The results show that the islandic operation is working fine as per intensions.

It can be seen from the results that there is a period of power outage. It is the time period when the load is at peak while the power from wind is very low and unable to meet the load demand and charge the battery. Here we can conclude that if there exists a power outage, then the capacity of the battery is required to be increased to avoid this power outage. Battery with higher capacity has higher discharge time and can support the load for longer period during high load demand and low generation periods. This can be seen from the results, as well that when battery capacity was increased, the battery discharged time was also increased thus supporting the islandic operation for a longer period of time increasing the system integrity and availability. Despite the high cost of the battery, the system reliability justifies the investment for balance between power generation and load demand. Additionally, in order to avoid this power outage, the electrical load can be reduced.

Another potential consideration is that wind power and solar power are intermittent in nature. The speed of the wind varies and does not follow the same pattern. The wind speed data utilized in this simulation indicated that the wind speed was very low during peak demand hours which is not consistent. There can be days when wind speed is higher during peak hour periods and there is enough wind power to meet the load demand, thus the outage can be avoided. It can be concluded that islandic operation is greatly dependent on the availability of wind.

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A

Appendix 1

A.1 MATLAB Code 1400 Seconds Simulation

This section presents the code written in MATLAB to define all the parameters and variables for wind turbine model, solar model and load model. It imports the texts file to MATLAB and then data is extracted and aligned for further programming. The inputs to the Simulink model are shaped through the code presented in this section. This code needs to be run before running the model and it will automatically run all the subcodes and functions

```
close all
clear all
clear

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Defining The Load Data %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
filename2 = ['Load_Less.xlsx'];
input2 = importdata(filename2);
time_sec=input2(:,1);% coulom1
Load1=input2(:,2);% coloumn2
Sampl_t=1;
% time_2=linspace(0,length(time_sec)*Sampl_t,length(time_sec))';
L= timetable(seconds(time_sec),Load1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Defining The Solar Irradiance Data %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
T= 25; %Temperature
%G=500;
a=1.5; %diode ideality factor
Rs=.39053; %Series resistance
Io=5e-8; %diode saturation Current
Ns=6; %Number of Panels in Series
Np=8; %Number of Panels in Parallel
Kelvin=273; %constant to change temperature to kelvin
q=-1.6022e-19; %charge on electron
K=1.3806e-23; %% Boltzman consnatntJ/K
Isc=9.99; %Short circuit current
Ksc=.0032; %Short circuit temperature coefficient
Rsh=180.3; %Shunt resistance
filename1 = ['Irradiance_1422_new.xlsx'];%Reading data from Irradiance file
input1 = importdata(filename1);
time_value=input1(:,1); % coulom1
Irr=input1(:,2); % coloumn2
G1 = mean(reshape(Irr, 21, []));
G2=G1(:);
Times=mean(reshape(time_value, 21, []));
T1=Times(:);
Sampl_t = 1;
time1 = linspace(0,length(T1)*Sampl_t,length(T1))'; % [s]
G = timetable(seconds(time1),G2);
```

```

%%%%%%%%%% Defining The Wind Turbine Data
%%%%%%%%%% %%%%%%%%%%
%===== Obtaining Data from the Data Files
=====
filename = ['B1_CL3_20_220124_12_47_29.txt']; % File with data containing data
with 28440 readings with sample time of 0.05sec
%filename = ['B1_CL4_20_220811_08_27_51.txt']; % File with data containing data
with 28440 readings with sample time of 0.05sec
%filename = ['B1_CL4_20_220705_13_37_34.txt']; % File with data containing data
with 28440 readings with sample time of 0.05sec
%filename = ['B1_CL4_20_220808_10_34_12.txt']; % File with data containing data
with 28440 readings with sample time of 0.05sec
%filename = ['B1_CL4_20_220811_08_27_51_updated.txt']; % File with data
%containing data with 28440*3 readings with sample time of 0.05sec(3 files
combined to one big file)
%filename = ['B1_METMCL2_1_240317_00_00_01.txt']; % File with data containing data
readings for 24 hours with sample time of 1 sec

delimiterIn = '\t';
avg=20; %variable to scale down the 20 readings to 1 by
taking an average of 20 values. The samling time is 0.05 sec which lead to 20
samples per second
input = importdata(filename,delimiterIn);
ReadingFileData; % Extracting data from the text file and arranging the data read
from different coloumns in text file
ChannelScaling; %Scaling down the data by taking average of reading
taken during 20ms to 1 sec

% ===== DC-generator Components: =====
J = 2600/(20^2); % Moment of Inertia[kgm^2]
b = 0.1; % Dampning
Kp = 3; % PI-reg
Ki = 5; % PI-reg

% ===== NREL-reg: =====
Sampl_t = time(2)-time(1); % [s] Sampling time of the
controller
CornerFrequency = 10; % [rad/s] Corner frequency of the generator
speed low pass filter
VS_CtInSp = 5.7; % [rad/s] Cut-in generator speed
VS_RtPwr = 25000; % [W] Rated generator power
VS_RtGnSp = 7.45; % [rad/s] Rated generator speed
VS_Rgn3MP = 1.6; % [rad] Pitch angle to stay in Region 3
VS_Slope15 = 2600; % [W/(rad/s)] Slope of torque curve in Region
1.5
VS_Rgn2Sp = 6.2; % [rad/s] Lower generator speed limit for
Region 2.
VS_Rgn2K = 35; % [W/(rad/s)^2] Region 2 generator torque
constant.
VS_TrGnSp = 7; % [rad/s] Lower generator speed limit for
Region 2.5.
VS_Slope25 = 3500; % [W/(rad/s)] Slope of torque curve in Region
2.5
VS_SySp = 6.5; % [rad/s] Generator speed where torque would
be zero if in Region 2.5. (Construction help point.)
VS_MaxTq = 225; % [Nm] Maximum generator torque
VS_MaxRat = 500; % [Nm/s] Maximum generator torque rate

