ABSTRACT

This project focuses on the implementation of a fixed-speed wind turbine model for induction generator-based Wind Energy Conversion Systems (WECS) and aims to simulate the model in MATLAB R2023b Simulink. Firstly, the project involves the development and implementation of the fixed-speed wind turbine model to facilitate a comprehensive study of its operational characteristics. Through this model, the power and torque curves of wind turbines will be thoroughly analysed to gain insights into their performance under varying wind conditions. Furthermore, particular importance will be placed on investigating the pitch control system's functionality, particularly in high wind-speed scenarios. Furthermore, it seeks to contribute to knowledge development by simulating the model in MATLAB R2023b Simulink and explaining the various parameters that can affect wind turbine system dynamics.

I. INTRODUCTION

The demand for energy is increasing steadily, and relying solely on fossil fuels won't be sufficient in the long run. Hence, turning to renewable energy sources is crucial. Among these, wind energy is particularly promising and is the main focus of this report. In a wind energy system, wind's kinetic energy drives turbines, creating mechanical motion. This motion is then converted into electrical power by generators connected through gearboxes. The electricity produced is then either used immediately or stored for later use.

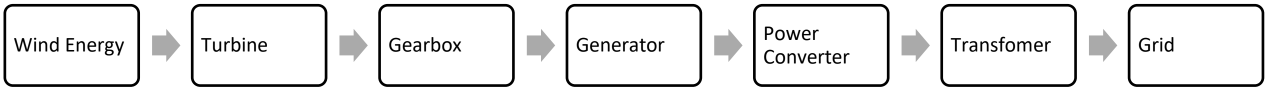


Fig.1 Schematic of wind energy conversion system

Wind energy systems come in two main types: fixed-speed and variable-speed turbines. Fixed-speed turbines maintain a constant rotation speed, ensuring a steady power output regardless of wind speed. However, they have drawbacks such as power fluctuations and a need for additional reactive power support. To explore these dynamics, this project aims to develop a detailed model of fixed speed turbine with various components and simulate it using MATLAB R2023b Simulink. Through this simulation, we seek to gain a deeper understanding of wind turbine operations and characteristics, contributing to advancements in renewable energy technologies.

II. SIMULATION DATA AND RESULTS

As part of our project, we are tasked with implementing a fixed-speed wind turbine system. To achieve this, we have been provided with parameters to develop the model using MATLAB R2023b. The parameters are mentioned in Table 1[1].

TABLE 1. Fixed Speed Wind Turbine Parameters

Parameter	**Symbol**	**Value**
Rated Generator Apparent Power	S_R	2.59 MVA
Rated Mechanical Input Power	P_m	2.3339 MW
Rated Generator Output Power	P_s	2.3 MW
Generator Line-Line RMS Voltage	$V_{s,LL}$	690 V (rms)
Generator Rated Frequency	f_s	50 Hz
Number of Pole Pairs	P	2
Rated Generator Speed	$n_{m,R}$	1512 rpm
Initial Generator Speed	$n_{m,init}$	1450 rpm
Stator Winding Resistance	R_s	1.102 mΩ
Stator Winding Leakage Inductance	L_{ls}	0.06492 mH
Rotor Winding Resistance	R_r	1.497 mΩ
Rotor Winding Leakage Inductance	L_{lr}	0.06492 mH
Magnetizing Inductance	L_m	2.13461 mH
Moment of Inertia	J	1200 kg-m^2

Parameter	Symbol	Value
Rated Turbine Output Power	$P_{M,R}$	2.3339 MW
Rated Generator Mechanical Input Torque	$T_{m,R}$	14.74 kN.m
Rated Turbine Speed	$n_{M,R}$	16 rpm
Air Density	ρ	1.225 kg.m^3
Turbine Rotor Radius	r_T	46.5 m
Gear Ratio	r_{gb}	94.5
Rated Wind Speed	$v_{W,R}$	12 m/s
Turbine Constants	C_1-C_7	0.7029, 116.055, 0.4, 0, 8.6614, 21.5, 0.00684
Grid Line-Line RMS Voltage	$V_{g,LL}$	690 V (rms)
Grid Frequency	f_g	50 Hz

As per these parameters, I had designed the fixed speed wind turbine system model in MATLAB R2023b[1]. The model is shown in Fig. 2

