Bangladesh University of Engineering and Technology

Department of Electrical and Electronic Engineering

Project Report

Grid Integration of Wind Energy Conversion System

Course No: EEE 306
Course Title: Power System I Laboratory

Submitted To:
Dr. Md. Nasim Ahmed Dewan
Professor, BUET
Shafayeth Jamil
Adjunct Lecturer, BUET

Submitted By:
Group No: 03

Group Members:
1906016 – Rowatul Jannat Rafi
1906017 – Rifat Ullah
1906018 – Sumon Howlader
1906019 – Dibbo Dey
1906020 – Shadman Saquib
1906027 – Progna Dipto Saha

Dept: EEE
Level: 3 Term: 1
Section: A

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Project Objective:

Wind energy has emerged as a promising alternative source for overcoming the energy crisis in the world. Wind power-based energy is one of the most rapidly growing areas among the renewable energy sources and will continue to do so because of the growing concern about sustainability and emission reduction requirements. The uncertain nature of wind and high penetration of wind energy in power systems are a big challenge to the reliability and stability of these systems. To make wind energy a reliable source, accurate models for predicting the power output and performance monitoring of wind turbines are needed.

In this project, our goal is accomplishing the followings:

- Study characteristics of a Wind Turbine Power Plant
- Investigate the Grid Integration Challenges of Wind Energy
- Design a Simulink Model of Wind Energy Conversion System

Wind Energy Conversion System (WECS):

Wind Energy Conversion System (WECS) is a complex system of interconnected components that converts kinetic energy of wind into mechanical energy and subsequently to usable electrical energy with the aid of generators. Scientifically, winds arise due to uneven heating of the surface of the earth. The varying heating rates create difference in pressure and temperature that act as the driving forces for air circulation. Typically, these differences are more pronounced near water bodies like lakes and oceans. Hence, coastal and offshore areas are great sites for establishing WECS.

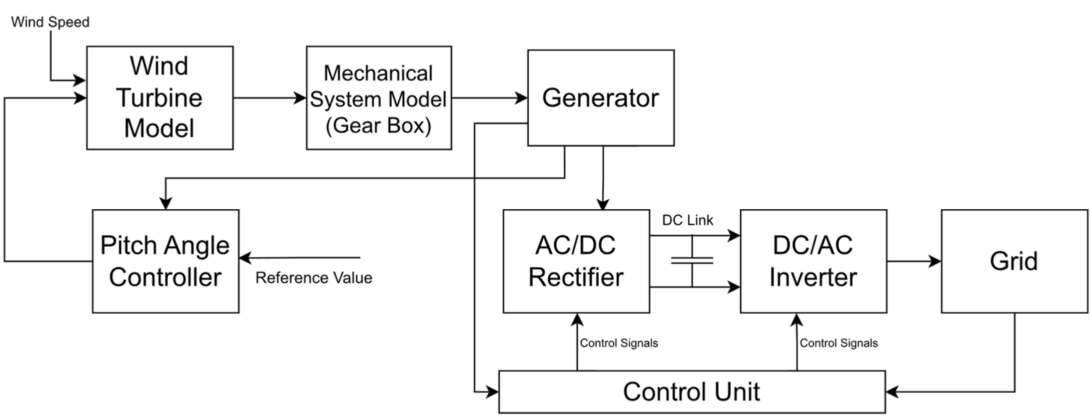


Figure 1: Block Diagram of a Wind Energy Conversion System

The major components of WECS are wind turbines, generators, controllers and power transmission system. Wind turbine harnesses kinetic energy from the wind. This acquired energy is passed on to the generator in the form of mechanical energy, more specifically as mechanical torque. The generator converts the mechanical energy to alternating current or electrical energy. For achieving maximum power, generator speed is controlled by special control units such as pulse-width modulation converters. The output power of generator is supplied to the grid using generator-side converter (AC/DC Rectifier) and grid-side converter (DC/AC Inverter).

Wind Turbine:

Aerodynamics of Wind Turbine:

Modern wind turbines consist of three blades mounted to a tower made from tubular steel. At higher altitudes, the tower enables the turbine to take advantage of faster wind speeds.

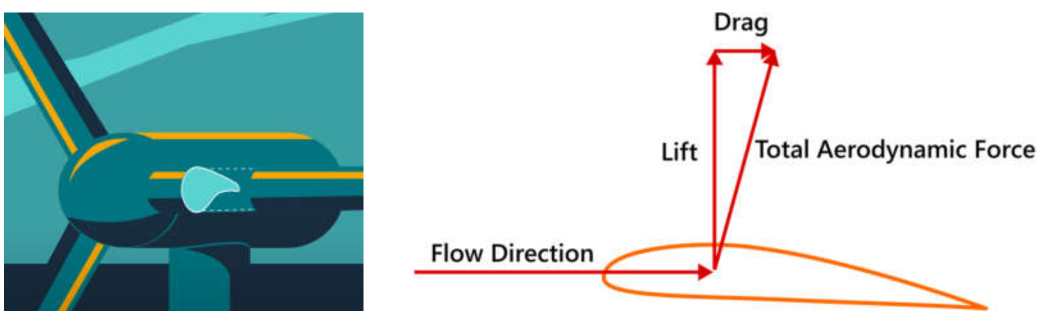


Figure 2: Aerodynamics od Wind Turbine

A wind turbine turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this ca uses the rotor to spin. The rotor connects to the generator, either directly (if it's a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator. This translation of aerodynamic force to rotation of a generator creates electricity.

Components of Wind Turbine:

A wind turbine consists of five major parts and many minor parts. The main components are the foundation, the tower, the rotor and hub (including three blades), the nacelle, and the generator.

1. Foundation

The foundation is in the ground for onshore turbines. It is invisible because it is covered with dirt. It is a large, heavy structural block of concrete that must support the entire turbine and the forces acting on it.

In offshore turbines, the foundation is underwater and not visible. For offshore turbines far from the sea, the base floats but has enough mass to support and sustain the weight of the turbine and any forces exerted on it.

2. Tower

The towers of most modern turbines are made of round steel tubes. A rule of thumb for a turbine tower is that it is the same height as the circle's diameter its blades make as they spin. Generally, the taller the turbine, the more susceptible to high-speed winds because the wind is stronger the farther we are from ground.

3. Rotor and Hub

The rotor is the rotating part of the turbine; it consists of three blades and a central part connecting the blades, the hub.

Although it is the most common, a turbine does not necessarily have three blades. But the three-blade rotor has advantages such as optimum efficiency. The blades aren't strong; they're hollow and made of composite material that's both lightweight and strong. The trend is to make them bigger (for more power), lighter, and more robust. For aerodynamics, the blades are shaped like an airfoil (like an airplane's wings). Also, they are not flat and have a twist between their root and tip. The blade can rotate up to 90° around its axis. This movement is called pitch.

The function of the hub is to hold the blades and allow them to rotate relative to the rest of the turbine body.

4. Nacelle

The nacelle houses all the components that need to be on top of the turbine.

The nacelle of a wind turbine is a complex electromechanical system with quite a few components that function correctly with precision. Significant turbine parts are the generator and the turbine shaft that transfers the harvested power from wind to the generator through a gearbox. The gearbox is an essential part of the wind turbine; it's on the cable car.

Since the turbine must follow the wind and adjust its direction according to the wind direction, its rotor must turn relative to the tower. This rotation is called yaw motion, in which the nacelle and rotor rotate around the tower axis.

5. Generator

A generator is a component that converts the mechanical energy of the rotor (obtained from the wind) into electrical energy. The generator has the same structure as the electric motor.

Types of Wind Turbine:

There are two basic types of wind turbines: those with a horizontal axis, and those with a a vertical axis.

The majority of wind turbines have a horizontal axis: a propeller-style design with blades that rotate around a horizontal axis. Horizontal axis turbines are either upwind (the wind hits the blades before the tower) or downwind (the wind hits the tower before the blades). Upwind turbines also include a yaw drive and motor -- components that turns the nacelle to keep the rotor facing the wind when its direction changes.

While there are several manufacturers of vertical axis wind turbines, they have not penetrated the utility scale market (100 kW capacity and larger) to the same degree as horizontal access turbines.

Figure 3: Horizontal and Vertical Axis Wind Turbines

Power Generation Factors:

The power production of a wind turbine depends on many factors. Some the important ones that affect the wind power output are listed below:

1. Wind Speed

   Wind power is exponentially proportional to wind speed. If wind speed doubles, power generation becomes eight times greater. So, wind speed study of any proposed site is done extensively to ensure good returns on investment. Typically wind speeds are measured for a year at the site before any decision is taken.

2. Wind Direction

   The alignment of the rotor swept area with the wind direction and the angle (pitch) at which wind hits individual turbine blades affect the amount of power extraction. For maximum power extraction, the nacelle is rotated by yaw mechanism to face the wind whenever the wind direction changes.

3. Turbine Design

   Wind turbines are designed to maximize the rotor blade radius to maximize power output. Larger blades allow the turbine to capture more of the kinetic energy of the wind by moving more air through the rotors

4. Air Density

   Power output is related to the local air density, which is a function of altitude, pressure, and temperature. Dense air exerts more pressure on the rotors, which results in higher power output.

5. Betz Limit

   German physicist Albert Betz calculated in 1919 that the maximum power that a wind turbine can extract from wind is 59%. He derived his calculation from the conservation of momentum principle because wind is nothing but air that has momentum. His calculations were independent of turbine design. Practically, wind turbines achieve 70-80% of the Betz Limit.