```

```

PC_MaxPit      = 1.5708;      % [rad]      Maximum allowed pitch angle (Fully
feathered position)
PC_MinPit      = 0.0349;      % [rad]      Minimum allowed pitch angle (Fully
fine position)
PC_KP          = 0.35;        % [rad/(rad/s)] Pitch controller Proportional
gain
PC_KI          = 0.22;        % [rad/(rad/s)] Pitch controller Integral gain
PC_KK          = 0.4;         % [rad]      The pitch angle at which the pitch
sensitivity is double the pitch sensitivity at pitch = 0 rad.
PC_MaxRat      = 0.2;         % [rad/s]      Maximum allowed pitch rate
VS_SlPc        = 10;
StoppingPitchSpeed = 0.0349; % Pitch rate when stopping the turbine
StartingPitchSpeed = -0.0249; % [rad/s] Pitch rate when starting the turbine
PC_RefSpd     = 7.85;        % [rad/s] Reference generator speed
Run_Stop      = 1;

%===== Wind Turbine Parameters =====
Lambda_opt=8.75; % Optimal lambda
rho=1.225; % [kg/m^3] Air density
d=16; % [m] Turbine diameter
R = d/2; % [m] Turbine radius
Cpmax=0.418; % Maximum Power Coefficient of the turbine with MinPit at 2
deg.
A=pi*R.^2; % [m^2]Turbine area.

%===== Stopping and Starting Pitch Speed Adjustment Near Feathered =====
SaS = [PC_MinPit 1;PC_MaxPit*0.85 1;PC_MaxPit*0.98 0.15;PC_MaxPit*1.2 0.15];

SaS_table = SaS(1:end,2:end);
SaS_BP = SaS(1:end,1)'; % Rad index for tabel

% ===== Cp(lambda, Beta) tabell =====
load('CP_data.mat'); % Data for Cp table
breakpoints1 = data(2:end,1)'; % Rad index for table
breakpoints2 = data(1,2:end); % Coloumn index for table
table_data = data(2:end,2:end); % Output value for table

% ===== Maximum Cp for all angles over 2 degrees =====
Cp_B0 = table_data;
Cp_B0(:,1) = 0;
Max_Cp = [breakpoints1' max(Cp_B0)'];
Vector_data = max(Cp_B0)';
%===== Spill Wind method =====
breakpoints3 = flip(table_data(32,1:7)); % Rad index for blade angle tabel
Beta = flip(breakpoints2(1:7)); %value for blade angel
Pspill = 5000; % Watts to be spilled

%===== Time and Power=====
time1=linspace(0,length(timeb),length(timeb))'; % [s] För att mätningarna
% ska börja på t = 0
Pel=(DCV2.* DCC2)./1000; % [kW] Electrical Power (Pel) using DC-link volatge
(DCV) and current (DCC)
Eleff=0.89; % Generator efficiency
Pmec=Pel/Eleff; % [kW] Mechanical Power

% ===== Input to the Simulink Model =====