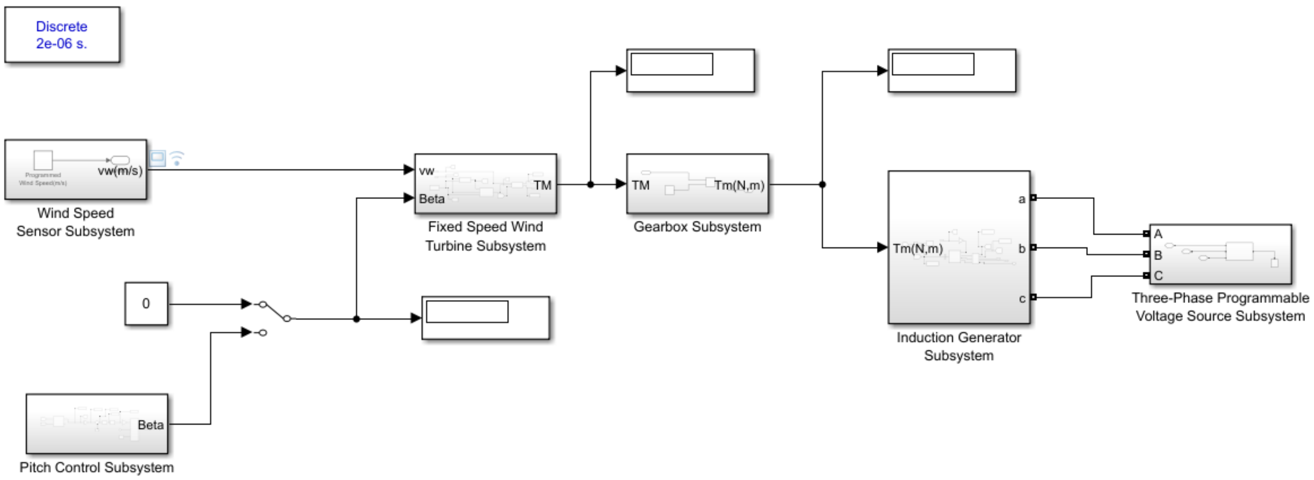


Fig. 2 Simulink Model of Fixed Speed Wind Turbine using Simscape Toolbox

In this model, we have designed various subsystems such as wind speed sensor, fixed speed wind turbine subsystem, gearbox subsystem, pitch control subsystem, induction generator subsystem, and three phase voltage source subsystems as per project instructions[1].

A. Simulation Results

Task-1[2]: Simulate model without Pitch Control Subsystem (0 to 2s)

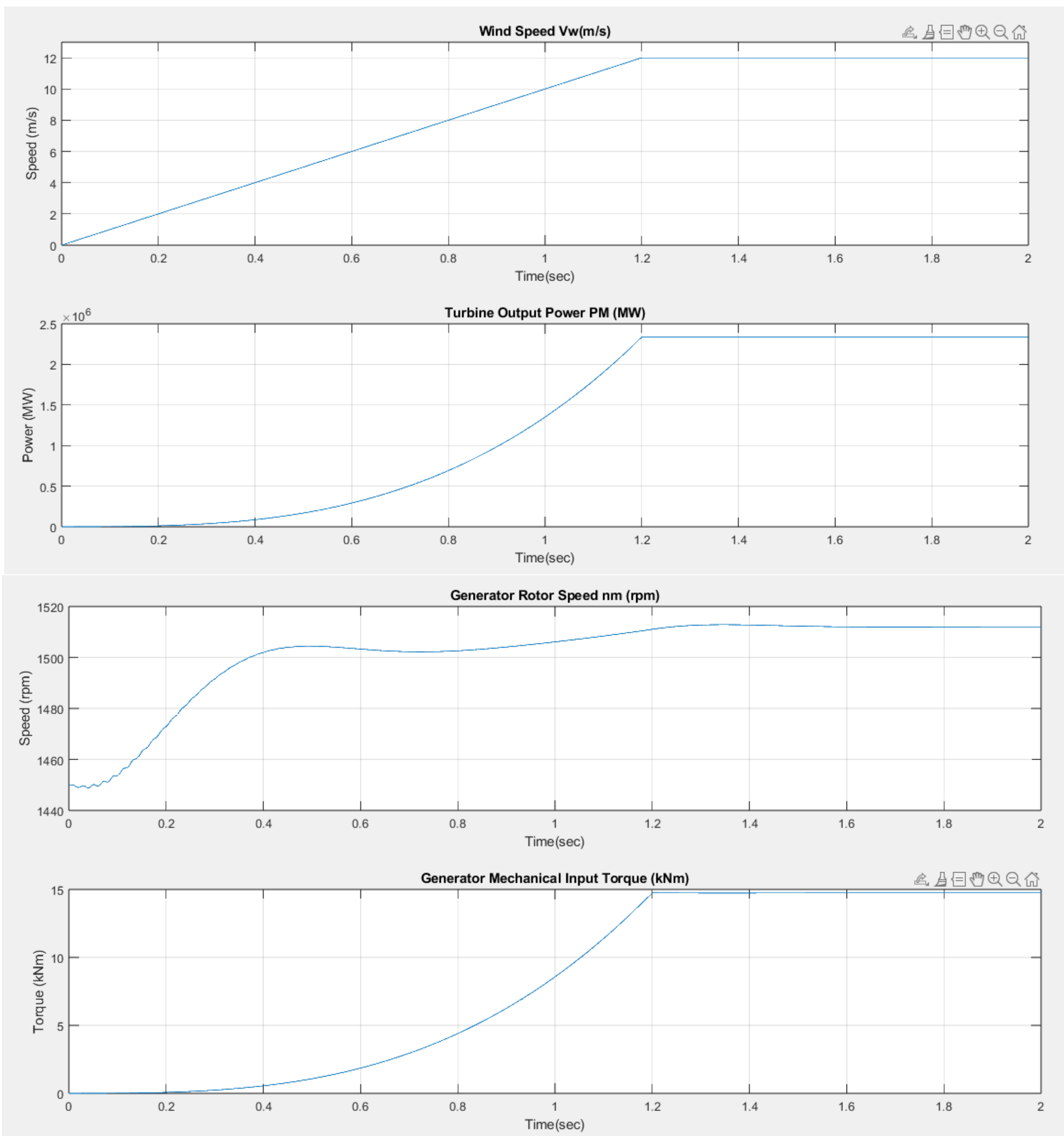


Fig. 3 Results of Task-1

Task-2[2]: Simulate Model with Pitch Control Subsystem (0 to 4s)