Wind Turbine Power Curve:

Power curve of a wind turbine, which gives the output power of turbine at a specific wind speed, provides a convenient way to model the performance of wind turbines. A typical power curve for a pitch regulated wind turbine is shown.

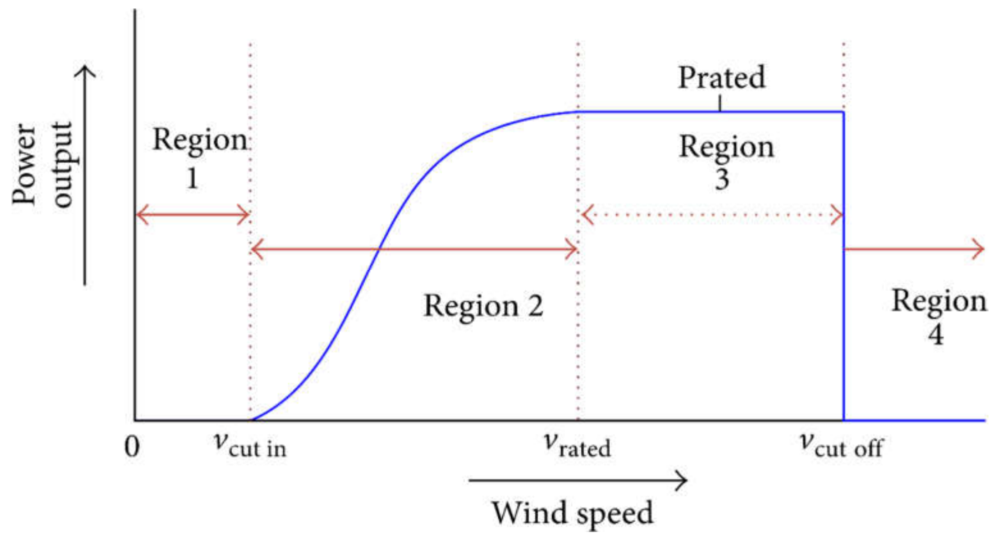


Figure 4: Power Curve of Wind Turbine

In the first region when the wind speed is less than a threshold minimum, known as the cut-in speed, the power output is zero. In the second region between the cut-in and the rated speed, there is a rapid growth of power produced. In the third region, a constant output (rated) is produced until the cut-off speed is attained. Beyond this speed (region 4) the turbine is taken out of operation to protect its components from high winds; hence it produces zero power in this region.

The power curve of a WT indicates its performance. Accurate models of power curves are important tools for forecasting of power and online monitoring of the turbines. A number of methods have been proposed in various works to model the wind turbine power curve. These methods which use data from manufacturers' specifications and actual data from the wind farms have been utilized by many researchers in various wind power applications

Commercial Wind Turbine Parameters:

We have browsed several brochures of commercial wind turbine manufacturers to get an idea of the dimensioning and range of parameter values for modelling realistic wind turbine model.

Vesta is one of the world's leading wind turbine manufacturers. The parameters of a 2MW wind turbine designed and manufactured by Vesta is shown below.

V90-2.0 MW™ IEC IIA/IEC S (Vesta)

Power regulation	Pitch regulated with variable speed
Operating data	
Rated power	2,000kW
Cut-in wind speed	4m/s
Cut-out wind speed	25m/s
Re cut-in wind speed	23m/s
Wind class	IEC IIA/IEC S
Standard operating temperature range from -20°C to 40°C	
Rotor	
Rotor diameter	90m
Swept area	6,362m²
Air brake	full blade feathering with 3 pitch cylinders
Blade dimensions	
Length	44m
Max. chord	3.9m
Electrical	
Frequency	50/60Hz
Generator type	4-pole (50Hz)/6-pole (60Hz) doubly fed generator, slip rings
Gearbox	
Type	one planetary stage and two helical stages
Tower	
Hub heights	80m (IEC S) Site and country specific

Figure 5: Parameters of a 2MW Commercial Wind Turbine

Grid Integration Challenges of WECS:

The integration of wind energy into the electrical grid can pose several challenges, including:

1. Intermittency: One of the main challenges of wind energy is that it is an intermittent source of power, meaning that the amount of energy produced by wind turbines can fluctuate greatly depending on weather conditions. This makes it difficult for grid operators to manage the supply and demand of energy, and can also lead to reliability issues.
2. Grid stability: Wind energy can sometimes cause stability issues in the electrical grid, such as voltage fluctuations and frequency deviations. This can result in problems with power quality, and can also pose risks to the stability of the grid as a whole.
3. Power quality: The fluctuations in wind energy production can affect the quality of power supplied to the grid, which can result in problems with voltage, frequency, and power factor. This can be challenging for grid operators to manage, and can also impact the reliability of the grid.
4. Grid capacity: The integration of wind energy into the electrical grid may require significant upgrades to the grid, such as the installation of new transmission lines and substations, to accommodate the fluctuating nature of wind energy. This can be expensive and time-consuming, and can also have environmental impacts.
5. Forecasting: Accurately forecasting wind energy production can be challenging, which can make it difficult for grid operators to manage the supply and demand of energy. This can result in overproduction or underproduction of wind energy, which can affect the stability and reliability of the grid.
6. Integration costs: The integration of wind energy into the electrical grid can involve significant costs, including the installation of new transmission lines, substations, and energy storage systems. This can be a barrier for communities and businesses that are looking to harness the power of wind energy.
7. Environmental considerations: The construction of wind turbines and associated infrastructure can have significant impacts on the environment, including wildlife habitat and cultural resources. To mitigate these impacts, wind turbine developers must work closely with environmental organizations and government agencies to ensure that wind turbines are installed in a manner that protects wildlife and sensitive ecosystems.

To overcome these challenges, it is important for grid operators to work closely with wind turbine developers and energy stakeholders to develop effective strategies for integrating wind energy into the electrical grid. This may involve the use of advanced technologies, such as energy storage systems and smart grid systems, to manage the intermittency of wind energy and ensure grid stability. By working together, we can harness the power of wind energy in a way that benefits communities and protects the environment.

Proposed Model Diagram:

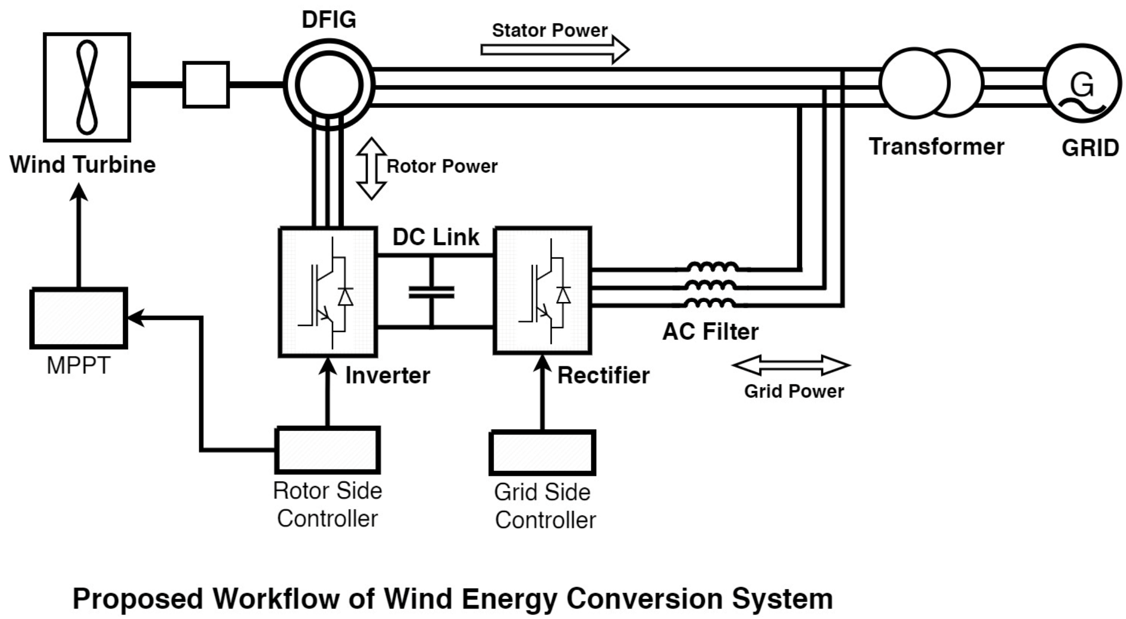


Figure 6: Project Model Diagram

A variable speed wind turbine based on doubly-fed induction generator is proposed and designed to generate 2.5MW electricity at 50Hz.

One approach to allowing wind turbine speed to vary is to accept whatever frequency the generator produces, convert it to DC, and then convert it to AC at the desired output frequency using an inverter. This is common for small house and farm wind turbines. But the inverters required for megawatt-scale wind turbines are large and expensive.

Doubly fed generators are another solution to this problem. Instead of the usual field winding fed with DC, and an armature winding where the generated electricity comes out, there are two three-phase windings, one stationary and one rotating, both separately connected to equipment outside the generator. Thus, the term doubly fed is used for this kind of machines. The stator is directly connected to grid and produces power at fixed grid frequency. The rotor winding is connected to variable frequency AC power. This input power is adjusted in frequency and phase to compensate for changes in speed in the wind turbine. This adjustment requires AC-DC-AC converter. This converted is usually constructed from large IGBT semiconductors. The converter is bidirectional and can pass power in either direction. The rotor winding can also supply power to the grid when the generator is operating in hyper-synchronous mode.