```

```

% Generator Speed
GenSpeed = timetable(seconds(time1),TurbSpeed22);

%Wind Speed
Wind = timetable(seconds(time1), WS302);

% Tip Speed
V_tip = timetable(seconds(time1), (2*pi*TurbSpeed22)/60*R);

% Electric Power
P_mec = timetable(seconds(time1), Pmec*1000);

% Mechanical Power
P_el = timetable(seconds(time1), Pel*1000);

% Blade angel
Vinkel = timetable(seconds(time1), PAB12); %pitch angle of Blade measured

display ('windturbine model run complete ');
sim('Final_Simulation1400Sec.slx');
open ('Final_Simulation1400Sec.slx');

```

A.2 MATLAB Code To Extract Data From Files

This section presents the code written in MATLAB to extract the data from the text file which contains all the measurements reading from the sensors in the proximity of Chalmers wind turbine at Björko. There are 66 output channels. The data is read from all the output channels and stored in a text file format. The code reads the data from text file and stores it in 66 different variables. Some of these variables are to be utilized in the main code. The code is stored in MATLAB editor file with the name ' ReadingFileData ' and this file is called as a function in the main code.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Reading the data from the files
taken from Chalmers Wind Turbine.%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% The Files contain Readings from
sensors at Chalmers Wind Turbine.%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

time=input(:,1);           %Time UTC+1 [s]
GenTorqSP=input(:,2);     %Generator Torque SetPoint [Nm]
DCCREF=input(:,3);       % DC-current ref [A]
PA_B1_SP=input(:,4);     %Pitch Angle SetPoint Blade 1[deg]
YS=input(:,5);           %Yaw Speed Hydraulic valve setpoint [%]
YDL=input(:,6);          %Yaw Damping Left valve setpoint [%]
YDR=input(:,7);          %Yaw Damping Right valve setpoint [%]
Dig_IO_Status=input(:,8); %Digital I/O States see sep table
SysMode=input(:,9);      %Wind turbine controller Mode [enum]
DCC=input(:,10);         %DC link generator Current [A]
DCV=input(:,11);         %DC link generator Voltage [V]
XTurbSpeed1=input(:,12); %Rotor Speed sensor 1 [rpm] LP filtered, 20 000
pulses/turn
TurbSpeed2=input(:,13);  %Rotor Speed sensor 2 [rpm] 30 pulses/turn
B1Pos=input(:,14);       %Blade 1 Position [deg] Increasing 0 -360 at forward
rotation, Zero when blade 1 is straight up.
GTEMP1=input(:,15);      %Generator TEMPeratue sensor 1 [degC]
GTEMP4=input(:,16);      %Generator TEMPeratue sensor 4 [degC]

```