Part1: With Pitch Control Subsystem in Off State

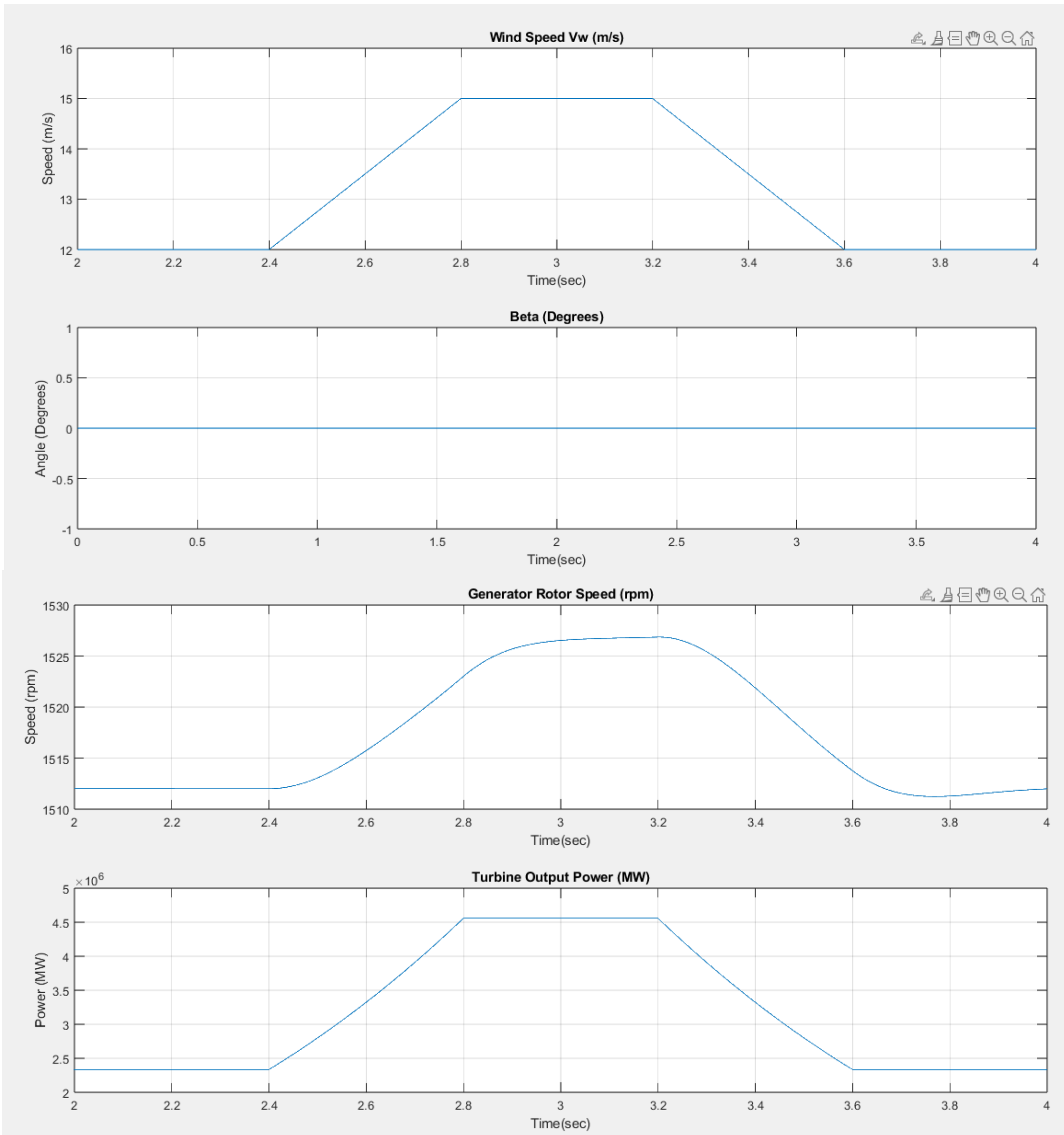


Fig. 4 Results of Task-2(Part-1)