Control system for the converters evaluates generator torque and reactive power references as a function of wind speed and grid voltage. Maximum Power Point Tracking system is designed to control turbine speed for maximum power extraction.

Wind Turbine Model:

A typical onshore wind turbine has a nominal power between 1.5 and 3 MW. We have selected to model a 2.5 MW wind turbine.

From data extracted from manufacturers' brochures and other specialized references, it's possible to propose some parameters that represent the energetic behavior of the wind turbine and its main mechanical and electrical dynamics.

The two main aspects to consider are the aerodynamic behavior of the rotor and the wind turbine control strategy parameters. Once the energetic behavior of the turbine is defined, it's possible to proceed to the sizing of the power electronic converters.

Parameter	Value	Unit
Radius	42	m
Nominal wind speed	12.5	m/s
Variable speed ratio (minimum–maximum turbine speed)	9–18	rpm
Optimum tip speed ratio λ_{opt}	7.2	—
Maximum power coefficient C_{p_max}	0.44	—
Air density ρ	1.1225	kg/m^3

Figure 7: Wind Turbine Data Extracted from Manufacturer's Brochure

Using these parameters and the following equations we implemented a simple wind turbine model without any sophisticated mechanical system.

$$C_p = 0.46\left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)\left(e^{-18.4/\lambda_i}\right)$$

$$\lambda_i = \frac{1}{\lambda + 0.02\beta} - \frac{0.003}{\beta^3 + 1}$$

$$\lambda = \frac{R\Omega_t}{V_v}$$

$$T_t = \tfrac{1}{2}\rho\pi R^3 V_v^2 C_t$$

Cp = Power Coefficient of turbine, a dimensionless quantity signifying effectiveness of wind turbine in transforming kinetic energy into mechanical energy
Λ = Tip speed Ratio
R = Turbine blade radius
ß = Pitch Angle
Tt = Turbine generated torque

Simulink Model:

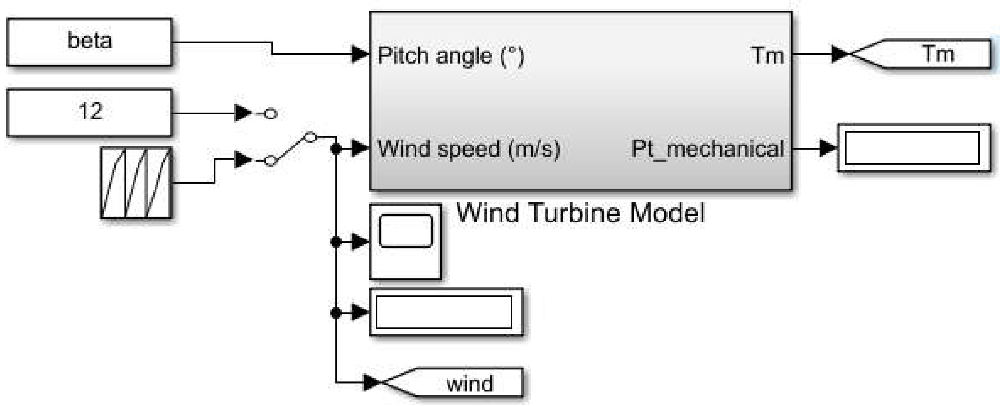


Figure 8: Simulink Model of Wind Turbine

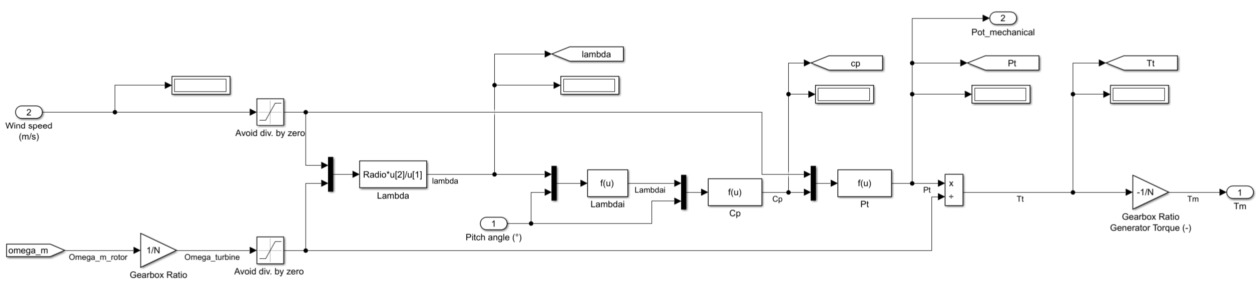


Figure 9: Implementation of Wind Turbine Model

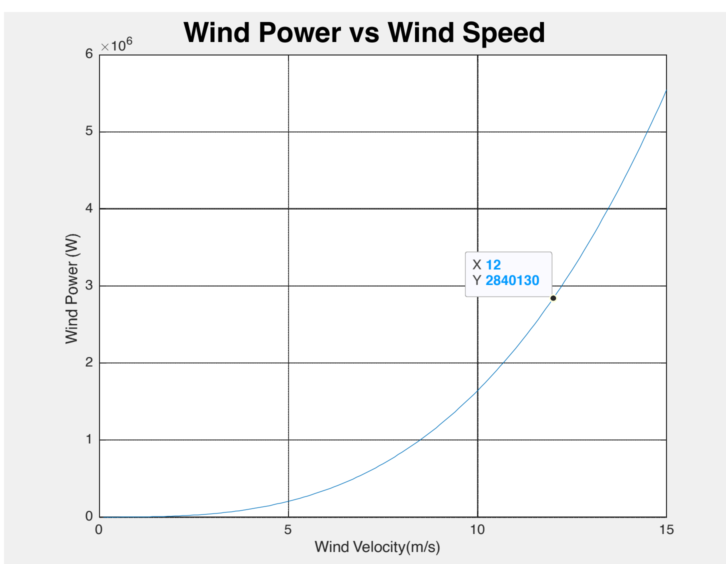


Figure 10: Wind Power vs Wind Speed Curve

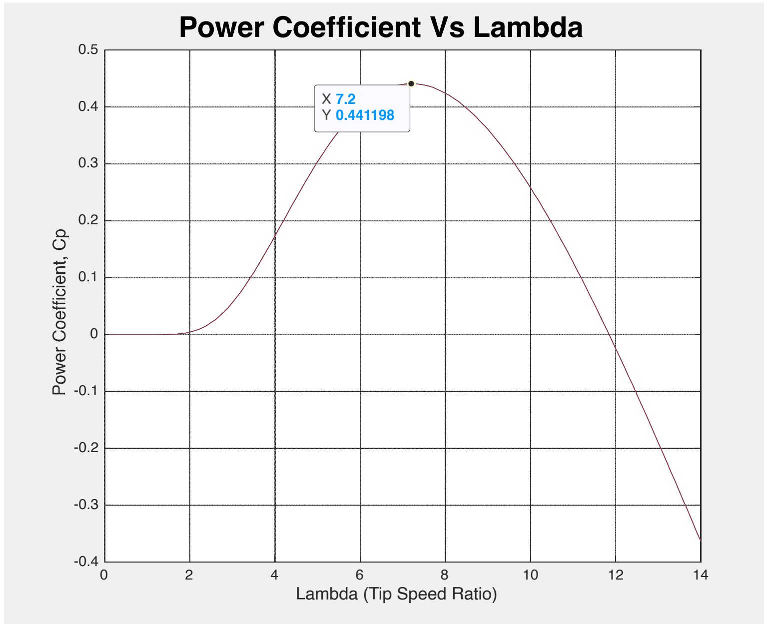


Figure 11: Power Coefficient vs Tip Speed Ratio Curve

The power coefficient, Cp is a quantity that expresses what fraction of the power in the wind is being extracted by the wind turbine. It is generally assumed to be a function of both tip-speed ratio and pitch angle. Above is the plot of the variation of the power coefficient with variations in the tip-speed ratio when the pitch is held constant. Ideally, one would like to have a turbine operating at the maximum value of Cp at all wind speeds. This means that as the wind speed changes, the rotor speed must change to such that Cp = Cp(max). A wind turbine with a variable rotor speed is called a variable speed wind turbine. While this does mean that the wind turbine operates at or close to Cp for a range of wind speeds, the frequency of the AC voltage generator will not be constant. This can be seen in the following equation:

$N = 120*f/P;$

where N is the rotor angular speed, f is the frequency of the AC voltage generated in the stator windings, P is the number of poles in the generator inside the nacelle.

For the selected parameters of turbine, the maximum power coefficient is 0.44 at tip speed ratio of 7.2 for 12 m/s wind speed.