```

AIRTN=input(:,17);           %AIR Temperature, Nacelle [degC]
HOP=input(:,18);            %Hydraulic Oil Pressure [bar]
HYMP1=input(:,19);         %Hydraulic Yaw Motor Pressure side 1 [bar]
HYMP2=input(:,20);        %Hydraulic Yaw Motor Pressure side 2 [bar]
NAX1=input(:,21);         %Nacelle Accelerometer X direction 1 [m/s2]
Accelerometer 1 is in front
NAX2=input(:,22);         %Nacelle Accelerometer X direction 2 [m/s2] All
accelerometer directions are relative to nacelle. X is axial (turbine shaft) dir.
+ is towards stern
NAY1=input(:,23);         %Nacelle Accelerometer Y direction 1 [m/s2] Y is
sideways. + is towards Starboard
NAY2=input(:,24);         %Nacelle Accelerometer Y direction 2 [m/s2]
Accelerometer 2 is mounted in rear part
NAZ1=input(:,25);         %Nacelle Accelerometer Z direction 1 [m/s2] Note the 5
deg tilt of the nacelle. Z is "vertical". + is upwards.
NAZ2=input(:,26);         %Nacelle Accelerometer Z direction 2 [m/s2]
YP=input(:,27);          %Yaw Position  $\theta$  - (5 * 360) deg [deg] YS MOD 360 equals
compass direction.
WDNA=input(:,28);         %Wind Direction Nacelle Analog [deg]
AIRHNA=input(:,29);       %AIR Humidity Nacelle [rel %] BRDTEMP=input(:,23);
%Brake Disc TEMPerature [deg C] IR sensor
BRDTEMP=input(:,30);     %Brake Disc TEMPeraturev [degC]
PAB1=input(:,31);        %Pitch Angle Blade 1 [deg]
PAB2=input(:,32);        %Pitch Angle Blade 2 [deg]
PAB3=input(:,33);        %Pitch Angle Blade 3 [deg]
B1POS=input(:,34);       %Blade 1 POSition (Voltage from sector system)
B2POS=input(:,35);       %Blade 2 POSition (Voltage from sector system)
B3POS=input(:,36);       %Blade 3 POSition (Voltage from sector system)
R24VMON=input(:,37);     %Rotating system 24V MONitor [V]
AIRHH1=input(:,38);      %AIR Humidity Hub 1 [rel %]
AIRTH1=input(:,39);     %AIR Temperature Hub 1 [deg C]
RST2=input(:,40);        %Rotor Shaft Torque [Nm]
B1EMR=input(:,41);       %Blade 1 Edge Moment Root [V/V]
B1FMR=input(:,42);       %Blade 1 Flap Moment Root [V/V]
B2EMR=input(:,43);       %Blade 2 Edge Moment Root [V/V]
B2FMR=input(:,44);       %Blade 2 Flap Moment Root [V/V]
B3EMR=input(:,45);       %Blade 3 Edge Moment Root [V/V]
B3FMR=input(:,46);       %Blade 3 Flap Moment Root [V/V]
B1FM20A=input(:,47);     %Blade 1 Flap Moment 2.0 meter a Upwind [V/V]
B1FM20B=input(:,48);     %Blade 1 Flap Moment 2.0 meter a Downwind [V/V]
B1FM35A=input(:,49);     %Blade 1 Flap Moment 3.5 meter a Upwind [V/V]
B1FM35B=input(:,50);     %Blade 1 Flap Moment 5.0 meter a Downwind [V/V]
B1FM50A=input(:,51);     %Blade 1 Flap Moment 5.0 meter a Upwind [V/V]
B1FM50B=input(:,52);     %Blade 1 Flap Moment 5.0 meter a Downwind [V/V]
B2FM20A=input(:,53);     %Blade 2 Flap Moment 2.0 meter a Upwind [V/V]
B2FM20B=input(:,54);     %Blade 2 Flap Moment 2.0 meter a Downwind [V/V]
B2FM35A=input(:,55);     %Blade 2 Flap Moment 3.5 meter a Upwind [V/V]
TMBNS=input(:,56);       %Tower Moment, Base North-South [Nm]
TMBEW=input(:,57);       %Tower Moment, Base East-West [Nm]
WD30=input(:,58);        %Wind Direction 30 m height met mast [deg] 10 Hz update
frequency
WS30=input(:,59);        %Wind Speed, 30 m height met mast (m/s) 10 Hz update
frequency
WDN=input(:,60);         %Wind Direction Nacelle (relative YP) [deg] 2 Hz update
frequency
WSN=input(:,61);         %Wind Speed Nacelle (m/s) 2 Hz update frequency
Marker=input(:,62);      %Not in use
TMBTOR=input(:,63);      %Tower Moment Base TORsion [V/V]
OptRpm=input(:,64);      %Optimal Rpm [rpm]

```

```
WindEst=input(:,65);      %Wind Estimation [m/s]
MaxPwrEst=input(:,66);   %Max Power Estimation/Available Power [kW]
```

A.3 MATLAB for Averaging the Data

This section presents the code where the data read from the text file is averaged. The text file with the measurement reading provide us the information that readings are taken every 50ms which mean each second 20 readings are taken. This code converts those 20 readings to 1 by taking average of those 20 readings.

```
DCV1 = mean(reshape(DCV, avg, []));           % Calculate averages without
using a loop                                 % Convert the result into a
DCV2 = DCV1(:);                               column vector
DCC1 = mean(reshape(DCC, avg, []));           % Calculate averages without
using a loop                                 % Convert the result into a
DCC2 = DCC1(:);                               column vector
TurbSpeed21 = mean(reshape(TurbSpeed2, avg, [])); % Calculate averages without
using a loop                                 % Convert the result into a
TurbSpeed22 = TurbSpeed21(:);                 column vector
WS301 = mean(reshape(WS30, avg, []));         % Calculate averages without
using a loop                                 % Convert the result into a
WS302 = WS301(:);                             column vector
PAB11 = mean(reshape(PAB1, avg, []));         % Calculate averages without
using a loop                                 % Convert the result into a
PAB12 = PAB11(:);                             column vector
timea = mean(reshape(time, avg, []));         % Calculate averages without
using a loop                                 % Convert the result into a
timeb = timea(:);                             column vector
```

B

Appendix 2

B.1 MATLAB Code 24 Hours Simulation

This section presents the code written in MATLAB to define all the parameters and variables for wind turbine models, solar model and load model to run the system for 24 hours. It imports the texts file to MATLAB and then data is extracted and aligned for further programming. The inputs to the Simulink model are shaped through the code presented in this section. This code needs to be run before running the 24-hour model and it will automatically run all the subcodes and functions.