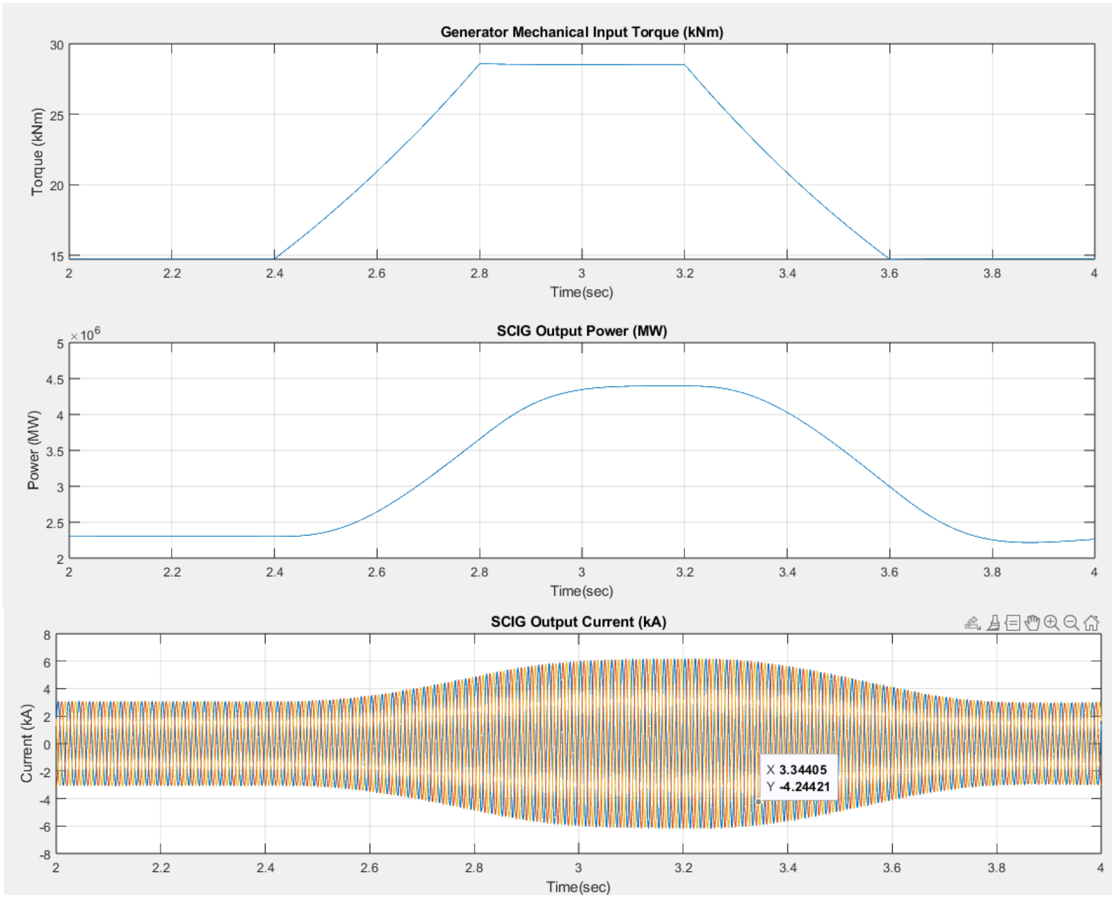
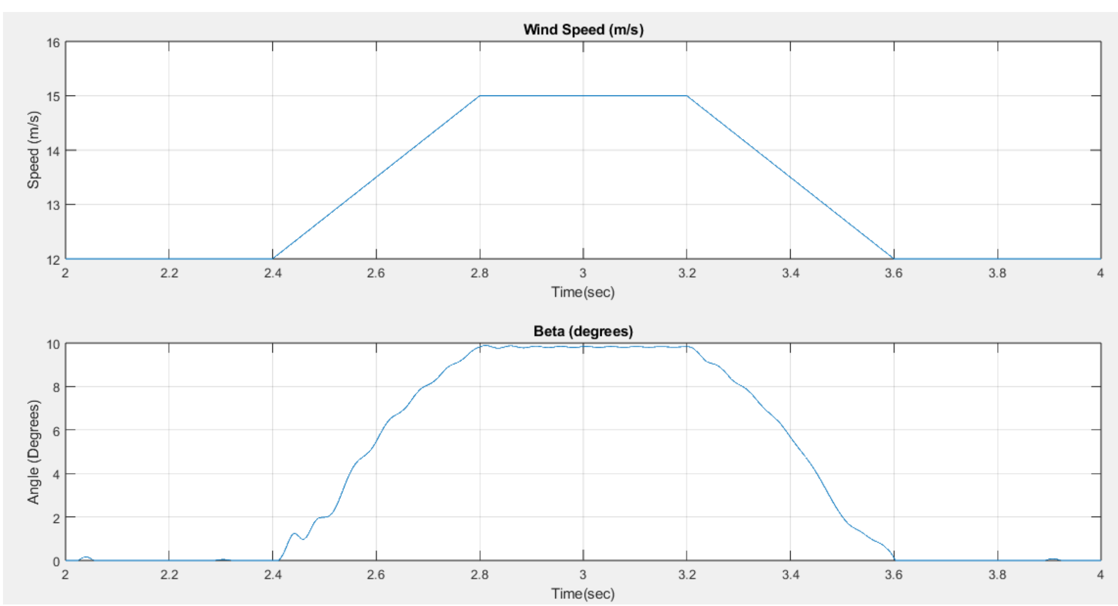


Fig. 4 Results of Task-2(Part-1)