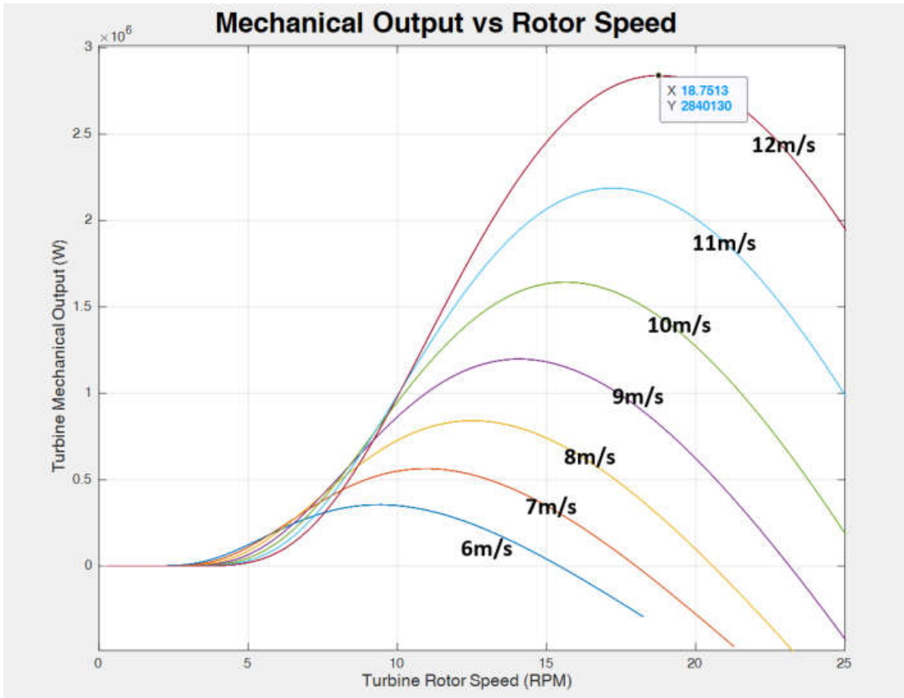


Figure 12: Mechanical Output of Turbine at Different Wind Speeds vs Turbine Rotor Speed

From the above plot, at 12 m/s wind speed, the maximum mechanical power generated by the turbine 2.84MW. The turbine rotor speed ideally should be at about 18 rpm. The generator rotor speed will be 100 times this speed because the gear ratio selected as 100:1.

Doubly-Fed Induction Generator:

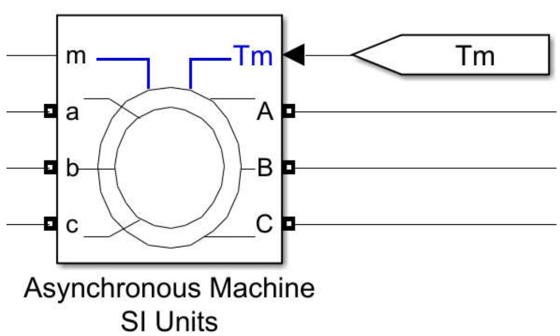


Figure 13: DFIG

An asynchronous machine block from the Simscape electrical toolbox is used to the DFIG. The parameters of this block are set as the following table.

Parameter	Value	Unit
Magnetizing inductance L_m	2.5×10^{-3}	H
Rotor leakage inductance L_{or}	87×10^{-6}	H
Stator leakage inductance L_{os}	87×10^{-6}	H
Rotor resistance R_r	0.026	Ω
Stator resistance R_s	0.029	Ω

Figure 16: Equivalent Model Parameter of DFIG

Parameter	Value	Unit
Nominal stator active power	2.0	MW
Nominal torque	12732	Nm
Stator voltage	690	V
Nominal speed	1500	rpm
Speed range	900–2000	rpm
Pole pairs	2	—

Figure 15: Terminal Characteristics of DFIG

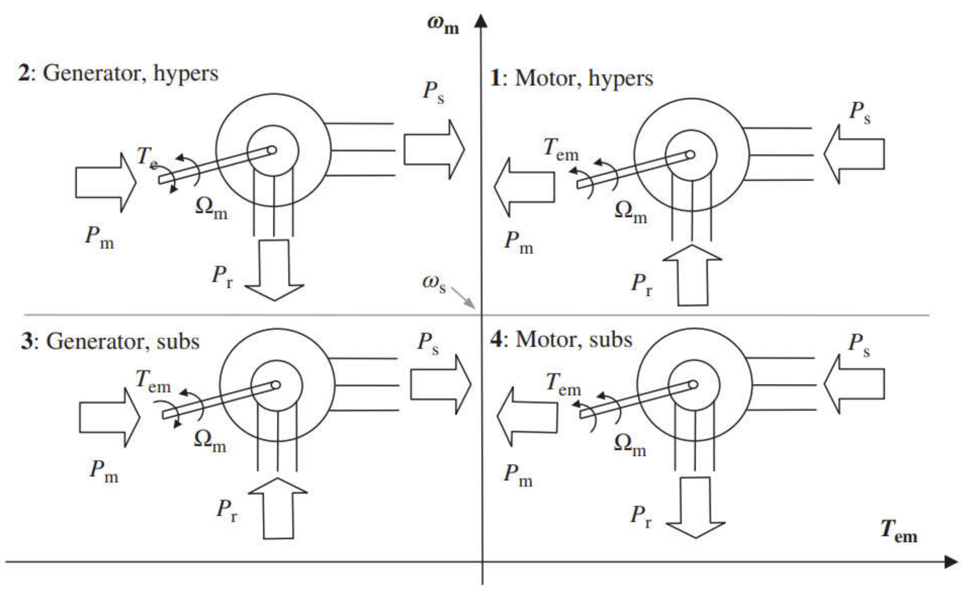


Figure 14: Four Quadrant Mode of Operation of DFIM

Both stator and rotor will supply power to the grid when the doubly-fed induction machine operates as generator in hypersynchronous speed.

AC-DC-AC Converters:

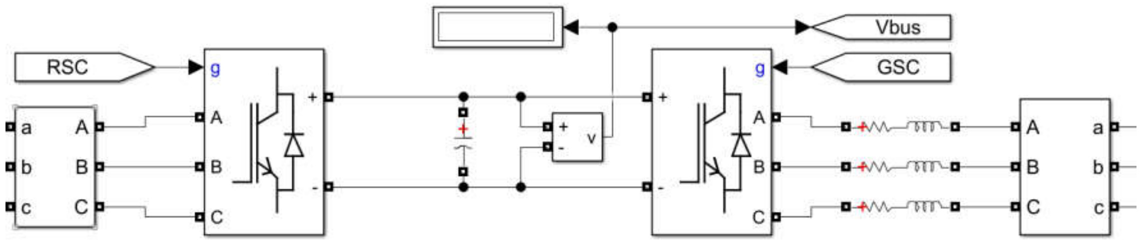


Figure 17: Rotor-side and Grid-side Converters and AC Filter

Inverter converts DC into AC for which switching is required . These switching which are generally done at high frequency is performed by IGBT. There are other switches like MOSFET , BJT , SCR (Silicon controlled rectifier) . But each have specific range of applications . IGBT is generally used in high frequency and high-power application.

Both grid side and rotor converters are modeled with bidirectional switches. They convert voltage and currents from DC to AC, while the exchange of power can be in both directions from AC to DC (rectifier mode) and from DC to AC (inverter mode). The switch normally is created by a controlled semiconductor with a diode in antiparallel to allow the flow of current in both directions. For large converters, the controlled semiconductor used is an insulated gate bipolar transistor (IGBT).

The RL filters between the grid-side converter's output and the grid are used to decouple the output voltage and the grid and to filter higher harmonics.

Insulated Gate Bipolar Transistor (IGBT) / Diode Based Converters:

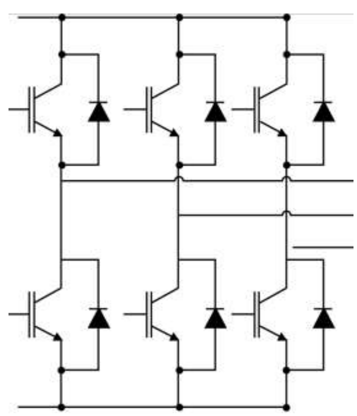


Figure 18: IGBT Converter Structure

This type of inverters is widely used in WECS because of their high reliability and efficiency. Commercially available wind turbine converters are rated for maximum 6.5MVA.