```
clc
close all
clear all
clear
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Defining The Load Data %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
filename2 = ['Load_86400_PNew.xlsx'];
input2 = importdata(filename2);
time_sec=input2(:,1);% coulom1
Load1=input2(:,2);% coloumn2
Sampl_t=1;
time_sec=linspace(0,length(time_sec)*Sampl_t,length(time_sec))';
L= timetable(seconds(time_sec),Load1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Defining The Solar Irradiance Data %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
T= 25; %Temperature
%G=500;
a=1.5; %diode ideality factor
Rs=.39053; %Series resistance
Io=5e-8; %diode saturation Current
Ns=6; %Number of Panels in Series
Np=8; %Number of Panels in Parallel
Kelvin=273; %constant to change temperature to kelvin
q=-1.6022e-19; %charge on electro
K=1.3806e-23; % Boltzman consnatntJ/K% J/K
Isc=9.99; %Short circuit current
Ksc=.0032; %Short circuit temperature coefficient
Rsh=180.3; %Shunt resistance

%===== Reading Data from Data File =====
filename = ['B1_METMCL2_1_240317_00_00_01.txt']; % 24 hours wind measurements data
file
delimiterIn = '\t';
input = importdata(filename,delimiterIn);
MeasuredWindReadings;

% ===== DC-generator Components: =====
J = 2600/(20^2); % Moment of Inertia[kgm^2]
```

```

b          = 0.1;           % Damping
Kp         = 3;            % PI-reg
Ki         = 5;            % PI-reg

% ===== NREL-reg: =====
Sampl_t    = time(2)-time(1); % [s]           Sampling time of the
controller
CornerFrequency = 10;      % [rad/s]         Corner frequency of the generator
speed low pass filter
VS_CtInSp  = 5.7;         % [rad/s]         Cut-in generator speed
VS_RtPwr   = 25000;       % [W]             Rated generator power
VS_RtGnSp  = 7.45;        % [rad/s]         Rated generator speed
VS_Rgn3MP  = 1.6;         % [rad]           Pitch angle to stay in Region 3
VS_Slope15 = 2600;        % [W/(rad/s)]     Slope of torque curve in Region
1.5
VS_Rgn2Sp  = 6.2;         % [rad/s]         Lower generator speed limit for
Region 2.
VS_Rgn2K   = 35;          % [W/(rad/s)^2]   Region 2 generator torque
constant.
VS_TrGnSp  = 7;           % [rad/s]         Lower generator speed limit for
Region 2.5.
VS_Slope25 = 3500;        % [W/(rad/s)]     Slope of torque curve in Region
2.5
VS_SySp    = 6.5;         % [rad/s]         Generator speed where torque would
be zero if in Region 2.5. (Construction help point.)
VS_MaxTq   = 225;         % [Nm]           Maximum generator torque
VS_MaxRat  = 500;         % [Nm/s]         Maximum generator torque rate
PC_MaxPit  = 1.5708;      % [rad]           Maximum allowed pitch angle (Fully
feathered position)
PC_MinPit  = 0.0349;      % [rad]           Minimum allowed pitch angle (Fully
fine position)
PC_KP      = 0.35;        % [rad/(rad/s)]   Pitch controller Proportional
gain
PC_KI      = 0.22;        % [rad/(rad/s)]   Pitch controller Integral gain
PC_KK      = 0.4;         % [rad]           The pitch angle at which the pitch
sensitivity is double the pitch sensitivity at pitch = 0 rad.
PC_MaxRat  = 0.2;         % [rad/s]         Maximum allowed pitch rate
VS_SlPc    = 10;
StoppingPitchSpeed = 0.0349; % Pitch rate when stopping the turbine
StartingPitchSpeed = -0.0249; % [rad/s] Pitch rate when starting the turbine
PC_RefSpd  = 7.85;        % [rad/s]         Reference generator speed
Run_Stop   = 1;

%===== Vindkraftverk parametrar =====
Lambda_opt=8.75; % Optimal lambda
rho=1.225; % [kg/m^3] Air density
d=16; % [m] Turbine diameter
R = d/2; % [m] Turbine radius
Cpmax=0.418; % Maximum Power Coefficient of the turbine with MinPit at 2
deg.
A=pi*R.^2; % [m^2]Turbine area.