Part2: With Pitch Control Subsystem in On State



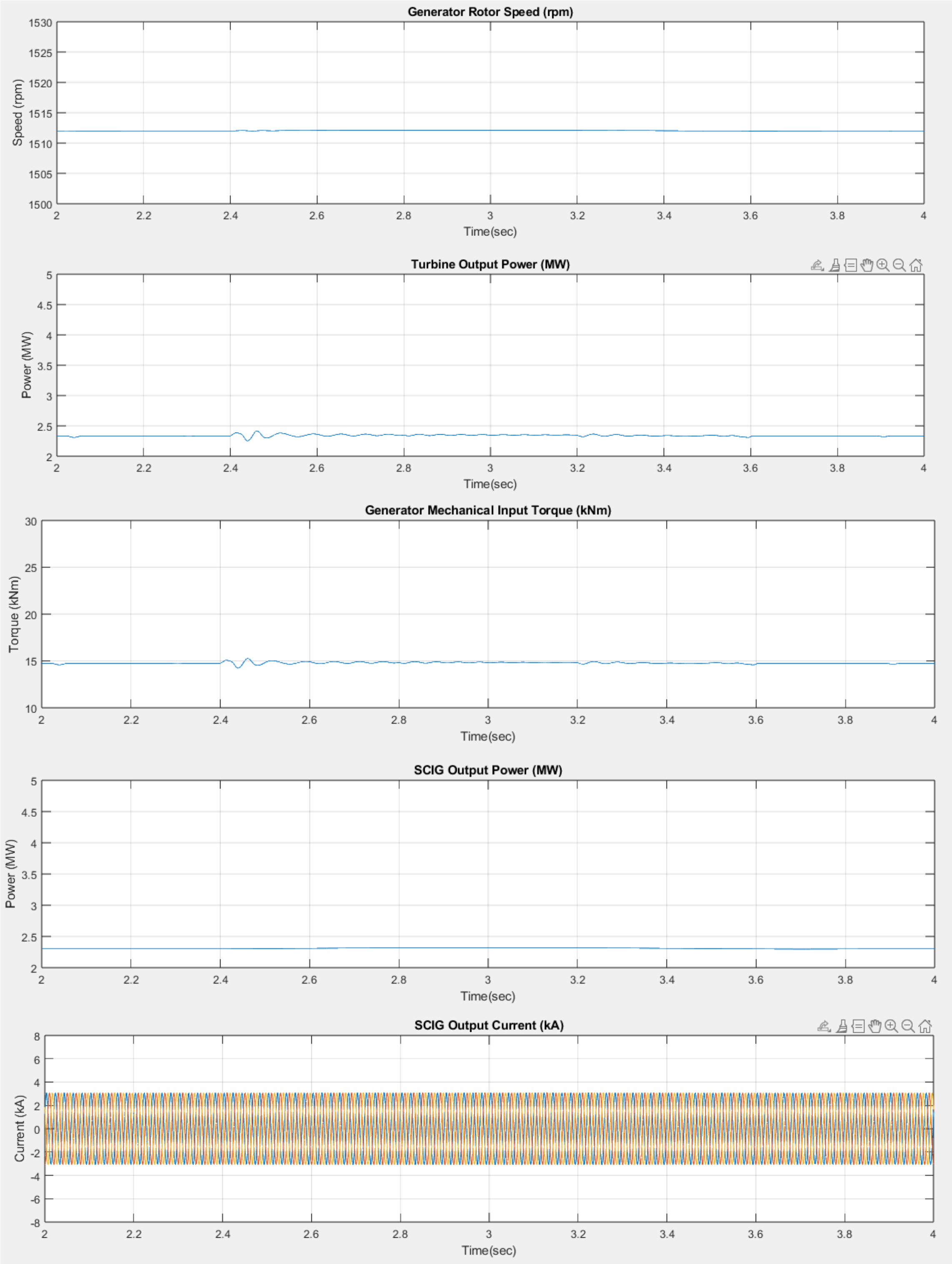


Fig. 5 Results of Task-2(Part-2)

Task-3: Compare theoretical data with simulated data

TABLE 2. Parameters comparison between theoretical and simulated values

Parameters	Measured Values		Calculated Values	
v_W (m/s)	12	15	12	15
β (deg)	0	9.831	0	9.825
$\lambda_{T,opt}$	6.493	6.493	6.4926	6.4926
λ_i	8.402	7.281	8.4033	8.4033
C_p	0.3246	0.1671	0.3245	0.1674
ω_M (rad/s)	1.6751	1.676	1.6755	1.6755
P_M (MW)	2.334e+06	2.347e+06	$2.3330 * 10^6$	$2.3506 * 10^6$
T_m (kNm)	1.474e+04	1.482e+04	$1.4733 * 10^4$	$1.4846 * 10^4$

B. *Calculations*

Part 1[2]: $v_W = 12$ m/s and $\beta = 0$

For, λ_T

$$\lambda_T = \frac{n_{M,R} \times \left(\frac{2\pi}{60}\right) r_T}{v_{w,R}}$$

$$\lambda_T = \frac{16 \times \frac{2\pi}{60} \times 46.5}{12}$$

$$\lambda_T = 6.4926$$

For, λ_i

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

$$\frac{1}{\lambda_i} = \frac{1}{6.4926} - 0.035$$

$$\lambda_i = 8.4033$$

For, C_p

$$c_P = c_1(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^2 - C_5)e^{-\frac{C_6}{\lambda i}} + C_7\lambda_T$$

$$Cp = 0.7029\left(\frac{116.055}{8.4033} - 8.6614\right)e^{\frac{-21\cdot5}{8.4033}} + 0.00684(6.5)$$

$$c_P = 0.3245$$

For, ω_m

$$\omega_m = \omega_{m,R}$$

$$\omega_m = \eta_{m,R} \times \left(\frac{2\Pi}{60}\right)$$

$$\omega_m = 1.6755$$

For, P_M

$$P_M = \frac{1}{2}\rho A v_w^3 C_P$$

$$P_M = \frac{1}{2} \times 1.225 \times 6792.908 \times (12)^3 \times 0.3245$$

$$P_M = 2.3330 \times 10^6$$

$$P_M = 2.3330\ MW$$

For, T_m

$$T_M = \frac{P_M}{\left(\frac{\omega_m}{r_{gb}}\right)} = 1.3906 \times 10^6$$

$$Tm = \frac{T_M}{94.5} = \frac{1.3906 \times 10^6}{94.5} = 1.47 \times 10^4$$

Part 2[2]: $v_w = 15$ m/s and $\beta = 9.825$

For, λ_T

$$\lambda_T = \frac{n_{M,R} \times \left(\frac{2\pi}{60}\right) r_T}{v_{w,R}}$$

$$\lambda_T = \frac{16 \times \frac{2\pi}{60} \times 46.5}{12}$$

$$\lambda_T = 6.4926$$

For, λ_i

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

$$\frac{1}{\lambda_i} = \frac{1}{6.4926 + (0.08 \times 9.825)} - \frac{0.035}{(9 \cdot 825)^3 + 1}$$

$$\lambda_i = 7.2766$$

For, C_p

$$c_P = c_1(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^2 - C_5)e^{-\frac{C_6}{\lambda i}} + C_7\lambda_T$$

$$Cp = 0.7029\left(\frac{116.055}{7.2766} - (0.4 \times 9.825) - 0 - 8.6614\right)e^{\frac{-21 \cdot 5}{7.2766}} + 0.00684(6.5)$$

$$c_P = 0.1674$$

For, ω_m

$$\omega_m = \omega_{m,R}$$

$$\omega_m = \eta_{m,R} \times \left(\frac{2\Pi}{60}\right)$$

$$\omega_m = 1.6755$$

For, P_M

$$P_M = \frac{1}{2}\rho A v_w^3 C_P$$

$$P_M = \frac{1}{2} \times 1.225 \times 6792.908 \times (15)^3 \times 0.1674$$

$$P_M = 2.3506 \times 10^6$$

$$P_M = 2.3506\ MW$$

For, T_m

$$T_M = \frac{P_M}{\left(\frac{\omega_m}{r_{gb}}\right)} = 1.402 \times 10^6$$

$$Tm = \frac{T_M}{94.5} = \frac{1.402 \times 10^6}{94.5} = 1.4846 \times 10^4$$

C. Explaination

For the Pitch Control Subsystem in OFF Condition:

In this condition, wind speed will reach 12 m/s, so the output power will have a cubic relationship with wind speed.

$$P_M = \frac{1}{2}\rho A v_w^3 C_P$$

$$P_M \propto v_w^3$$

So, as wind energy increases, the output power will also increase. As the output torque depends on the output power, as the power increases, the output torque also increases. So, we will see a cubic relationship in torque as well[3].

$$T_M = \frac{P_M}{\left(\frac{\omega_m}{r_{gb}}\right)}$$

$$T_M \propto P_M$$

For the Pitch Control Subsystem in OFF condition with a wind speed of 15 m/s:

As the wind speed increases, the output power also increases. Due to this, the output power will exceed the rated power of the wind turbine, which increases the flow of current. This will damage the wind turbine system and affect power generation. As per the analysis of the simulation, we can see that when the wind speed increases by the rated wind speed, the output power also increases, and the current flow in induction generation also increases by the rated value. We can see some fluctuations in current and power between a time interval of 2.6 sec and 3.8 sec.

For the Pitch Control Subsystem in ON condition with a wind speed of 15 m/s:

When the value of wind speed exceeds the rated value, the pitch control system takes every parameter into account, allowing it to control the varying parameters and keep the values steady during high wind speeds, which will protect the turbine from damage. As per the analysis of the simulation, we can see that the wind speed reached its maximum value, but the current from the generator and the generator mechanical input torque remain steady due to the pitch control subsystem. As we can observe from 2.6 sec to 3.8 sec, the value of the current remains steady at -4 kA to 4 kA.

III. PROJECT QUESTIONS

Q1. What parameters can be adjusted to increase the power output of wind turbine? Justify your explanation.
Ans) As per the formula for output power,

$$Pm = \frac{1}{2}\rho A v_w^3 C_P$$

The power output of a wind turbine can be increased by increasing the radius of the blades. As in fixed speed, wind speed is constant, power coefficient is constant, and air density is also constant. So, we change the area by changing the radius of the turbine blades.

Q2. What is the maximum value of power coefficient (Cp) for the wind turbine model in this lab? What are the values of λ_i, λ_T and β to achieve maximum value for the Cp?
Ans) The maximum value of the power coefficient (C_p) for the wind turbine model is 0.3246. For achieving the maximum value for the $C_{p,}$ we should have $\lambda_i = 8.4033$, λ_T = 6.4926 and $\beta = 0$

Q3. Write the relation between λ_i and λ_T when pitch angle β is zero.
Ans) As per the formula of $\lambda_{i,}$

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

So, if we consider $\beta = 0$, then

$$\frac{1}{\lambda_i} = \frac{1}{\lambda_T} - 0.035$$

We can neglect 0.035, then

$$\lambda_i \approx \lambda_T$$

Q4. What is the purpose of gearbox? What is the value of gear ratio (r_{gb}) for the given wind turbine model? What is the r_{gb} value for direct drive wind turbines?
Ans) The purpose of the gearbox is to adjust the speed of the turbine with the generator. The turbine rotates at a slow speed, and if the generator works at a slow speed, then we will not have enough power generation. So, to overcome that problem, we use a gearbox so that the slow speed of the turbine is adjusted to the high speed of the generator to have enough power generation.

The value of the gear ratio as per our model is taken as 94.5.

For direct-drive wind turbines, the gear ratio will be equal to 1.

Q5. What are the limits (range) for cut-in wind speed, rated wind speed, and cut-out wind speed for MW-level variable-speed wind turbines? What is the wind speed limits for pitch control system?
Ans) The limits for wind speed as:

Cut-in wind speed: 3-5 m/s
Rated wind speed: 10-15 m/s
Cut-out wind speed: 25-30 m/s

The wind speed limits for pitch control systems is 12-25 mph

IV. CONCLUSION

The report details the effective deployment of a MATLAB Simulink model to simulate a fixed-speed wind turbine system utilizing the Simscape toolbox. It explores the impact of wind speed on energy generation, presenting data from turbines both with and without pitch control mechanisms. Fluctuations in wind speed can lead to operational instability and power output inconsistencies. Here, the pitch control system emerges as a critical factor, actively influencing outcomes by mitigating fluctuations and safeguarding the system against potential damage.

V. REFERENCES

[1] Prof. Apparao Dekka, "Project Instructions."

[2] Prof. Apparao Dekka, "Lecture Slides."

[3] B. Wu, Y. Lang, N. Zargari, and S. Kouro, *Power Conversion and Control of Wind Energy Systems*. 2011. doi: 10.1002/9781118029008.