A Commercial Wind Inverter Specification:

Technical data

ACS880 full power wind turbine converter

Converter model	ACS880-77LC in-line configuration	ACS880-87LC back-to-back configuration
Converter type	Full power converter for permanent magnet and asynchronous generators	
Generator power range	0.8 to 4.6 MW	1.5 to 8 MW
Cooling	Liquid cooling with totally enclosed cabinet	
Control principle	Direct torque control (DTC)	
Electrical data		
Rated grid voltage	525 to 690 V AC, 3-phase, ±10%	
Rated generator voltage	0 to 750 V AC	
Nominal grid frequency	50/60 Hz	
Efficiency at converter's rated point, typical value	97%	
Generator-side converter du/dt, measured value	1.25 kV/µs	
Grid harmonics Total harmonic current distortion, measured value	2.5%	

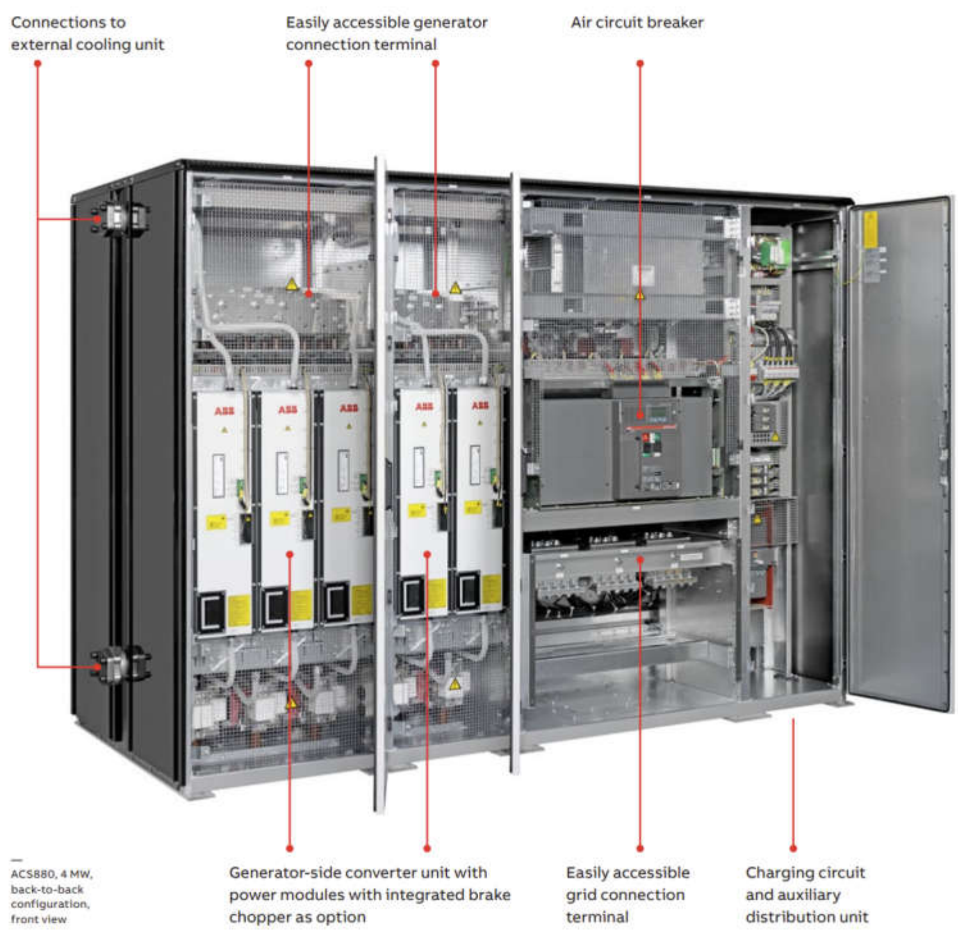


Figure 19: A commercial Wind Inverter

DC Link:

The DC part of the back-to-back converter is typically called the DC link. Thanks to the energy stored in a capacitor (or combination of several capacitors), it tries to maintain a constant voltage in its terminals. It is the linkage between the grid side and rotor side converters.

In order to derive the model of the DC link, the DC bus voltage must be calculated. This voltage is dependent on the current through the capacitor:

$$V_{bus} = \frac{1}{C_{bus}} \int i_c dt$$

The DC link voltage in our model is set to 1200V which is slightly higher than grid-side line-line voltage 690*sqrt(3) = 1195V.

Control System:

The DQZ and alpha-beta-gamma transforms are often used in the context of electrical engineering with three-phase circuits. The transform can be used to rotate the reference frames of AC waveforms such that they become DC signals. Simplified calculations can then be carried out on these DC quantities before performing the inverse transform to recover the actual three-phase AC results.

In analysis of three-phase synchronous machines, the transformation transfers three-phase stator and rotor quantities into a single rotating reference frame to eliminate the effect of time-varying inductances and transform the system into a linear time-invariant system.

Vector Control of DFIM is the most established control system used with AC-DC-AC converters. We have modelled the following control system in Simulink.

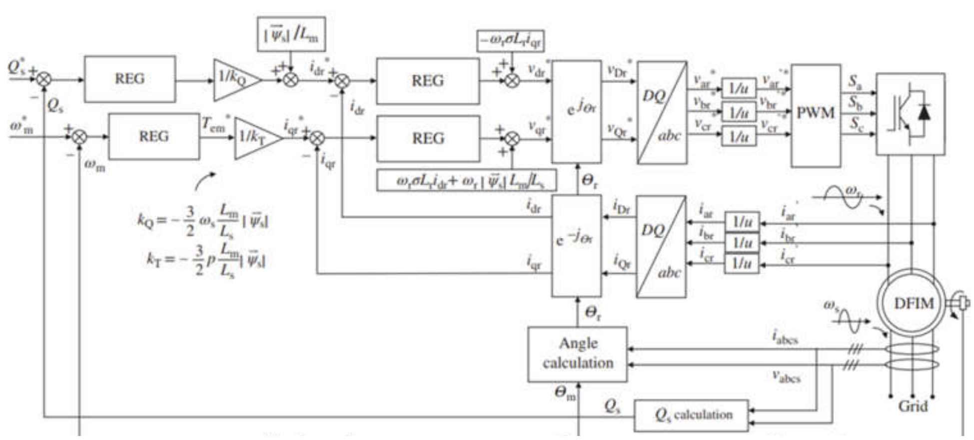


Figure 20: Complete Vector Control of DFIM

Simulink Models of the Control system:

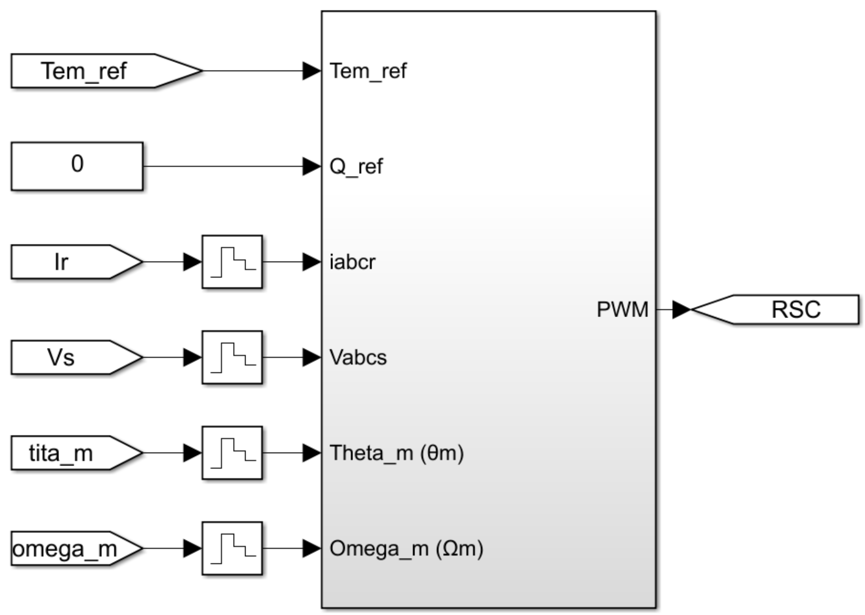


Figure 21: Rotor-Side-Control

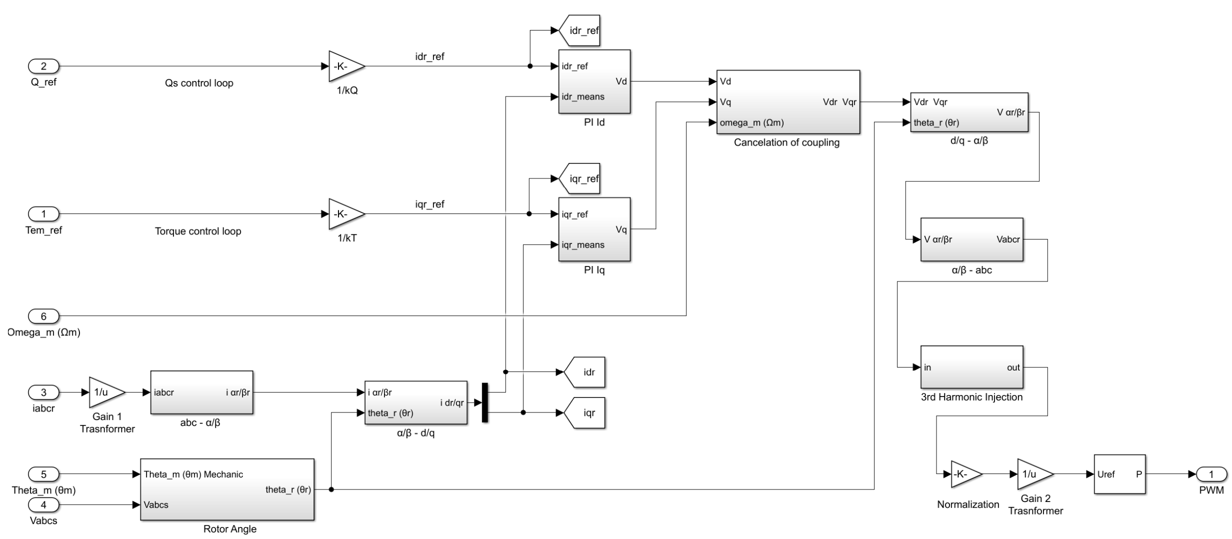


Figure 22: Implementation of Rotor-Side-Control

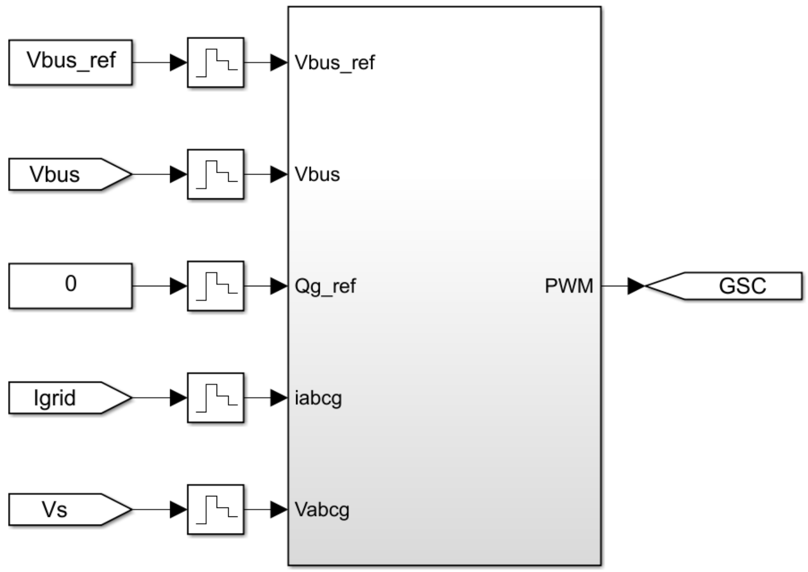


Figure 23: Grid-side-Control

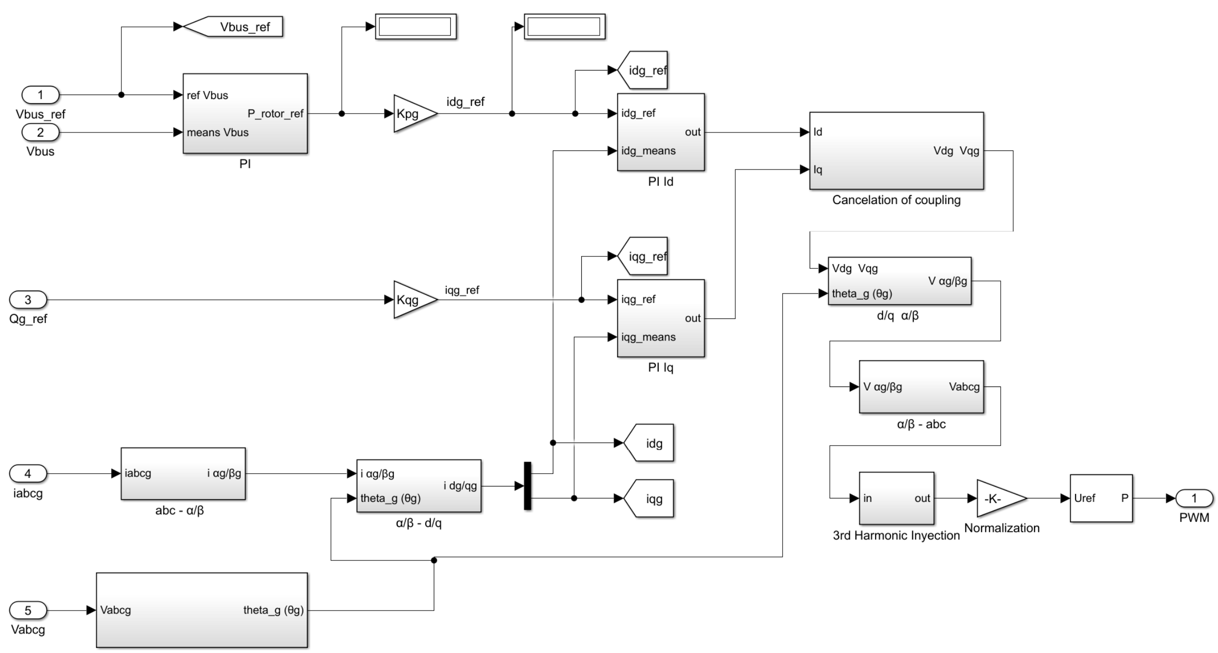


Figure 24: Grid-Side-Control Implementation

The rotor-side control system uses stator voltage and rotor speed to computes an angle which is used to transform rotor current from abc phase representation to DQ vector space. The quadrature component of rotor current is proportional to torque. A torque reference and measured value of quadrature current is given input to a PI controller. Adjusting the torque reference allows control of the torque and subsequently speed of the machine. The direct component of rotor current is related to stator reactive power supplied to the grid. Stator reactive power reference is generally set by grid operators to ensure proper power factor.

Structure of the grid-side-control system is exactly similar. Here, the role rotor current is replaced by the grid current. The quadrature component of grid current is now responsible for grid reactive power and direct component of grid current is responsible for maintaining DC bus voltage. The bus voltage reference and grid reactive power reference are given along with measured values to PI controllers which regulate the proper variables.

The output of PI controllers first reverse transformed from DQ vector space to abc phase quantities and then fed to a PWM generator. This PWM output controls the switching in the converters.

MPPT (Maximum Power Point Tracking):

The wind turbine control strategy consists of four operation zones illustrated in the following figure.

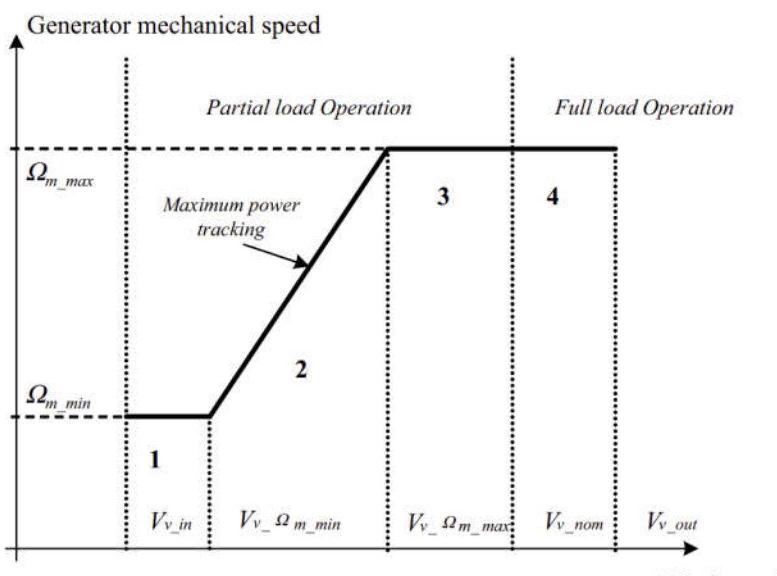


Figure 25: Wind Turbine Control Strategy Based on Four Speed Regions

The four speed regions are:
1. Limit the minimum speed of operation.
2. Follow the curve of maximum power extraction from variable speed operation with partial load.
3. Limit the maximum speed at partial load operation.
4. Limit the maximum operating speed at rated power output.

In zone 2, the objective of speed control is to follow the path of maximum power extraction. Variable speed wind turbines are dynamically stable around any point in the power vs speed curve when operated in zone 2. This stability property is used to design an indirect method of controlling speed of generator rotor.

When the wind speed changes, the turbine speed and torque will also change. When the turbine is operating on the maximum power point, the aerodynamic torque extracted is given by the following equations.

$$T_t = \frac{1}{2}\rho\pi\frac{R^5}{\lambda_{opt}^3}C_{p,max}\Omega_t^2 = k_{opt\_t}\Omega_t^2$$

$$k_{opt\_t} = \frac{1}{2}\rho\pi\frac{R^5}{\lambda_{opt}^3}C_{p,max}$$

Turbine speed is given input to MPPT system which generates a torque reference for the generator based on the above equations. This reference is passed to the rotor-side-control which controls the speed of the generator and rotor. Subsequently, speed of turbine is controlled as the generator rotor and turbine are connected by drive trains.

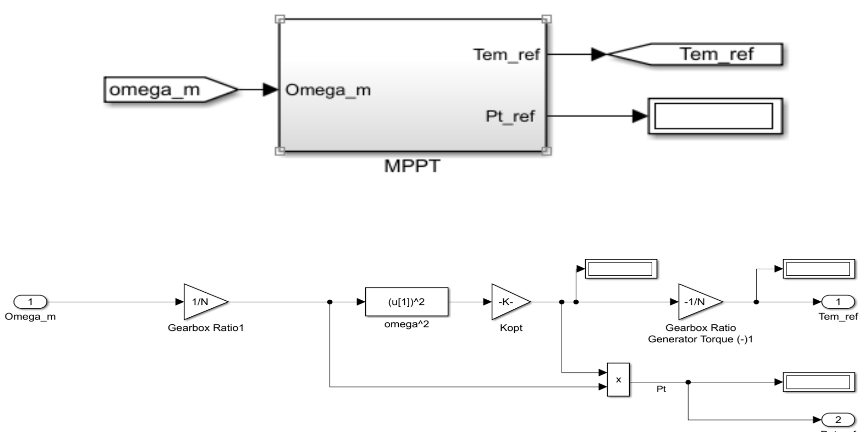


Figure 26: MPPT for Wind Turbine

Complete Project Model:

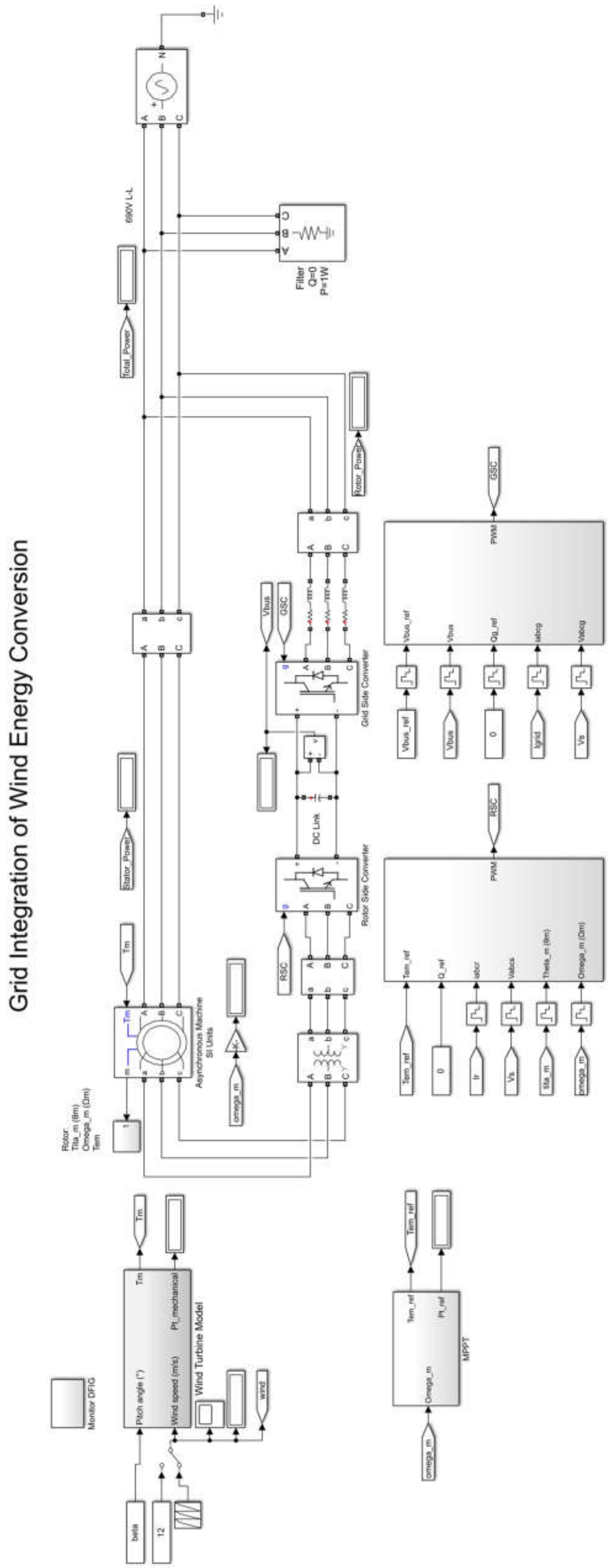
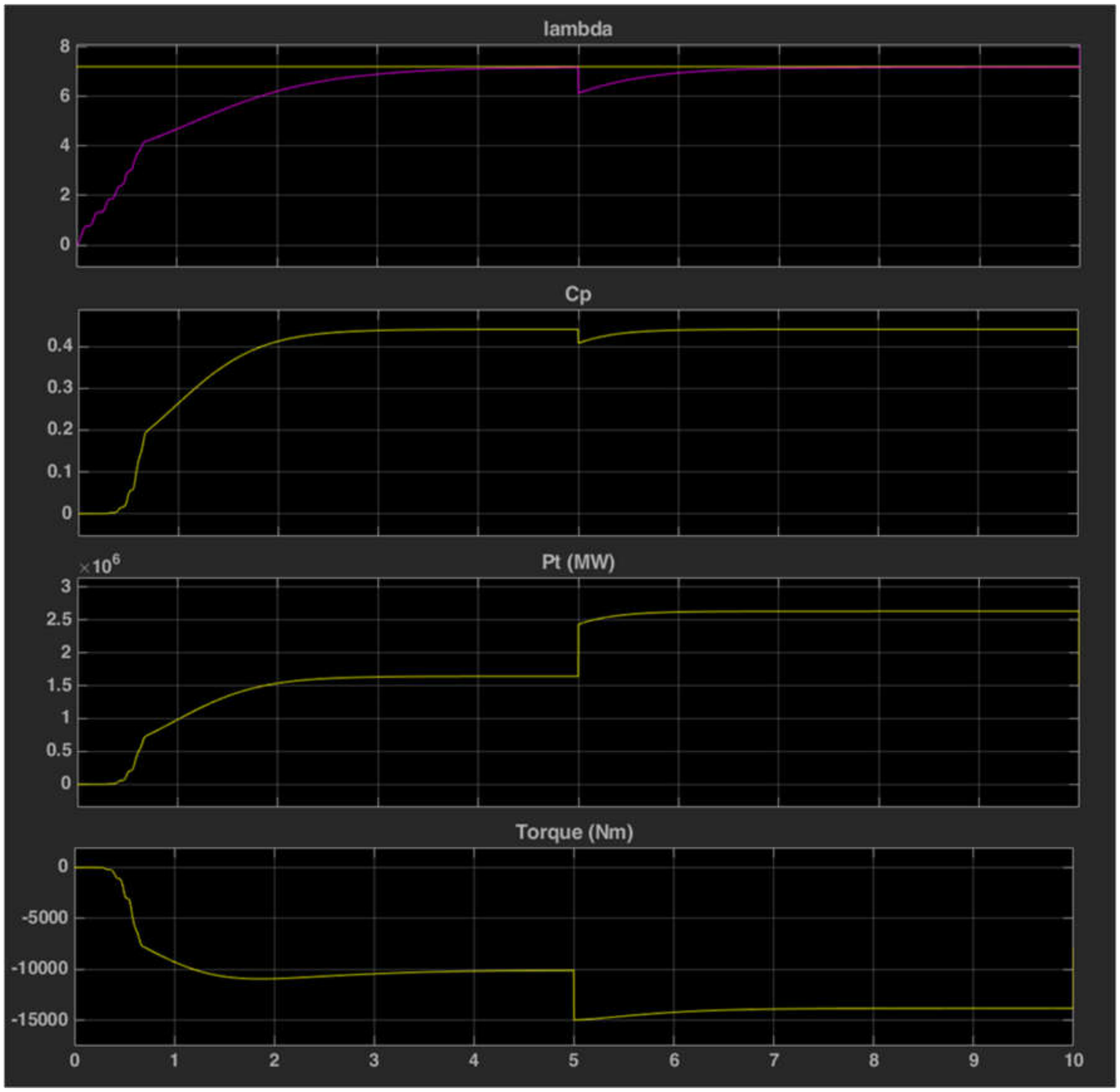


Figure 27: Grid Integration of Wind Energy Conversion System

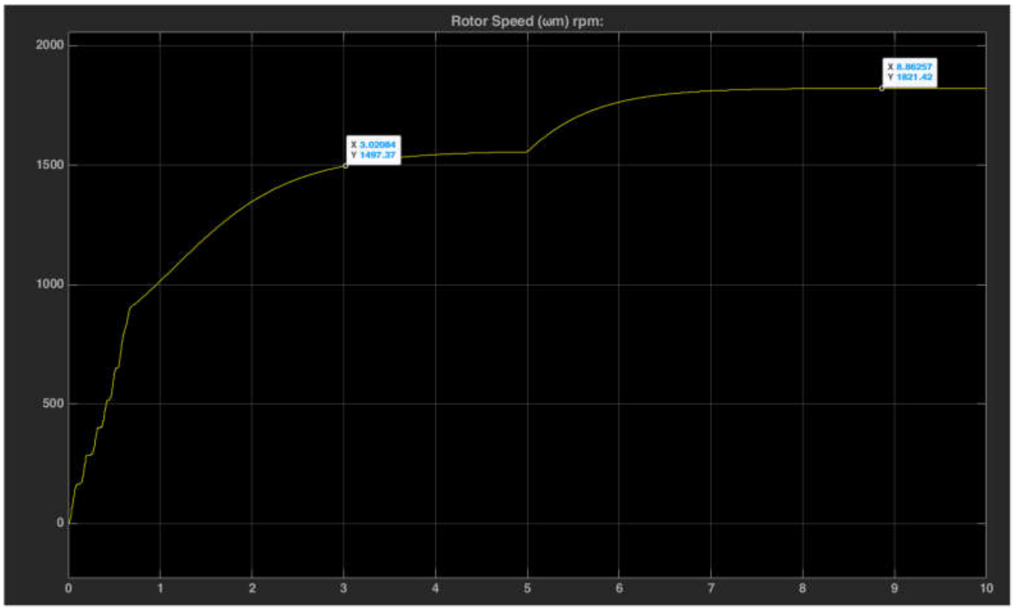
Simulation Results:

The simulation is run for 10 seconds. At starting, slip is 1 which means the generator is stationary. Wind speed is initially 10 m/s and is kept at this value for 5seconds. At 5th second, wind speed is suddenly changed to 11.7 m/s and is kept constant for the remainder of simulation.