%===== Stopping and Starting Pitch Speed Adjustment Near Feathered =====
SaS = [PC_MinPit 1;PC_MaxPit*0.85 1;PC_MaxPit*0.98 0.15;PC_MaxPit*1.2 0.15];

SaS_table = SaS(1:end,2:end);
SaS_BP = SaS(1:end,1)'; % Rad index för tabell

```

```

% ===== Cp(lambda, Beta) tabel =====
load('CP_data.mat');           % Data for Cp tabel
breakpoints1 = data(2:end,1);   % Rad index for tabel
breakpoints2 = data(1,2:end);   % Kolumn index for tabel
table_data = data(2:end,2:end); % Output values for tabel

% ===== Max Cp for all angles over 2 degrees =====
Cp_B0 = table_data;
Cp_B0(:,1) = 0;
Max_Cp = [breakpoints1' max(Cp_B0)'];
Vector_data = max(Cp_B0)';
%===== Spill metod antal =====
breakpoints3 = flip(table_data(32,1:7));
Beta = flip(breakpoints2(1:7)); %Varden for bladvinkel

%===== Time settings=====
time1=linspace(0,length(time)*Sampl_t,length(time))';

% ===== Input to Simulink =====

%Wind = timetable(seconds(time1), WS301);%without smoothing and averaging

%smoothed_wind_speed = movmean(WS301, 100); %With averaging but not smoothing
%Wind = timetable(seconds(time1), smoothed_wind_speed);%With averaging but not
smoothing

Wind1= smoothdata(WS301,'movmean',300); %With averaging and smoothing
Wind = timetable(seconds(time1), Wind1); %With averaging and smoothing

Irradiance=timetable(seconds(time1), Solar_Irradiance);

sim('twentyfourhoursModel.slx');
open ('twentyfourhoursModel.slx');

```

B.2 MATLAB Code to Extract Data From Files

This section presents the code written in MATLAB to extract the data from the text file which contains all the measurements reading from the sensors which record solar irradiance and wind speed throughout the day. There are 18 output channels. The data is read from all the output channels and stored in a text file format. The code reads the data from text file and stores it in 18 different variables. Some of these variables are to be utilized in the main code. The code is stored in MATLAB editor file with the name ' MeasuredWindReadings ' and this file is called as a function in the main code.

```

time=input(:,1);           %Time UTC+1 [s]
WD22=input(:,2);          %Wind Direction Gill MaxiMet 600 22m Height mast 1
[deg]
WS22=input(:,3);          %Wind Speed Gill MaxiMet 600 22m Height mast 1 [m/s]
AIRTA22=input(:,4);       %Air Temperature Gill MaxiMet 600 22m Height mast 1
[deg C]
AIRPA22=input(:,5);       %Air Pressure Gill MaxiMet 600 22m Height mast 1 [hPa]

```