VI. APPENDIX

1. Intermittent TSR Subsystem

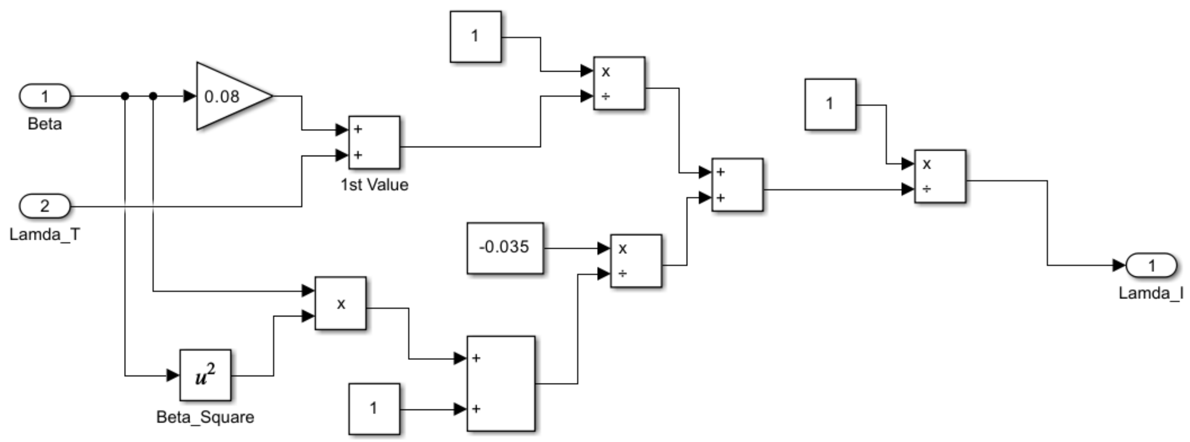


Fig. 6 Intermittent TSR Subsystem Block

2. Power Co-efficient Subsystem

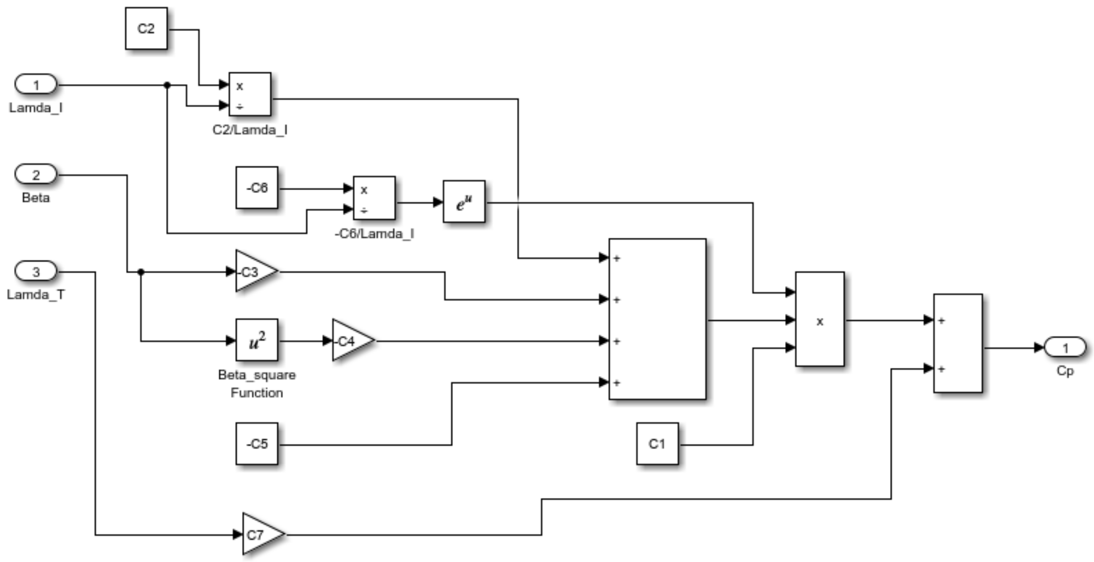


Fig. 7 Power Co-efficient Subsystem Block

3. Power and Torque Subsystem

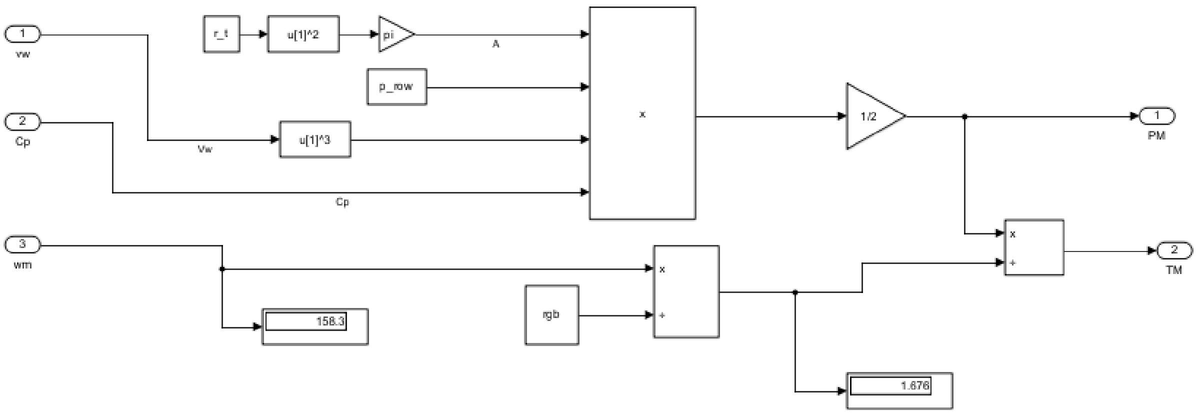


Fig. 8 Power and Torque Subsystem Block

4. Induction Generator Subsystem

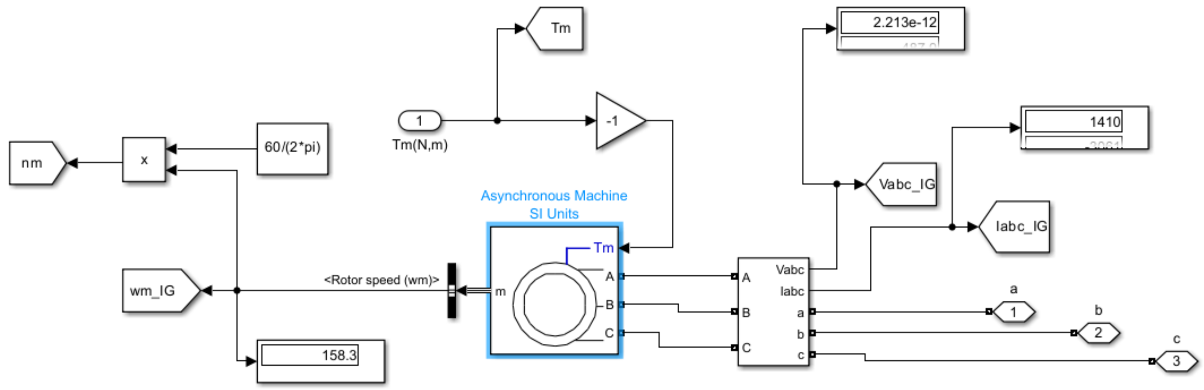


Fig. 9 Induction Generator Subsystem Block

5. Pitch Control Subsystem

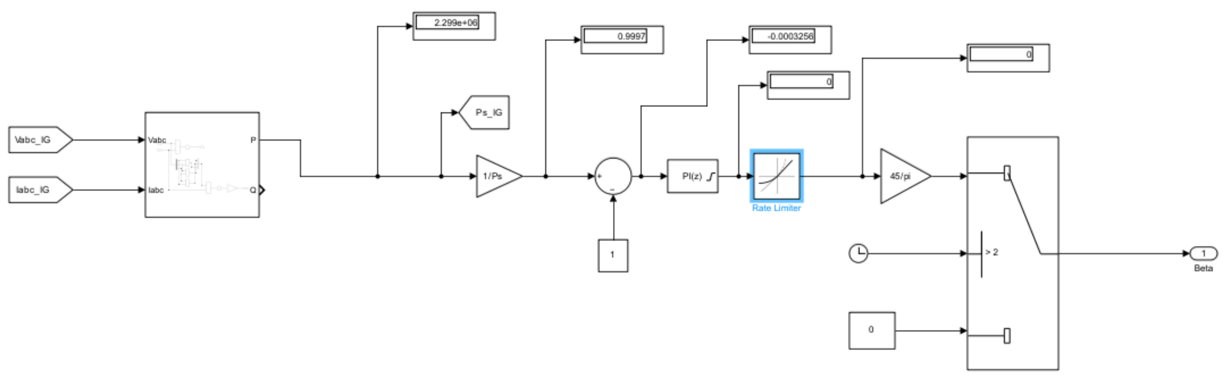


Fig. 10 Pitch Control Subsystem Block

Code:

Part 1: For Passing the constant values to Simulink Model

```
clc;
clear all;
close all;
Ps = (2.3e6);%Rated Generator output power (MW)
p_row = 1.225;%Air Density (kg/m3)
rgb = 94.5;%Gear Ratio

%To calculate optical tsr
n_mr = 16;%Rated RPM of Turbine
r_t = 46.5;%Turbine Radius (M)
v_wr = 12;%Rated Wind Speed
optical_tsr_value = (n_mr*(2*pi/60)*r_t)/v_wr;%Optical TSR Value

%Power Constants
C1 = 0.7029;
C2 = 116.055;
C3 = 0.4;
C4 = 0;
C5 = 8.6614;
C6 = 21.5;
C7 = 0.00684;

%Turbine Mechanical Speed
n_MR = 1512;%Rated RPM of Generator
WMR = (n_mr*(2*pi/60));%Rated Turbine Speed

%Sqirrel Cage Induction Generator Parameters
SR = 2.59e6; %Rated Apparent Power (VA)