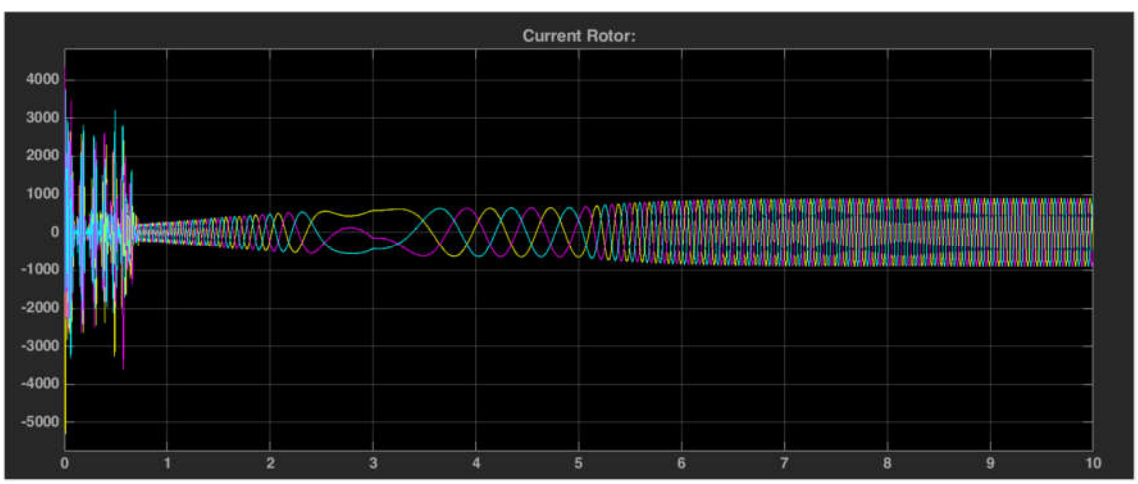


Tip speed ratio, lambda and power coefficient, Cp start from zero and reach the optimal values within 4s due to maximum power point tracker. The turbine output power and torque reach steady state value of about 1.6 MW and 10000 Nm. At t = 5s, the wind speed is changed to 11.7 m/s. This cause sudden decrease in lambda and hence in power coefficient. However, since the wind speed increased, available wind power increased and so, the turbine output power and torque increased. This output power is not the maximum power extractable at 11.7 m/s wind speed. The MPPT system tracks lambda and Cp again to optimal values.

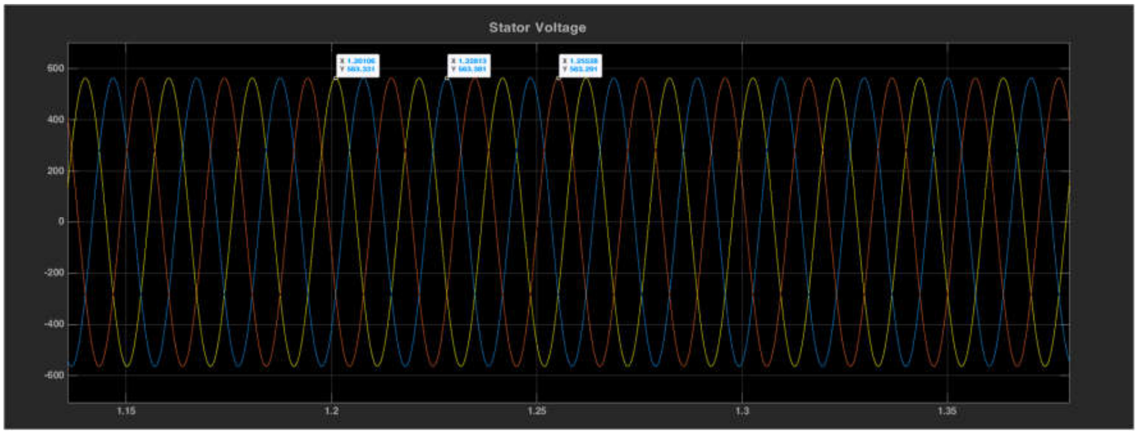
New steady state turbine output is about 2.6MW. Some amount of power will be lost in conversion from mechanical power to electrical power. Since we want electrical output to 2.5MW, the turbine rated output should be somewhat higher. This wind speed is be the rated wind speed and if the wind speed increases further, the output power should be held be constant.



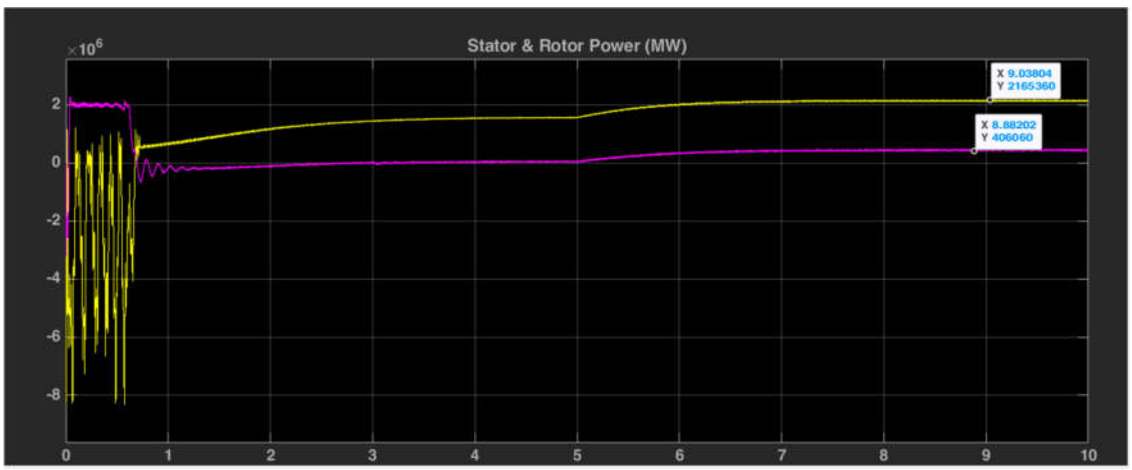
Next, we observe the change in generator rotor speed. For 2.5MW generation, the steady state rotor speed is 1821 rpm. The nominal speed of the rotor is 1500 rpm. This speed is crossed at t=3s and the generator switches from sub-synchronous to hyper-synchronous mode of operation. The rotor receive power from grid until 3s and start supplying power to grid after t=3s.



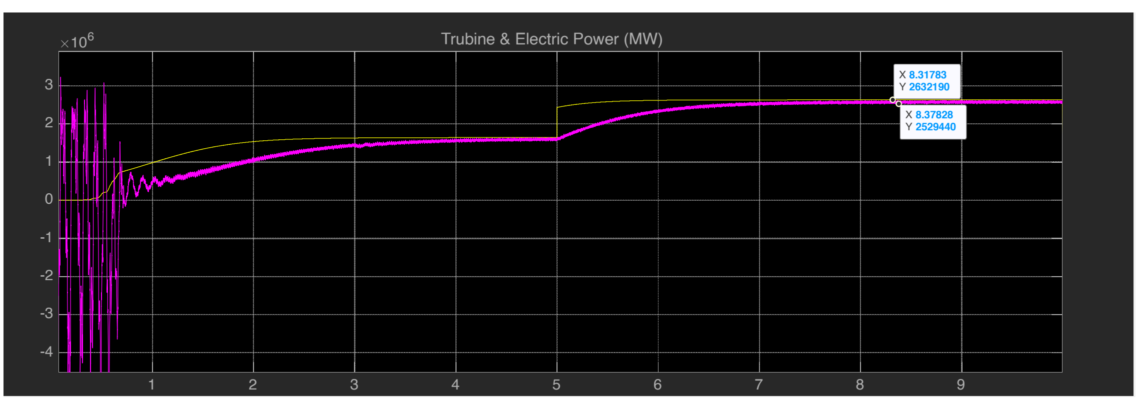
This plot shows the rotor current. Skipping the transient portion of the graph, we observe phase switching at t = 3s. This is expected as direction of power flow takes place at this instant.



The stator voltage is observed in the graph. The stator is directly connected to the grid which is modelled as a programmable voltage source. The grid voltage is set to 690V L-L (rms). The graph is plotted for phase-to-neutral stator voltages. The peak value for each phase is 563V. So, the line-to-line rms value is $\frac{563}{\sqrt{2}} * \sqrt{3} = 690V$.



Next, we observe the stator and rotor power curve. At steady state, both are supplying power to grid. Stator being the major contributor, provides about 2.1MW and rotor provides 0.40W.



Finally, both turbine mechanical power and generator electrical power is plotted in the same window. Mechanical power is 2.63MW and the converted electric power is 2.53MW.

Limitation of the Model:

The model's primary drawback is that it does not contain turbine speed control techniques for all four modes of operation. If the wind speed exceeds the rated speed, the model does not maintain constant output power. The rotor's maximum speed is not regulated. The model also lacks a pitch controller and a yaw mechanism. The model uses ideal wind energy equation to build a simplified aerodynamic model for a wind turbine and ignores the complex mechanical equivalent system of a gear drive train, which will have high inertia and damping effects. For the gear ratio, it simply employs a gain. Simple PI controllers are used in the control system for rotor and grid side converters. Phase Locked Loop can be used to construct more complicated controllers (PLL).

Conclusion:

The integration of wind energy conversion systems into the grid is a crucial step towards a more sustainable and reliable energy future. With the increasing demand for renewable energy sources, the integration of wind energy into the grid will play a vital role in reducing greenhouse gas emissions and promoting energy independence. However, it is important to consider the technical and economic challenges associated with this integration, such as variability and unpredictability of wind energy, as well as the need for storage systems and improved grid management practices. Nonetheless, with the right policies, infrastructure and technologies in place, wind energy can make a significant contribution to meeting the energy needs of society, while reducing dependence on fossil fuels and protecting the environment.