```

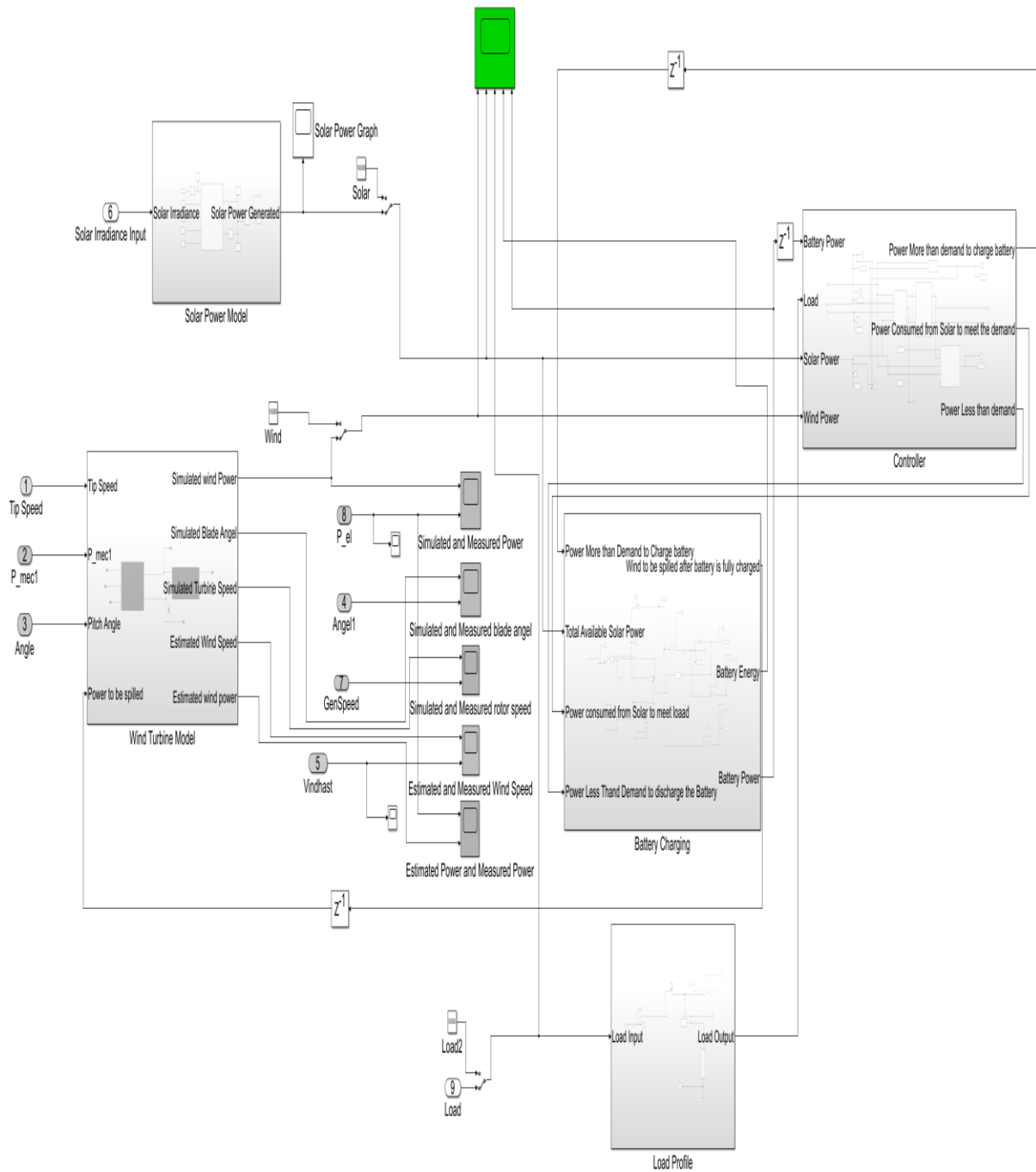
RI22=input(:,6);           %Rain Intensity Gill MaxiMet 600 22m Height mast 1
[mm/h](PRECIPI)
PRECIPT22=input(:,7);     %Precipitation Total Gill MaxiMet 600 22m Height mast 1
[mm]
Status22=input(:,8);      %Gill MaxiMet 600 22m Status Signal. Zero means OK
SysMode=input(:,9);       %Wind turbine controller Mode [enum]
WD301=input(:,10);        %Wind Direction Gill Observer 30m Height mast 1 [deg]
WS301=input(:,11);        %Wind Speed Gill Observer 30m Height mast 1 [m/s]
SonicAIRTA=input(:,12);   %Air Temperature Gill Wind Observer 30m Height mast 1
[deg C]
Status30=input(:,13);     %Wind Observer 30m Status Signal. Zero means OK
WD38=input(:,14);         %Wind Direction Gill wind master 38m Height mast 1
[deg]
WS38=input(:,15);         %Wind Speed Gill wind master 38m Height mast 1 [deg]
WS38V=input(:,16);        %Vertical Wind Speed Gill wind master 38m Height mast 1
[deg]
Status38=input(:,17);     %Gill Wind Master 38 m height Status Signal. Zero Means
OK
Solar_Irradiance=input(:,18); %Solar Irradiation EKO MS-40S PYARNOMETER 5M
HEIGHT MAST [W/m2]

```

C

Appendix 3

C.1 Full System Controlling the Islandic Operation of Wind Turbine



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