VsLL = 690;%Line-Line rms Voltage (V)
Fs = 50;%Frequency (Hz)
Rr = 1.497e-3;%Rotor Winding Resistance
Llr = 0.06492e-3;%Stator Leakage Inductance
Lm = 2.13461e-3;%Magnetizing Inductance
P = 2;%Number of Pole Pairs
Rs = 1.102e-3;%Stator Winding Resistance
J = 1200;%Moment of Inertia
Pm = 2.3339e6;%Rated Mechanical Input Power (W)
nmInit = 1450;%Initial Rotor Speed (rpm)
Lls = 0.06492e-3;%Stator Leakage Inductance
nsyn = 120*Fs/(2*P);%Synchronous Speed (rpm)
slip = (nsyn-nmInit)/nsyn;%Slip

%Grid Parameters
VgLL = 690;%Grid RMS Voltage (V)
Fg = 50; %Frequency (Hz)
```

Part 2: For plotting graph for different parameters

```
%Time defined for plotting data between 0 to 4 sec
t = 0:0.000002:4;
time = t';
subplot(211);
plot(time,out.Tm/1000);
grid on; ylim([10 30]);
xlim([2 4]);
title("Generator Mechanical Input Torque (kNm)");
xlabel("Time(sec)"); ylabel("Torque (kNm)");
subplot(212);
plot(time,out.Iabc_IG/1000);
grid on; xlim([2 4]); ylim([-8 8]);
title("SCIG Output Current (kA)");
xlabel("Time(sec)"); ylabel("Current (kA)");
```

In plot code, variable t will be adjusted as per the output that comes from the Simulink. As per the output limit, the x-axis and y-axis are adjusted. As per requirement, we will plot the output and change the plot data.